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PhD Thesis Title:

3DCITYGH: an Expeditious Parametric Approach for Digital Urban Survey and City Information Modeling of city-block Structural Models

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To Catania, Florence and London,
the cities that made me an engineer and architect

“The mind is not a vessel to be filled but a fire to be kindled.”

Plutarch

ABSTRACT

The aim of the thesis is the definition of a parametric modelling methodology that allows, in a short time and at a sustainable cost, the digital acquisition, modelling and analysis of urban aggregates with the aim of facilitating seismic vulnerability mapping actions in historic centres. The research involves the use of direct data (site surveys) and derived data (available geodata) for the realisation of a parametric City Information Model (CIM). Grasshopper, a Visual Programming Language (VPL) within Rhinoceros, already widely used in the scientific community, was chosen as the working environment for the parametric computational design.

The methodology consists of several progressive steps that can be pursued through two innovative methods (*Survey-to-CIM* and *Scan-to-CIM*) defined and developed in this thesis. The choice of which method to adopt depends on the availability of project resources and the type of urban centre being studied. The first method, *Survey-to-CIM*, is intended to be a low-cost solution that integrates different data and acquisition techniques (direct survey, photo-rectification, expeditious 360 photogrammetry, Street-Level imagery, etc.) within a parametric and responsive flow useful for smaller urban centres and without the need for special professional skills. The second method, *Scan-to-CIM*, is developed to automate the cognitive operations of interpretation and input of survey data performed by the surveyor. This task is carried out by an Artificial Intelligence system that uses *Machine Learning* techniques (in particular *Random Forest*) to identify remarkable geometric-architectural features (openings, walls, stringcourses) within point clouds obtained through digital surveying. Both methods lead to the definition of a parametric CIM system developed in VPL.

The generated CIM model is equivalent to the definition of a semantic 3D City Model since all generated geometries, from the envelope to the interior, adhere to a semantic structure that defines relationships and dependencies. Since there are no guidelines in literature regarding the semantic structuring of city models in a parametric environment, an innovative format defined CityGH is proposed in this thesis. Based on the CityJSON standard, it proposes the same semantic structure of CityJSON but adapting it to the Data Structure of Grasshopper (Data Trees). This format is therefore proposed as an interchange format within parametric models to facilitate their dissemination and application. Thanks to its semantic structure, the parametric CIM model is capable of storing attributes and metadata that are fundamental steps in facilitating the beginning of the FEM analysis activities.

The parametric CIM model defined so far also allows the extraction of structural geometric models, both NURBS and MESH, necessary for the execution of FEM analyses. In particular, a workflow was developed in the thesis that allows FEM analysis both within the VPL environment (Karamba3D, Alpaca4D - OpenSees plugins) and in external software dedicated to structural analysis (SAP2000, FEM-Design).

KEYWORDS

- City Information Modeling;
- 3D City Models,
- Computational Design;
- Parametric Modelling;
- VPL;
- Digital Survey,
- Urban Survey,
- Seismic Risk,
- Scan-to-FEM

SOMMARIO

Scopo della tesi è la definizione di una metodologia di modellazione parametrica che consenta, in tempi brevi e con costi sostenibili, l'acquisizione digitale, la modellazione e l'analisi di aggregati urbani con l'obiettivo di facilitare le azioni di mappatura della vulnerabilità sismica nei centri storici. La ricerca prevede l'utilizzo di dati diretti (rilievi in sito) e derivati (geodati disponibili) per la realizzazione di un City Information Model (CIM) parametrico. Come ambiente di lavoro per la progettazione computazionale parametrica è stato scelto Grasshopper, un Linguaggio di Programmazione Visuale (VPL) all'interno di Rhinoceros, già ampiamente utilizzato nella comunità scientifica.

La metodologia è composta da diverse fasi progressive che possono essere perseguite attraverso due metodi innovativi (*Survey-to-CIM* e *Scan-to-CIM*) definiti e sviluppati in questa tesi. La scelta di quale metodo da adottare dipende dalla disponibilità di risorse del progetto e dal tipo di centro urbano oggetto di studio. Il primo metodo, *Survey-to-CIM*, mira ad essere una soluzione low-cost che integra diversi dati e tecniche di acquisizione (rilievo diretto, foto raddrizzamenti, fotogrammetria 360 speditiva, Street-Level imagery, etc.) all'interno di un flusso parametrico e responsivo utile per centri urbani minori senza la necessità di particolari competenze professionali. Il secondo metodo, *Scan-to-CIM*, è sviluppato per automatizzare le operazioni cognitive di interpretazione ed inserimento dei dati di rilievo eseguite dal rilevatore. Questo compito è svolto da un sistema di sistema di Intelligenza Artificiale che utilizza tecniche di *Machine Learning* (in particolare *Random Forest*) per individuare caratteristiche geometriche-architettoniche notevoli (aperture, muri, marcapiani) all'interno di nuvole di punti ottenute tramite rilievo digitale. Entrambi i metodi portano alla definizione di un sistema CIM parametrico sviluppato in VPL.

Il modello CIM generato corrisponde alla definizione di un 3D City Model semantico in quanto tutte le geometrie generate, dall'involucro agli interni, rispondono ad una struttura semantica che definisce rapporti e relazioni. Non essendo presente in letteratura alcuna linea guida circa la strutturazione semantica dei modelli di città in ambiente parametrico, in questa tesi viene proposto un formato innovativo definito *CityGH*, che su riferimento dello standard CityJSON propone la medesima struttura semantica di CityJSON ma adattandola alla *Data Structure* di Grasshopper (*Data Trees*). Tale formato si propone quindi come formato di interscambio all'interno di modelli parametrici per facilitare la diffusione e l'applicazione degli stessi. Grazie alla struttura semantica, il modello CIM parametrico è capace di immagazzinare attributi e metadati che risultano passi fondamentali per facilitare l'inizio dell'attività di analisi FEM.

Il modello CIM parametrico fin qui definito consente anche l'estrazione dei modelli geometrici strutturali, sia NURBS che MESH, necessari per l'esecuzione delle analisi FEM. In particolare, nella tesi è stato sviluppato un flusso di lavoro che consente l'analisi FEM sia all'interno dell'ambiente VPL (plugin *Karamba3D, Alpaca4D - OpenSees*) che in software esterni dedicati all'analisi strutturale (*SAP2000, FEM-Design*).

PAROLE CHIAVE

- City Information Modeling;
- 3D City Models,
- Computational Design;
- Modellazione Parametrica;
- VPL;
- Rilievo Digitale,
- Rilievo Urbano,
- Rischio Sismico,
- Scan-to-FEM

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01.

INTRODUCTION

1.1 Research Context

Earthquakes are natural phenomena that testify the dynamic activity of the planet in which we live. Their activity over the millennia has influenced the dynamics of entire civilizations always pushing for greater progress in construction and architecture because of the need to survive calamitous events. Seismic risk is a present-day subject for many countries around the world. Despite the knowledge and methods we currently have for earthquake countermeasures, economics has always been a barrier to the establishment of a safe state in many at-risk nations. As matter of fact, engineering seismic risk mitigation actions involve a knowledge phase that has costs even before those related to the necessary structural interventions.

In this scenario, knowing the different degrees of seismic vulnerability of an urban area makes it possible to establish priorities for intervention in order to optimize the financial resources available for the communities. For seismic risk mitigation, it is necessary to operate in terms of prevention and to propose plans that aim at the progressive reduction of exposure where economic capacity does not allow for intervention in the short term. Risk assessment is fundamental to trigger anti-seismic improvement processes based on intervention planning, especially with reference to historical city centers that were constructed decades (and centuries) before any regulation regarding seismic safety. Therefore, seismic vulnerability mapping is needed to estimate the level of risk, taking advantage of databases containing elementary and easily available information (number of floors, age of construction, materials, etc.) even at the scale of the individual building, in the unicum that it represents.

Among the areas most at risk there is the Mediterranean one, in which Italy is one of the countries at a very high level of risk. Indeed, Italy is located at the meeting point of the Eurasian plate and the African plate, in this area there are numerous faults, which determine the geological instability of the territory. Taking into account the earthquakes that have occurred in the past and continue to occur, the Italian peninsula appears to be particularly affected. More than thirty very strong earthquakes (with a magnitude greater than 5.8) have occurred since 1900 (Milano, 2013).

The vast extent of the historic (currently inhabited) building heritage and the large number of monumental architectures distributed all over the country made institutions define methodologies and approaches for the analysis of urban areas and valuable architectures. In 2011, the Italian Ministry of Infrastructure and Transport approved the “Guidelines for Seismic Risk Assessment in Cultural Heritage” (which in this thesis will be referred to as LLGG 2011) in which a workflow is defined for the knowledge of the urban built environment functional to seismic safety analysis (Ministry of Culture, 2018). The geometric survey and analysis of the historically-built masonry building, its technological system, and the construction techniques that distinguish it, are fundamental steps in analyzing and assessing seismic safety. Geometrical survey and technological recognition on a large scale (also by means of a rigorous classification of building elements) therefore become the main tools to be investigated and used for the purposes of mapping vulnerabilities as closely as possible to the actual state.

Therefore, being able to store and process in the same three-dimensional model the data relating to the registry of each building, its technical-constructive system, and its state of conservation represents today, more than ever, an invaluable resource to be able to estimate, quickly and with acceptable margins of error for an urban scale assessment, seismic vulnerability, possible safety interventions and the priority of interventions for the recovery of entire urban city blocks of considerable cultural importance. Currently, there might already be numerous data useful for designing a model such as the one described. Indeed, there are several (international, national, and local) databases and previous research that have not yet been systematically organized in a comprehensive city-wide analysis process.

Nowadays, many disciplines are experiencing a transformation process through complex digital media as part of the fourth industrial revolution (Industry 4.0), which is envisioned as a synergy of processes (automated and not) amongst diverse sectors. This transition has an impact on the construction, architectural, and spatial planning industries as well. These industries are transforming their working methods in favor of a digital strategy that optimizes processes by cutting costs and time while boosting the quantity and quality of output.

In this direction, one of the tools used by Civil Protection[1] to estimate the damage and viability of buildings in the post-earthquake phase is the manual compilation of Aedes matrix-based templates (fig. 1). Over the years, these have been complemented by the Erikus digital information system (Regione Piemonte, 2018). This digital system makes it possible to put together data from different sources (such as previous survey reports) and semi-automatically compile it within a Geographic Information System (GIS) environment Aedes forms. Although in several public administrations a process of digitization of the data present in the Aedes cards has been undertaken, these are delivered through GIS software which hardly manages to effectively represent data and features at the architectural scale.

GIS and BIM (Building Information Modeling) methodologies allow for the consideration of the territorial scale (GIS) to the individual building organism (BIM) in relation to specific and multipurpose data management activities (fig. 2). These methodologies are well suited to the needs imposed by the activities required for seismic risk assessment. Unfortunately, they are often adopted separately compared to the required level of knowledge, which leads to a wider approximation for the urban scale, affecting insufficient detail to establish the level of seismic safety with scientific validity.

[1] Civil Protection is an italian national institution for the safety of the citizens against any kind of risk scenario.

Fig. 1 | *Templates used for preventing and managing activities related to seismic risk scenarios (from left to right: GNDT, AeDES, SIVARS). These forms are filled out manually by an operator following predefined procedures. Thus, the validity of these forms depends on the competence of the operator.*

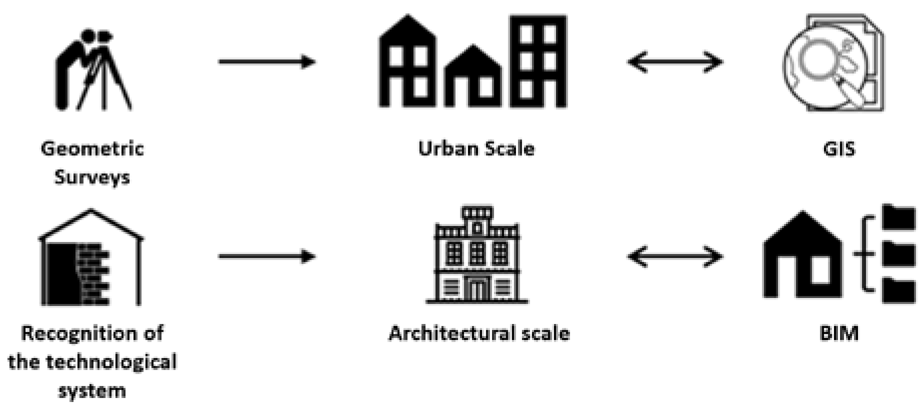


Fig. 2 | *Conceptual diagram of the workflows related to the knowledge process described in LLGG 2011.*

Over the past few decades, the human-machine relationship has progressed significantly due to the evolution and deployment of increasingly advanced technologies. One of the main objectives in the AEC sector has become to develop semi-automated solutions and workflows that can minimize repetitive and time-consuming activities, thus allowing professionals to focus on more valuable and relevant tasks. This has also had repercussions in the technological advancement of the previously mentioned methodologies by providing a range of solutions useful for different scenarios: from environmental analysis to form optimization and risk analysis.

In the context of this range of methodological paradigms and innovative solutions, the need has arisen in the national and international research community for a new approach that allows the integration of data from GIS and BIM environments with the aim of developing monitoring, management, and intervention strategies on an urban scale with a holistic approach: the so-called City Information Modeling (CIM). Academic contributions in this field are copious, spread all over the world, and have a strongly interdisciplinary character. CIM is an urban-scale Information Model in which features common to GIS and BIM models converge, from small to large scales. It is therefore a methodology that enables better structuring, processing, integration, and management of data and consequently multi-criteria queries and analyses.

In many cases, the logic used to structure CIMs is algorithmic, utilizing programming environments that permit the generation of codes that directly work in the 3D modeling space and construct parametric and responsive models for very specific objectives. There are currently few applications in the field, and those that exist have been created mostly in academic and software-related fields where it is simpler (for a general domain expert) to acquire computational skills and interact with other programmers. This is due to the high-level programming abilities required for these projects.

However, the gap between 'designer' and 'programmer' has been considerably reduced with the introduction of Visual Program Languages (VPLs) within modeling software to develop computational codes. Their ease of use lies in their visual nature and in a vocabulary of 'components' where the main grammatical rule consists in the relationship between input and output. The flexibility of VPLs makes them powerful tools in the management and processing of data (solving data interoperability issues between different BIM and GIS software, processing data of different natures), in the combination of data and geometric-spatial information, and in the use of complex computational techniques ranging from evolutionary optimization to Artificial Intelligence applications. In addition, the use of VPL can in fact smooth the learning curve required to adopt this solution thus supporting the development of increasingly advanced digital solutions used by a wider spectrum of professionals (fig. 3).

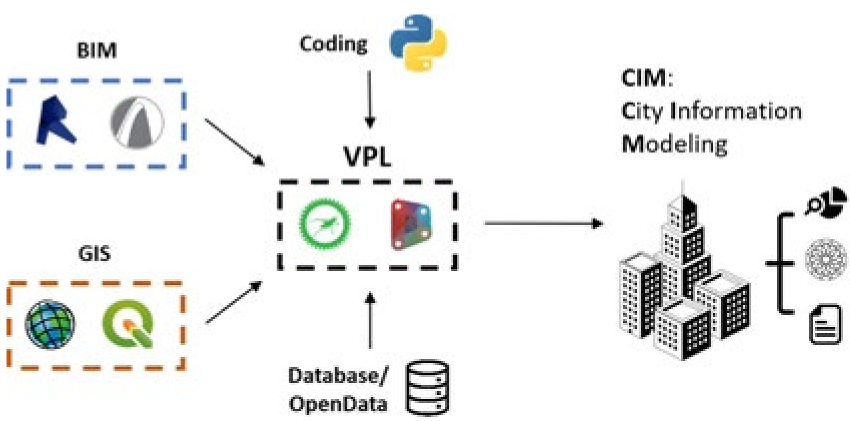


Fig. 3 | *Conceptual scheme for City Information Modeling using VPL programming environments related to the AEC industry.*

A parametric and responsive CIM can form the core of a possible DSS (Decision Support System), i.e. a digital support system for all those who need to undertake strategic decisions or automate manual operations so that professionals are allowed to concentrate on the tasks that need more of their focus. These systems make it possible to increase the effectiveness of analysis by overcoming the limitations of operational research and quickly extracting all useful information from large amounts of data. Moreover, due to its parametric and responsive nature, the structure of a CIM model can be easily extended, accommodating new instances that will become new parameters, and re-adapted to other study contexts/scenarios.

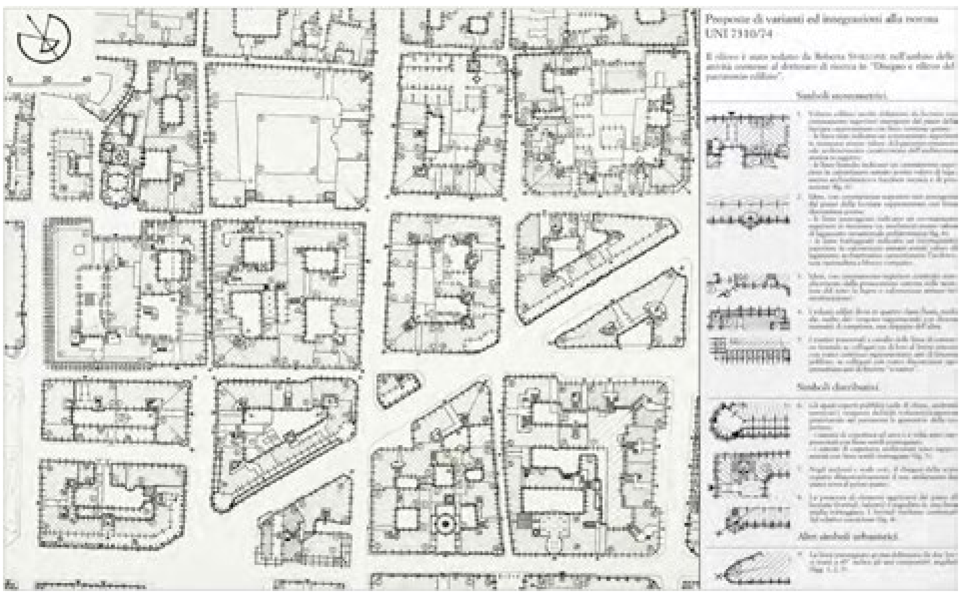
Aim of the this work is the definition of a parametric modeling methodology that allows, in a short time and with sustainable costs, the digital acquisition, modeling, and analysis of urban aggregates with the aim to facilitate actions of seismic vulnerability mapping in historical centers.

In particular, this research focuses on how the disciplines of architectural representation and surveying, in their digital applications, can accelerate the preliminary knowledge phase functional to seismic safety analysis in this way reducing the work burden on structural engineers. The main topic covered is 3D city modeling, seeking its contextualization with reference to the current City Information Modeling methodology approach and with application toward the creation of geometric models for FEM analysis. The application fields in which the work lies are those of digital surveying and explicit parametric modeling through the use of VPLs as programming tools. With reference to these fields, this work digresses with regard to current urban modeling procedures with an in-depth look at Scan-to-FEM techniques that enable discretized geometric models at the urban scale to conduct structural analysis.

1.2 Motivation for the study

The high seismicity of the Italian territory is undermining the integrity of our cities' built heritage. The workflow indicated by the LLGG 2011 Guidelines for seismic risk assessment and reduction describes an analysis of individual buildings. However, its extension to the scale of the city and urban aggregates requires that the survey takes into account the complexity and multidimensionality of the different aspects that characterize the city and urban structure. In fact, every single unit, besides being characterized by its specificity, is also related to the surrounding buildings. The consolidated methodologies of the Urban Survey (Baculo, 1994; Vernizzi, 2006; Caniggia et al., 2008; Garzino et al., 2019, Boido et al., 2021), describe and represent "the set of values present in the investigated realities, in order to build the set of formal and structural invariants" (Coppo and Boido 2010, p. 12), are still very topical today (fig. 4).

Fig. 4 | *Survey of the neighborhood of Via Pietro Micca (Turin) and analysis of the built environment according to UNI 7310/74 (Coppo & Boido, 2010).*



They provide the scientific background to the experiments related to the application of the City Information Modeling paradigm for the development of informed and responsive city models for seismic vulnerability assessment.

According to ISTAT data, more than half the population in Italy lives in buildings constructed before the 1970s. Moreover, the entire national territory (with the exception of Sardinia at present) is completely exposed to seismic risk. These indicative data demand attention since the first mandatory seismic standards for the design of residential buildings date back to the 1980s. There is therefore a need to adapt and improve the performance of the existing building stock in relation to seismic events.

However, economic resources are limited compared to the extent of the current building heritage, so it is essential to establish priorities for intervention (both public and private). This scenario is especially true in small realities, the so-called minor urban centers, which unfortunately when hit by seismic events are particularly vulnerable and for this reason are often the object of a gradual and often irreversible depopulation process, making the vast urban and architectural heritage represented by historic centers even more fragile.

A number of works in the literature highlight the efforts of the scientific community to manage the complexity of urban space in all its dimensions (physical, economic, social, risks, etc.). The smart cities paradigm for enhanced management of all urban processes is becoming an increasingly widespread practice but is almost always relegated to large urban centers with the support of considerable economic resources.

In reference to seismic vulnerability in terms of SLV (Lifesaving Limit State), as described in the LLGG 2011, it is possible to determine it, with a level of accuracy suitable for urban planning needs, by means of methodologies applicable on an urban scale. "*The assessment of the SLV (Lifesaving Limit State) using simplified methods based on a limited number of geometric and mechanical parameters or using qualitative data (visual interrogation, reading of building characters, critical and stratigraphic survey)*" - LLGG 2011. These methods are widely used for LV1 assessments ("for seismic safety assessments to be carried out at a territorial scale on all protected cultural heritage assets" - LLGG 2011) while LV2 and LV3 levels (which represent "an accurate assessment of the seismic safety of the artifact") are the objects of greatest interest and are obtained through modeling procedures that are onerous in terms of time, resources and skills employed.

In addition, the inability to determine certain building elements of the contruction, its geometric characteristics, or construction techniques during the expeditious survey phase, invalidates the reliability of these models at all three levels of evaluation, further diluting the analysis time.

These considerations lead to reflections on how to facilitate the knowledge process as set out in the LLGG 2011 in a sustainable and accessible way, even for smaller realities. Getting from survey to data and from these to seismic assessment as quickly as possible can be the key to seismic prevention in the territory.

Statistical methods and damage probability matrices are currently used to facilitate seismic safety knowledge and assessment operations. These methods, despite being fast and low-cost, often return results that differ from reality and are prone to the expertise of the operator. Indeed, in order to have more accurate information, it is necessary to conduct Finite Element Analysis (FEA) in digital environments. However, this type of analysis requires considerable surveying and modeling time and therefore is hardly applied to the urban scale. The key to implementing this analysis at the urban scale lies in the way of acquisition of urban data (geometric and informative) and in their management within appropriate modeling environments that allow their treatment. In many regions exposed to seismic risk, the data needed to perform this type of analysis are often out of date, unusable, or absent (Geiß, 2015). Furthermore, traditional processes for acquiring this information, which includes building-by-building inspections, are costly and time-consuming, making them impractical for evaluating a large building stock (Sulzer et al., 2018; Greco et al., 2020).

On the other hand, thanks to the evolution of geomatics methodologies several solutions are available today for acquiring large amounts of geometric data and generating complex models of real-world structural systems by exploiting point cloud processing. These procedures (known as Scan-to-FEM) are of support to define informative digital models useful for the purposes of modeling for FEA analysis. Although point cloud classification is largely optimized[2], automatic transition to useful informative digital models (BIM/GIS) for FEM analysis is currently a subject of research and in recent years parametric modeling is almost mainly used to solve problems related to interoperability with structural analysis software.

Compared to the research and mapping already carried out in the international and national fields that have contributed to the creation of different types of databases (WebGIS of territorial administrations, cadastral databases, open source portals such as OpenStreetMap, NASA topographical data, research on typical historical construction equipment, etc.) there are few experiments oriented towards the systemization of the different data using sophisticated and advanced techniques, through the automatic or semi-automatic implementation of three-dimensional systems at the scale of the city, up to the use of Artificial Intelligence to facilitate the seismic safety assessment of historical city blocks.

OpenData represents a huge potential for applications in various sectors and, in particular, in territorial government. To date, OpenStreetMap (OSM) is the largest collection of open-licensed geospatial data. It is a collaborative project started in 2004 to which one can contribute as Volunteer Geographic Information (VGI). These data can be used to create and implement 3D city models that represent Digital Twins (DT) of real cities. The concept of DT, although born in the manufacturing industry, has become central in several fields of knowledge, and represents a new way to better understand cities and intervene in their future. In the conceptualization of DT, its effectiveness is closely linked to the sensor network from which it acquires data (Batty, 2018).

Therefore, dealing with Big Data (conspicuous masses of digital data of different nature and sources) may contribute to the development of new appli-

[2] Over the past few years, great progress has been made in semantic segmentation through the application of Artificial Intelligence (Grilli et al., 2021).

cations, also considering the numerous databases of seismic vulnerability assessments already drawn up in Italy. In this direction, possible experimentation could be conducted by developing an innovative methodology using a CIM-type Informed Model of the city that allows, in the same digital ecosystem and overcoming interoperability issues, to process data typical of GIS environments by relating them to three-dimensional informed models typical of the BIM approach.

Indeed, considering the impact that BIM methodologies are having in the construction sector (also due to the cogency of some recent regulations on public procurement, D. Lgs. 50 of 2016 - Public Contracts Code and more generally related to the digitization of the assets of public administrations and the city) it is conceivable to assume that in the next few years there will be an increasing number of public administrations that will have at their disposal a large number of BIM models (as virtual replication of existing buildings semantically enriched with data) even for small private buildings that constitute a large part of minor and major historic urban centers.

In this scenario, City Information Models which rely on BIM and GIS assets could represent the digital environment in which data useful for FEM analysis can be created, treated, and exploited. The adoption of Computational Design into the field of 3D City Models led to the combining BIM and GIS procedures while minimizing input data and steps required for the main purpose of the 3D city model requested. In addition, the granularity of the data allows for a high level of interoperability among software environments involved in these processes.

Taking the above into account, two particular research gaps are highlighted in relation to the topic under consideration.

Currently, there are many 3D city model applications that integrate GIS and BIM elements, often also making use of the interoperability potential of VPL environments. However, frequently these applications result mostly in visualization with low levels of interaction (in some cases exclusively consultation of the input material). There are very few examples in the national and international landscape of integrating geometry and data semantically in accordance with the principles defined by City Information Modeling. This deficiency can be traced to the inobservance of international standards for 3D city modeling such as those defined by OGC CityGML (OGC CityGML 3.0, 2022). This shortcoming is very often due to the fact that these standards are tied to a digital format (CityGML) that is difficult to replicate in the absence of high programming skills. This leads to the absence of applications in the field of parametric modeling of informed city models adhering to the directions and standards close to the CIM methodology.

Regarding the pipeline of work related to the creation of structural geometric models based on reality capture strategies, it is also worth mentioning that there are not many applications for the adoption of computational design tools for optimizing and accelerating the Scan-to-FEM pipelines (Funari et al., 2021). Another research gap can be found in the lack of applications between city block acquisition modeling and a semi-automatic transition to FEA.

In conclusion, it is worth investigating a system that can accommodate these models and extract from them valuable information for seismic risk assessment and mitigation by also integrating material from expeditious surveys conducted on-site (photogrammetry, laser scanners, visual surveys, non-destructive surveys, etc.). Therefore, it is useful to realize a CIM-type Informed Model capable of gathering data from already existing databases as well as on-site acquired/collected data. The CIM model thus defined in a VPL-based parametric modeling environment can be appropriately tuned to obtain discretized structural geometric models ready to be launched within structural FEM software.

1.3 Research Goals

The theme of this thesis is the definition of a parametric modeling methodology that allows, in a short time and with sustainable costs, the digital acquisition, modeling, and analysis of urban aggregates with the aim to facilitate actions of seismic vulnerability mapping in minor and major historical urban centers.

Hence, the **Main Research Question (MRQ)** has been defined:

- MRQ: through which strategy is it possible to speed up the knowledge process established in the LLGG 2011 in a sustainable way that leads to an assessment that is as accurate and adherent to reality as possible in relation to the urban scale and the requirements of structural analysis?

Due to the complexity of the subject and the consequent need for an interdisciplinary approach, it seemed effective to pursue this direction of research by addressing three additional research questions (RQs) that are instrumental in defining the research objectives:

- **RQ 1:** Is it possible to semi-automate the process of geometric knowledge on the urban and architectural scale of the built heritage in historical centers?
- **RQ 2:** Is it possible to conduct expeditious and sustainable digital urban survey campaigns?
- **RQ 3:** Is it possible to obtain structural geometric models from a City Information Model to speed up the execution of structural analyses?

In connection with the above-mentioned RQs, it is possible to define the **Aim (A)** and **Objectives (O)** of the research as follows below:

- **A:** To develop an accessible, semi-automatic, and expeditious procedure to support seismic assessment procedures of historic urban centers and fabrics according to mechanistic methods.
  - **O1:** To develop a procedure for the investigation, survey, and parametric urban modeling of the existing heritage (specifically residential buildings in historical urban city blocks).
  - **O2:** Analysis and comparison of expeditious digital acquisition techniques of urban canyons.
  - **O3:** Discretization of parametric information CIM models into structural geometric models useful for generic FEM analysis engines.

1.4 Methodology proposal

The methodology proposed in this research finds its background in the ARIM methodology and the 2014 FIR project entitled "*The Seismic Vulnerability of Historic Aggregate Buildings. New structural modeling and expeditious methodologies and approaches*" (Calvano et al., 2019). This thesis advances this methodology by proposing an integrated approach between the two disciplines (urban surveying and parametric modeling, on the one hand, and building science on the other) without solutions of continuity.

The research involves the use of direct data (site surveys) and derived data (Geo-Data present in the territory) to create a City Information Model to support seismic assessment at the urban scale (fig 5).

This can be done by means of a parametric modeling system designed taking into account the possibility of using existing databases and data types that can be derived from operational protocols already employed by professionals. Two scenarios for the digital acquisition of urban canyons are considered. These are meant to represent the scalability of the digitization process and the different opportunities that small and large urban centers can adopt in accordance with their resources.

The first *(Survey-to-CIM)* takes into account current methods used for direct expeditious surveys by professionals and implements their workflow through VPL code developed using a GIS approach and starting from open databases such as OpenStreetMap. This approach is intended to be a low-cost solution that does not involve the use of advanced technologies nor requires high levels of expertise but significantly improves the collection and organization of data in order to inform the CIM model.

The second approach *(Scan-to-CIM)* adopts more advanced technologies and techniques related to the automatic semantic classification of urban canyon point clouds using Artificial Intelligence techniques (Random Forest). These semantic decomposed clouds are interpreted by the code developed in this work and the result is the automatic modeling of the city block under study. This approach, although a greater degree of automation is gained than the previous one, requires more expertise (particularly in the first phase of classification with Random Forest) and possibly mid and high-end acquisition sensors. However, in the long-term view, this approach will require less and less effort on the part of the operator.

In both scenarios, the system allows the individual three-dimensional units (the historic buildings of interest) to be enriched with information and geometries, with different levels of reliability in relation to the source of the information, and managing all single architecture components together by means of semantic relationships as employed in BIM methodology.

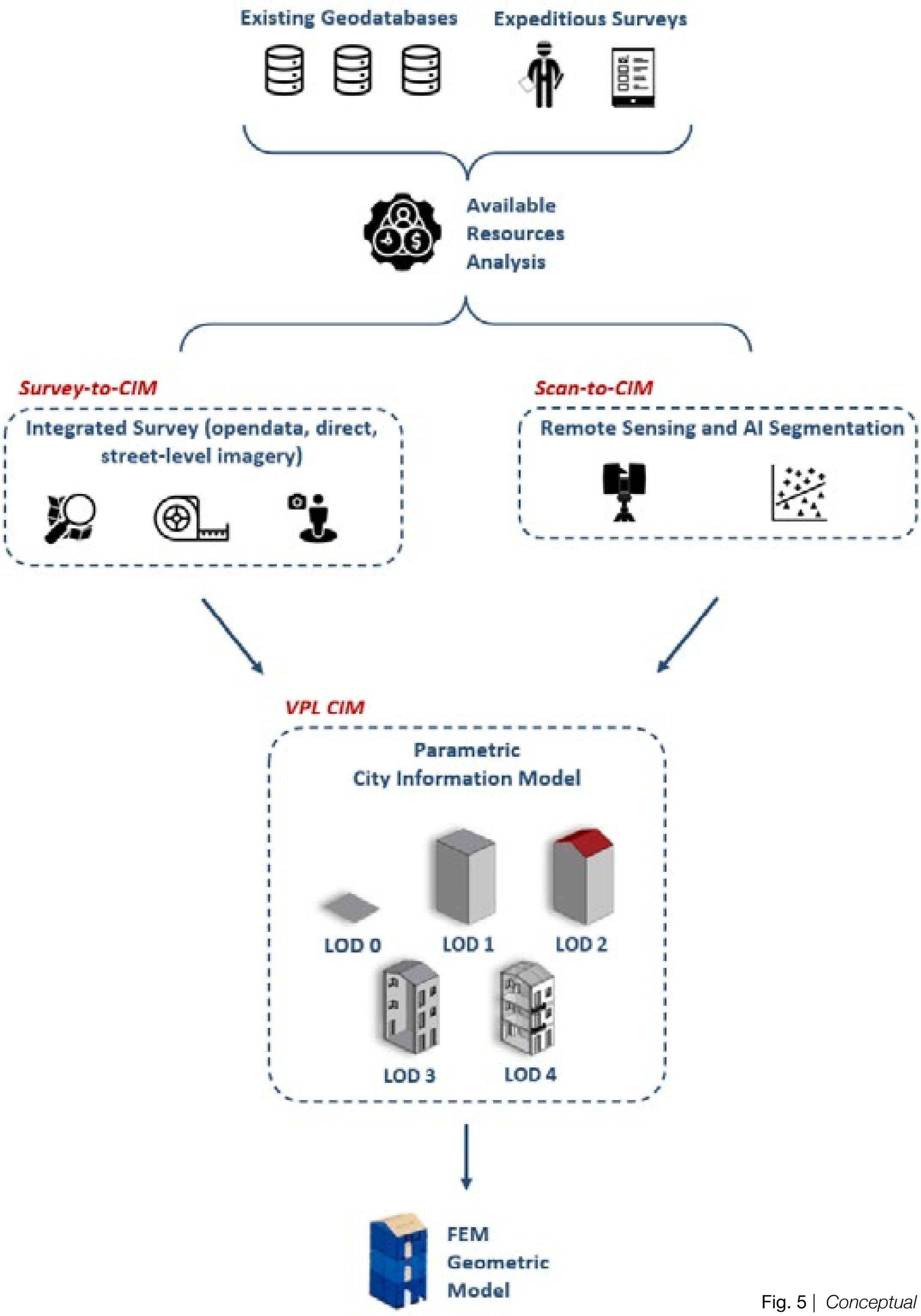


Fig. 5 | *Conceptual outline of the proposed methodology.*

At this point, the Informed Model permits to automate the creation of the structural model from the CIM model allowing a rapid generation of geometric models for structural analysis with a high level of interoperability between different structural analysis software.

Following is a summary description of the main phases and actions that constitute the methodology adopted in this research:

Phase 1 | *Data input and model at the territorial/urban scale*

- Data collection, protocol and input data definition
- City model at the urban scale | LOD 0 - LOD 2

Phase 2 | *Knowledge of the historic built environment*

- Digital expeditious survey of the urban canyons
- Study of recurring building types

Phase 3 | *Model at the architectural scale*

- City model at the architectural scale | LOD 3 - LOD 4

Phase 4 | *Semantic structuring and information enrichment*

- Semantic structuring of the parametric model according to the principles of the CityJSON standard (from the city block to the building component)
- Information enrichment of individual objects through the assignment of attributes collected during Phase 2

Phase 5 | *Structural geometric model*

- Discretization (Mesh) of the NURBS model for the purpose of structural analysis
- Interoperability validation of the model

1.5 Significance of the Study

1.5.1 Theoretical

Historical centers represent the memory of the choices that have drawn the history of a place; that is, the outcome of transformations and stratifications of the cities across the centuries. The knowledge of a historical urban environment requires an analytical methodology articulated on several interconnected levels of investigation to model a multi-layered complexity that encompasses the geometric and stylistic features of places (blocks irregularities, narrow streets, stratified buildings), the accessibility (pedestrial zone, no flyzone), the use of existing data (GIS, cartographies).

Urban survey and 3D modeling play a pivotal role in the various phases of the cognitive process. Indeed, the interpretation of the collected geometric-spatial data together with the critical reading of historical documents (i. e. cadastral maps, archive sources) allows to understand the link between the traces of the past and the present. Today the challenge for historical centers is dual: on one side, to make use of digital technologies to acquire data, on the other one to create systems that allow to manage, visualize, enquire and use (i. e. for simulation purposes) these data in a unique digital ecosystem. Moreover, the anthropic and natural hazards (earthquakes, floods, etc) to which historical centers are prone require a continuous monitoring of their state of conservation, necessarily sustainable in time and resources.

The work aims to broaden the debate about digital urban surveying activities by adding among the limitations to be considered the sustainability, timing and effectiveness of the acquisitions conducted with a view to optimizing operations and overall cost reduction against the entire stock of buildings to be assessed.

In addition, this thesis seeks to open, particularly at the national level, a debate about the conscious adoption of the City Information Modeling methodology so as to facilitate, as was the case with BIM, both theoretical and technological and regulatory development towards holistic and interdisciplinary solutions.

1.5.2 Potential impact

The VPL codes obtained in this thesis were conceived and developed as prototype plug-ins that could be easily used (by experts and non-experts alike) so as to maximize their benefits in industry and research applications as well as in the public sector.

Addressing the topic of City Information Modeling and current standards in 3D city modeling within a parametric environment provides a practical paradigm to refer to for future developments in the field of urban modeling using parametric tools.

In addition, the various critical issues encountered in the digital acquisition of the urban scenarios of the case studies have led to the realization of analyses and comparisons, both analytical and qualitative with respect to the objective, which contribute to the international academic debate about urban survey operations in typical situations of historic city centers common to many countries around the world.

The CIM models to be obtained present high levels of adaptability and responsiveness over time, thus becoming a powerful tool for knowledge, analysis, and monitoring of the built heritage. Such models will also be able to serve as a system for storing data collected by any acquisition instruments (such as accelerometers) including those already installed in some of the city's historical buildings, thus also favoring the process of seismic micro zoning and relating this data to the family of parameters (geometric and technological) belonging to the individual building. This represents a step towards the transition from the traditional forms of urban planning to the new management of cities according to the Smart Cities model with a view to holistic sustainability, all through advanced strategies of expeditious urban digital surveying and parametric modeling.

1.6 Experimental context and case studies

The present work focuses on the definition of VPL code that can elaborate survey data of different kinds for the reconstruction of semantically rich 3D urban landscapes and city blocks. The thesis and the experimental works are developed within the Ph.D. Course in *Evaluation and Mitigation of Urban and Land Risk* at the Department of Civil Engineering and Architecture (DICAr) of the University of Catania (UniCT) from which the work is funded. The research topics developed in the Ph.D. course are closely related to the territory of the city of Catania, which is subject to multiple categories of risk (seismic, volcanic, hydrogeological, etc.). This territory, particularly fragile and at the same time with a significant architectural heritage, appears to be a benchmark for other similar national and international scenarios (especially in the Mediterranean context).

Specifically, the thesis has been developed within the *Laboratory of Architectural Photogrammetry and Surveying "Luigi Andreozzi"* (DICAr) under the supervision of Prof. Cettina Santagati (supervisor, Professor of Parametric Modelling and Digital Survey) and Prof. Mariateresa Galizia (co-supervisor, Professor of Architectural Drawing). Regarding the task related to structural analysis, the work was co-supervised by Prof. Ivo Caliò (Professor of Dynamics of Structure at UniCT) and Engineer Marco Intelisano (Structural Engineer and Computational Design expert).

The development of the methodologies and workflows applied in the case studies shown in this thesis were obtained through visiting and collaboration with other European research institutes:

- Ph.D. Visiting Student (2020) as part of an ERASMUS+ Traineeship project at the *Virtual Environments Lab* Science and Technology in Archaeology Research Center (STARC), of the Cyprus Institute (Nicosia, Cyprus)
- Ph.D. Visiting Student (2022, remotely) at the Technical University of Delft (TU Delft), 3D geoinformation group
- Ph.D. Visiting Student (2022) at the 3D Optical Metrology unit at the Bruno Kessler Foundation (FBK)

In April 2021, an application developed within the Ph.D. thesis was awarded the *Best Paper Award - 3D Modeling & BIM | Digital Twin 2021*.

In March 2022, an application developed within the Ph.D. thesis was awarded the *Best Paper Award - 3D-ARCH 2022.*

The case studies where the methodology proposed has been tested include a minor urban center, Fleri (Catania, Sicily), which was hit by an earthquake in Christmas 2018, and two blocks of the historic urban center of the city of Catania (Sicily).

1.7 Thesis Structure

The thesis is structured as follows:

Part I - Introduction and Background

Chapter 1 introduces the topic of the thesis, defines the research gap and thus the aim and objectives of the research.

Chapter 2 deals with a summary of the evolution of urban surveying in Italy, the evolution of parametric modeling, the methodologies to date adopted for seismic risk analysis at the urban level, and the state of the art in City Information Modeling.

Part II - Methodology proposal

Chapter 3 introduces the methodology proposed in this thesis by contextualizing it with respect to the current academic debate. In addition, it introduces the reference standards and main workflows.

Part III - Case studies, Results and Discussion

Chapter 4 discusses case studies involving the definition of City Information Models at both spatial and urban scales. A comparative analysis is carried out between different techniques of digital expeditious acquisition for urban canyons and the Scan-to-FEM procedure is exposed, which allows mesh models to be obtained from parametric models to be used for structural analysis.

Chapter 5 presents the advancements from the state of the art through a discussion of the results.

Chapter 6 closes the thesis with conclusions and future developments of the research presented.

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02.

BACKGROUND

The research questions and objectives outlined in the introduction set a high degree of interdisciplinary nature of the work itself. The topics covered from geomatics to parametric modeling and 3D city models with applications connected to expeditious seismic assessment. In addition, the specificity of the sites chosen as prototypes of the proposed methodologies add characteristics and conditions that determine advancement in the state of the art and thus make hard an exact overlap with previous case studies both in complexity and in the topics covered. Therefore, works in the literature were examined by prioritizing the methodological profile and resources required. This is due to the fact that the topics covered intersect multiple fields and many experiences despite being applied for purposes that are different from the seismic analysis are still relevant to the objectives of the thesis.

The state of the art will be discussed in this chapter by dividing it according to the subjects covered. Each section presents an oversight of the main concepts with respect to the topic discussed going on to specify in more detail the aspects of interest that define gaps in the research and compose the background of the work presented here. The purpose of this chapter is to provide an overview on the topics of urban digital surveying, methodologies related to parametric modeling, and the evolution of seismic analysis in southern Italian territories. Having defined these fundamental themes, the main topic of 3D City Models and City Information Modeling is introduced, which is subordinate to the themes discussed above and constitutes the main reference framework for the work presented in this thesis. The order of exposition of the topics covered in the state-of-the-art review mirrors the order of processes related to reality-based parametric information modeling: acquisition, parametric modeling, information enrichment and analysis.

Therefore, this chapter will discuss the main concepts related to digital surveying with an in-depth discussion related to urban surveying (with reference to Italian schools of thought) and artificial intelligence-based segmentation and classification techniques (section 2.1). This is followed by an introduction to parametric modeling with insights related to its evolution (implicit and explicit modeling), the evolution of Visual Programming Languages (VPL), and the adoption of Grasshopper as a digital environment for urban modeling (section 2.2). An overview is then presented on the extant schools of thought related to seismic risk analysis on an urban scale with a focus on studies carried out in Catania, Italy, and current implementations of seismic analysis processes such as Scan-to-BIM-to-FEM and parametric applications with VPL (section 2.3). In conclusion, the topic of 3D City Models is introduced with reference to definitions, standards, and the methodology of City Information Modeling (section 2.4).

2.1 Digital Urban Survey: evolution and techniques

The city is a complex evolutive system that adapts to the history of places and also is interpreted and modified by successive generations. In the evolution of historicized urban centers, there are many repeated constants and many variables, consisting mostly of new readings of places, new interpretative approaches that represent the change that allows the system to adapt. In this context, the role of urban survey, as highlighted by Dino Coppo, is to identify, highlight, recognize, relate, describe and represent, the set of values present in the investigated area with the aim to build the formal and structural invariants present in the construction of the image of a city (Coppo & Boido, 2010). In this perspective, urban survey can be envisioned as a multi-layered knowledge system, open and implementable over time.

The principal distinctions between urban surveying and architectural surveying concerns the evolutionary nature itself of any urban area. Indeed, the pattern of a consolidated urban area or a historical town center has evolved to its present state of definition as a consequence of a number of interventions, whether they be for the purposes of completion or restoration, which are difficult (if impossible at all) to associate to documentable design hypotheses. Even though a shortcoming of data can also be encountered in architectural surveying, it cannot be compared to urban surveying. The main difference therefore lies in the more pronounced character of surveying as a continuously evolving process which therefore rarely finishes with the end of a project. Therefore, the idea of surveying within an urban context of multi-layered forms and structures must be understood as an open investigative process. This goal can be pursued by adopting a holistic and interdisciplinary approach including surveying, history, urban planning, architecture, sociology, and administrative policy methods. The overall quality of an urban survey is not related to the number of information collected but to the level of development of an open survey methodology that makes use of various surveying, cataloging, and data processing methods and is accomplished by breaking down the complexity under study into particular subsectors (mostly defined by the scope of the survey) while guaranteeing flexibility and responsiveness for critical reconstruction or interpretation of the data gaps object under evaluation (Coppo, Boido, 2010).

According to the traditional methodologies referenced by Italian schools of thought, the analytical process of the urban survey can be broken down into the following basic stages: identification of the cartographical base, classification and representation of morphological and formal construction characteristics, creation of technical maps with temporal sequences of individual construction events and related socio-political motivations, the graphical definition of the overall formal image, and identification of the goals behind the proposed intervention with the creation of the relative database.

It is worth noticing that the definition of a proper database that stores all the data gathered until that moment is the last phase of this methodology together with the definition of the scope of the survey itself (the intervention). This approach depends heavily on the analogical tools used for the representation and management of the collected data. The difficulty in modifying the represented objects pushed towards a basic workflow for all scenarios with an in-depth study of the database and the purpose of the survey only at the end, so as to limit time-consuming and onerous modifications. However, with the innovation of CAD systems in the 80s, there was a progressive change in the perception of this methodology. The new tools, which were digital and fast, made it possible to drastically reduce the time for processing changes.

The first change in the direction of urban 3D information systems came about thanks to the efforts of the Turin drawing school headed by Augusto Cavalieri Murat in 1974. The work in question concerned the study of the historic center of Turin for the new urban plan. As a result of this pioneering work, it was defined the standard described by UNI 7310 that would set the course for database-driven three-dimensional urban modeling. For the survey of Turin, the paper planimetry of the Gatti cadastre on a scale of 1:1000 was used as a working basis. On this were reported the results of visual surveys conducted on the elements listed above (including, for example, the number of floors, the typology of the buildings' summit cornices and basements, and the position of windows) using the symbols that would become those of the UNI standard. This representation better featured 3D information in a 2D paper medium, which changed the perception of the building in the study phase. However, the paper support of a 1:1000 scale representation only allowed containing a certain number of symbols, thus limiting the description of the city's complexity (Coppo, Boido, 2010).

Therefore, this has meant that until the 1990s, as will be seen, analyses of urban areas gave centrality to the cartographic support (which was enriched with meanings through the synthetic capacities of symbols or legends), starting with the Neapolitan experience conducted by Adriana Baculo Giusti it is possible to to see the separation of content and drawing. In this new perspective, graphic representation begins to become a representation of reality to which specific qualities borrowed from a database separate from the drawing itself can be conferred. The work consists of representing the city of Naples in axonometry. It was realized over a period of 20 months by a working group led by Baculo and comprising 80 architects. In order to make the work homogeneous, it was necessary to create an abacus of signs that determine the technical and formal characteristics of each building. The presence of these signs allowed the drawing to be deconstructed semantically within a GIS database that enabled each individual building to be easily understood (Baculo Giusti, 1994) (fig. 1).

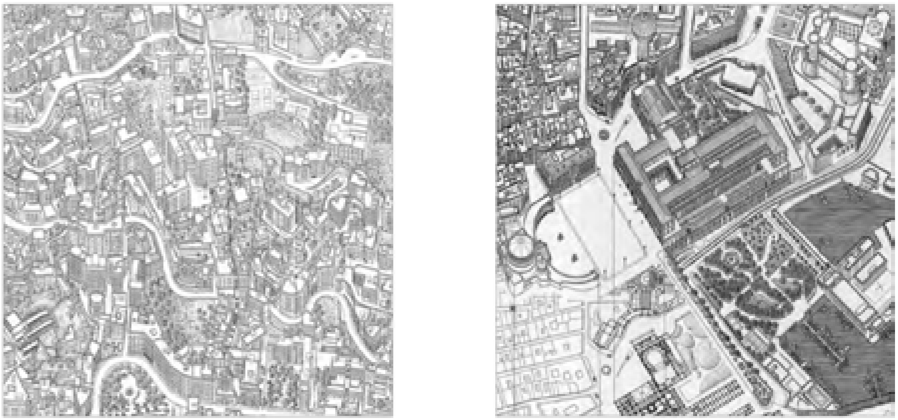


Fig. 1 | *Left: a table of the axonometry of Naples. Right: detail of the axonometry on Piazza Plebiscito. Source: Baculo Giusti, 2000.*

From the end of the 1990s onwards, satellite technologies and GIS systems combined with CAD environments enabled the development of software dedicated to the management of representations on a territorial and urban scale. From a methodological point of view, there is a reversal in the order of the phases. In fact, as Coppo warns, the risk appears to be that of postponing the moments of analysis and verification of hypotheses until the end of the entire survey and restitution process, with the risk of losing sight of the real objectives of the survey operations themselves. Before the advent of digital culture, the practice of manual drawing obliged to develop these hypotheses and transform them into theses during surveying and restitution operations. Today, on the other hand, there is too often a tendency to accumulate a quantity of data that is often redundant and sometimes insufficient for the intended purposes. (Coppo, 2010) (fig. 2).

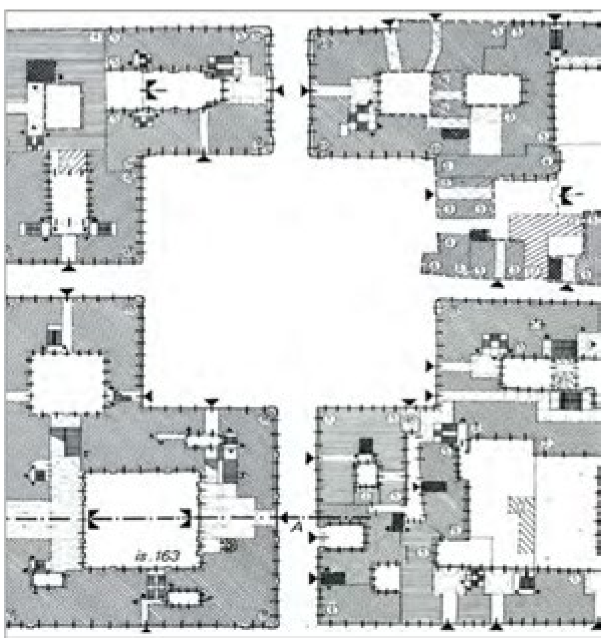


Fig. 2 | *Conjectural philological survey of Piazza Savoia in Turin. Source: D. Coppo, C. Boido, 2010.*

The surveying of urban centers has always represented, in the history of surveying techniques one of the most important applications. Even today, the production of cartographic instruments still constitutes the majority of applications of surveying techniques. The cartographies of the Roman era, drawn up for cadastral purposes, undoubtedly represent a paradigm that is still widely applied today in the production of technical cartography on an urban scale. After the Middle Ages' iconographic phase, cities returned to being represented metrically in a scientific manner during the Renaissance. The creation of new cadastres at the end of the 17th century (such as the Napoleonic cadastre) initiated the evolution of increasingly advanced land mapping techniques that led to the development of more precise and reliable instruments. The second half of the 19th century witnessed the development of photogrammetry (thanks to the studies of the French Colonel Aimé Laussedat at the Academy of Sciences in Paris), which would be further consolidated as the main tool for land mapping thanks to its use for military purposes during the First World War. In Italy, photogrammetry began to be used methodically (for civil purposes) in 1938 for the production of the first modern urban mapping maps.

It is possible to assume the rise of the digital survey for urban representation purposes with the use of digital images instead of analog images in photogrammetry since the early 1980s. Although digital images existed before, it was not until the early 1980s that their technology reached a quality that was comparable to the results obtained with analog images. The digital progress of the 1980s facilitated the ability to develop reliable and self-contained algorithms for the correlation of digital pictures, which in turn made it possible to automate the difficult tasks that had to be completed before the real thorough survey could begin, such as the external orientation of the images, or determining the geometric characteristics required for a precise estimation of the coordinates of the places of interest. In addition, these digital procedures reduced the cost of expertise needed since the software could handle many tasks once dealt with by several surveyors (Rinaudo, 2010).

Equally important was the evolution of LiDAR (Light Detection And Ranging) and CMM (Coordinate Measuring Machine) technologies designed during the 1950s mainly for military and aerospace purposes. It was not until the 1960s that these technologies were made available for civil use, but only for basic measurement purposes. The evolution of these systems continued in the projects of NASA, which exploited this technology to begin mapping operations on the lunar surface under the Apollo 15 project. Only with the full maturity of GPS systems these technologies see massive will be used in the civil sector. Although the development of these technologies predates that of digital photogrammetry, compared to the versatility of the latter, laser scanning will become a widespread and effectively used technology from the 1990s (the first commercial airborne LiDAR system was developed in 1995) onwards, before booming in the early 2000s (Petit, 2020; Wang et al 2020) (fig. 3).

Fig. 3 | *Every first-generation scanner that was marketed from 1998 to 2000 was controlled via connection to a laptop. Riegl's original LMS-Z210 is shown with Dr. Andreas Ullrich (left) and Dr. Johannes Riegl (right). Source: https://www.xyht.com/lidarimaging/early-3d-scanning-competition-1998-2000-part-13/*

Following on, the author describes technologies and approaches that, with respect to the objectives of the thesis, were considered to be of reference for the digital survey operations conducted during the thesis work (section 2.1.1). The chapter concludes with an in-depth examination of the techniques of segmentation and semantic classification with artificial intelligence (section 2.1.2) of point clouds obtained through digital surveying, which provides the research context for the application described in section 4.2.2.

2.1.1 An overview of digital surveying technologies and approaches

Nowadays, digital tools give precious support to the investigation on complex urban contexts and processes, generally characterized by articulate relationships between multiple aspects (Boido et al, 2021; Galizia, Santagati, 2012). Moreover, the fragility of historical city centers requires specific methodologies that respond to the need to have a rapid mapping of the investigated site (Predari et al, 2019) and/or models for the simulation or the management of critical scenarios (Bocconcino et al, 2021; La Russa, Santagati 2020).

The opportunities related to digital surveying are numerous. Thanks to the new tools of metric data acquisition, there is a considerable reduction in error (at the scale of mm) and also its quantification ascertained by the manufacturers. The in-situ survey phase becomes faster, quicker, and with greater quantity and quality of the measured data. The digital approach also allows the simultaneous acquisition of data belonging to different themes. An example is the survey of geometric, calorimetric, and reflectance data simultaneously using a single sensor. The georeferencing to scale, the objective quality of the data, and the possibilities of sharing, management, and verification are just some of the other features that make the new digital approach efficient and effective at the same time.

The product of this survey is, most of the time, a three-dimensional model (mainly composed of points) which provides excellent reproduction of the real artifact. The approach to the survey phase becomes more objective on the part of the operator since the interpretative-subjective phase, typical of the traditional approach, takes place at a later stage. This prevents the operator from making semantic choices in the restitution of the artifact (Migliari, 2001). The three-dimensional model mentioned above is also called a 'point cloud'. Currently, such a model can be produced from different types of instruments that can be divided into passive optical sensors and active optical sensors (Caroti et Al., 2015).

Passive optical sensors make it possible to acquire the geometry of the object by observation only. These optical instruments capture the reflected light from the object (i.e. its image) and reproduce it in a 2D image (hence are defined as image-based). Among the different acquisition methodologies related to passive optical sensors, there is a particular one that allows to obtain point clouds: multi-image photogrammetry. Through the capture of several images with sufficient overlap between consecutive shots, it is possible to obtain three-dimensional information. Nowadays there are many software applications that: apply algorithms for the automatic recognition of homologous points in different photos; automate internal and relative orientation procedures (necessary for the use of photogrammetric techniques); produce three-dimensional models made up of points (with RGB information) and from there they return 'image products' (such as orthophotos or mosaics) or 'vector products' (cartographies, profiles, etc.) (Remondino, Rizzi, 2010) (fig. 4).

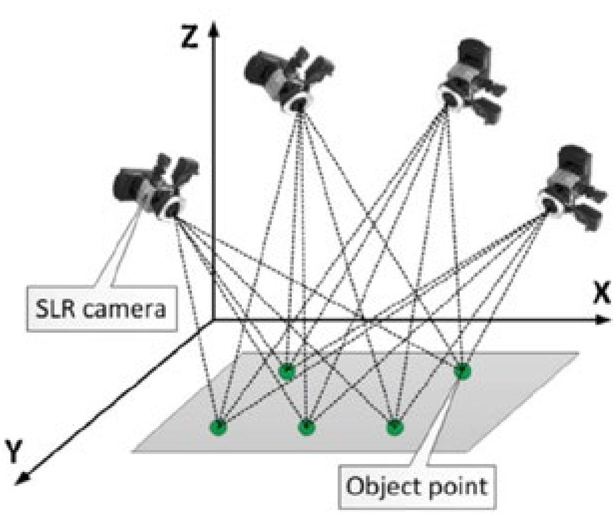


Fig. 4 | *Schematic drawing of photogrammetry. Source: Li et al., 2013*

Active optical sensors, on the other hand, measure a distance from the instrument to the point to be detected. Such instruments use the electromagnetic radiation of the laser to measure, via a light emitter and a light receiver, the distance mentioned above. The product is a point cloud that in addition to RGB information has other attributes (such as reflectance) depending on the devices mounted on the scanner (e.g. thermal imaging camera: thermographic data). These high-performance scanners allow a considerable reduction in error (a few mm even at a distance of tens of meters) and it is possible to know in advance (from reading the technical specifications) the error committed by the instrument. In this way, it is possible to design the shots in advance in such a way as to guarantee the necessary accuracy throughout the acquired model. Similar to passive optical sensors (although for different reasons), laser scanners find it difficult to acquire in the presence of reflective surfaces (such as mirrors, windows, and certain types of metal surfaces) (Vosselman et al., 2003) (fig. 5).

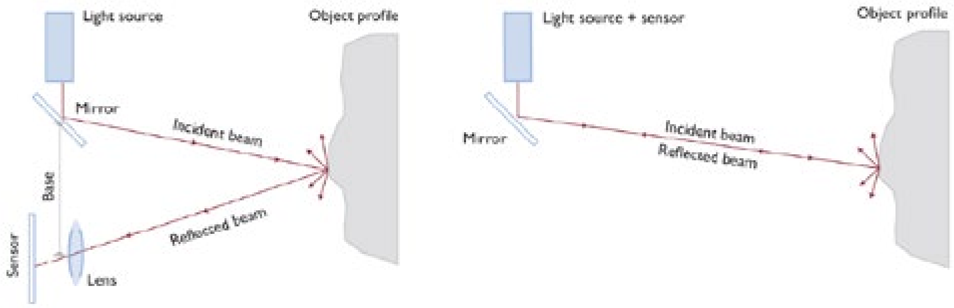


Fig. 5 | *Laser scanner operating principles: triangulation (left) and range scanners (right). Source: Guidi, Remondino, 2012.*

A digital survey project that can be defined completely in all its parts can foresee an initial phase where the territorial reference systems are defined (useful for georeferencing purposes), then data acquisition is carried out by choosing the most suitable survey techniques with reference to the context and the nature of the object (laser scanner, photogrammetry, direct survey, aerial survey). Once the survey campaign is over and all the data are stored in the most appropriate devices (usually dealing with huge masses of data in the order of Gb), the filtering and processing phase begins, which aims to eliminate redundancies and data noise (typical of complete survey systems). Once the survey datasets have been cleaned up, the registration of photographs and/or scans can be undertaken. This last step delivers a digital product in the form of a point cloud that could be further improved by semi-automatic and manual operations of cleaning (deleting unreliable and noisy portions of data). Finally, the cleaned point cloud is ready to be used as a digital hub from which to export different technical representations according to the error obtained during the registration phase (La Russa, 2019).

Next, there is a summary of techniques and case studies related to both passive and active sensor-based procedures and technologies adopted for dealing with urban-scale objects. In particular, the case studies reported have been selected specifically for their remote sensing approach since they proved to be relevant to the research goals addressed in this research project.

The last years have seen a growing development of technologies and sensors for fast 3D acquisitions which allow expeditious mapping campaigns in very complex environments. The fastest solution for mapping the city can be envisaged in vehicle-mounted MMS, although they are not very suitable in presence of high-density historical urban centers. Indeed, they are characterized by pedestrian and narrow streets, buildings of different heights and varied street ratios (Barrera-Vera, Benavioles-Lopez, 2018). In these cases, it is preferable to adopt other solutions such as spherical photogrammetry or iMMS tools. The latter is based on SLAM algorithms that allow capturing 3D point clouds in real-time by walking in the area of interest. The drawback is related to the low levels of density and accuracy of these sensors (compared to TLS solutions), as well as the drift errors along the trajectory that may affect the global accuracy. These new devices are constantly evolving technologies that need to be assessed against more consolidated techniques such as photogrammetry and TLS. In literature can be found different approaches to evaluate iMMS data both in indoor and in outdoor contexts (Nocerino et al, 2017; Sammartano, Spanò, 2018; Chiabrando et al, 2018; Sammartano et al, 2021; Salgues et al, 2020; Marotta et Al., 2022) (fig. 6).

Fig. 6 | *ZEB Horizon LiDAR SLAM-based scanner with backpack mobility option for indoor and outdoor mobile mapping. Source: https://www.aniwaa.com/buyers-guide/3d-scanners/slam-3d-scanners-imms-mobile-mapping/*

As regards spherical photogrammetry, in their studies Abate et al (2017) and Barazzetti et al (2018) demonstrate that accurate metric reconstructions can be achieved using low-cost sensors. In addition, Teppati Losè et al (2021) verify in their work the integration between iMMS and spherical photogrammetry for the survey of the Montanaro bell tower. Photogrammetry 360 is also and especially a valuable tool for urban expeditious surveying due to the possibility of capturing frames through video acquisition. The high resolution that 360 cameras are achieving allows for excellent density overlays of automatically obtained point clouds (Barazzetti et Al., 2022) (fig. 7).

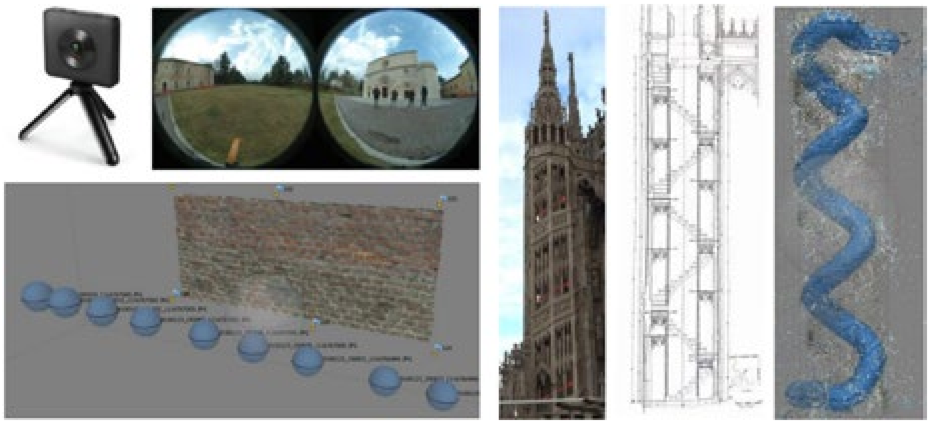


Fig. 7 | *Example of a 360 camera, the Xiaomi Mijia Mi Sphere 360 (top-left); reconstruction of a planar wall with spherical camera (bottom-left); 360 SFM survey of a spire (right). Source: Barazzetti et al., 2018.*

Since the Blk2go is new in the market, few studies about its performance are currently available. In particular, one is addressed at the evaluation of its usability for the generation of DTM in highly vegetated areas for detecting and documenting archaeological anomalies (Limongiello et al, 2020); another one concerns narrow spaces such as indoor corridors or multi-store buildings (Piniotis et al, 2020). In both cases, the outcomes of the evaluation return an accuracy that represents scales of 1:100 or 1:200, fully compatible with the aim of this research work (fig. 8).

Fig. 8 | *BLK2GO Handheld Imaging Laser Scanner. Source: https://leica-geosystems.com/en-gb/ products/laser-scanners/autonomous-reality-capture/leica-blk2go-handheld-imaging-laser-scanner*

In addition to these references, which served to determine the context of the research with regard to the remote sensing issues covered, there are other case studies in section 2.4.3 which, were preferred to be placed in the discussion of 3D City Models as they are less focused on remote sensing but equally of interest for the acquisition techniques used in the urban environment.

2.1.2 Artificial Intelligence for Cloud Segmentation and Classification

As seen in the previous section, the adoption of digital acquisition techniques is now an established practice in both industry and research. Currently, acquisition-registration workflows are increasingly automated, speeding up work and reducing errors. However, the use of the 3D models obtained has remained unchanged for a long time as the point clouds obtained are used as static references for generating views and sections, thus reducing the potential of the digital product itself.

For this reason, 3D data categorization has recently been a very active study area as a result of the 3D models' steadily expanding use in a variety of applications. It has gotten increasingly important in a variety of applications and domains, including robotics (Maturana et al., 2015), autonomous driving (Wang et al., 2017), urban planning (Xu et al., 2014), heritage (Grilli and Remondino, 2019), geospatial (Özdemir and Remondino, 2018), etc., to automatically group huge data into many homogenous regions with comparable qualities. The objective is to automatically classify semantically continuous portions of point clouds (e.g. walls, windows, columns, etc.) in order to optimize modeling operations on point clouds with automatic and semi-automatic workflows. The means by which this can be achieved is through the use of Artificial Intelligence in geomatics, in particular by adopting Machine Learning (ML) and Deep Learning (DL) techniques (Grilli et Al., 2019; Matrone et Al., 2020) (fig. 9).

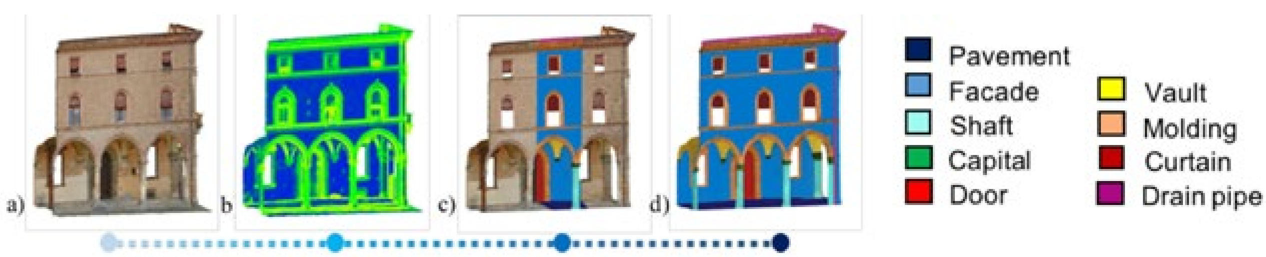


Fig. 9 | *3D classification process based on artificial intelligence: surveyed point cloud (a), automated features extraction (b), manual annotation of a small portion to define classes (c), final automated classification results (d). Source: Grilli et al., 2019.*

ML is a branch of statistical learning. It works through the use of classifiers such us Support Vector Machine (SVM) and Random Forest (RF). These classifiers are trained using a collection of features and training data with associated label information (i.e. classes). An attribute that is useful or significant to the classification process is defined as a feature, which, in the case of point clouds, might be geometric or radiometric. The definition of the right features is fundamental to obtain a training phase efficient enough to semantically segment the full dataset based on the prediction of the classifier used. Extracting and/or generating the right features can sensibly change the results obtained.

3D features in the case of 3D point cloud data generally derive from a particular geometric property of the global or local distribution of the points, and a substantial number of them have been proposed in the literature (Georgianos et al., 2015; Guo et al., 2016; Weinmann et al., 2014). The covariance matrix of the 3D point coordinates in a certain neighborhood of points is used to produce the most prevalent 3D features utilized to characterize the local geometric behavior of the point cloud.

Following is a description of the methodology used as a reference in this research project and which constitutes the framework adopted in one of the applications described in Chapter 4. In particular, the methodology adopted is based on Random Forest as described in Grilli et Al., (2019). It can be summarized in the following steps: (i) neighborhood selection, (ii) features extraction, (iii) features selection, (iv) manual annotation, and (v) classification (Weinmann et al., 2016). Initially, distinct geometric characteristics are extracted at various scales. Then iteratively evaluate just the more pertinent characteristics and re-run the classification procedure after conducting a multi-scale classification with a Random Forest classifier. Last, using the standard confusion matrix ratings, the various findings are compared (fig. 10).

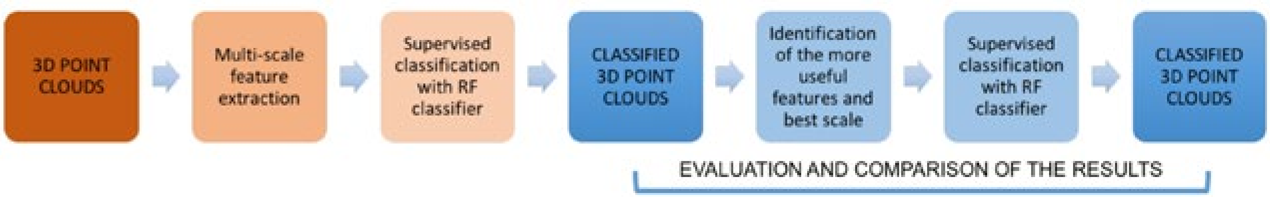


Fig. 10 | *Classification workflow (left) and its extension (right) to evaluate features relevance for the classification process. Source: Grilli et al., 2019.*

The features extracted for the training of the classifiers are the ones of the covariance matrix related to local regions of the point cloud to classify (Chehata et al., 2009). The values of these features emphasize certain topological and geometrical characteristics of the cloud depending on whether the individual regions of the point cloud are analyzed by giving priority to linearity, planarity, or volumetry of the neighborhood under consideration. In the figure below the complete list of the features taken into account (fig. 11).

Fig. 11 | *Considered local 3D shape features/covariance features. Source: Grilli et al., 2019.*

Linearity	$L_\lambda = \frac{\lambda 1 - \lambda 2}{\lambda 1}$	(1)
Planarity	$P_\lambda = \frac{\lambda 2 - \lambda 3}{\lambda 1}$	(2)
Sphericity	$S_\lambda = \frac{\lambda 3}{\lambda 1}$	(3)
Omnivariance	$O_\lambda = \sqrt[3]{\prod_{j=1}^{3} \lambda j}$	(4)
Anisotropy	$A_\lambda = \frac{\lambda 1 - \lambda 3}{\lambda 1}$	(5)
Eigenentropy	$E_\lambda = -\sum_{j=1}^{3} \lambda_j \ln(\lambda_j)$	(6)
Sum of Eigenvalues	$\Sigma_\lambda = \sum_{j=1}^{3} \lambda_j$	(7)
Surface Variation	$C_\lambda = \frac{\lambda 3}{\Sigma \lambda}$	(8)
Verticality	$V = 1 - nz$	(9)

The features considered can be extracted several times with different radius size as concerns the 3D neighborhood (Niemeyer et al., 2014). This may increase the possibility of success in the prediction as stated in Weinmann et al. (2013) (fig. 12).

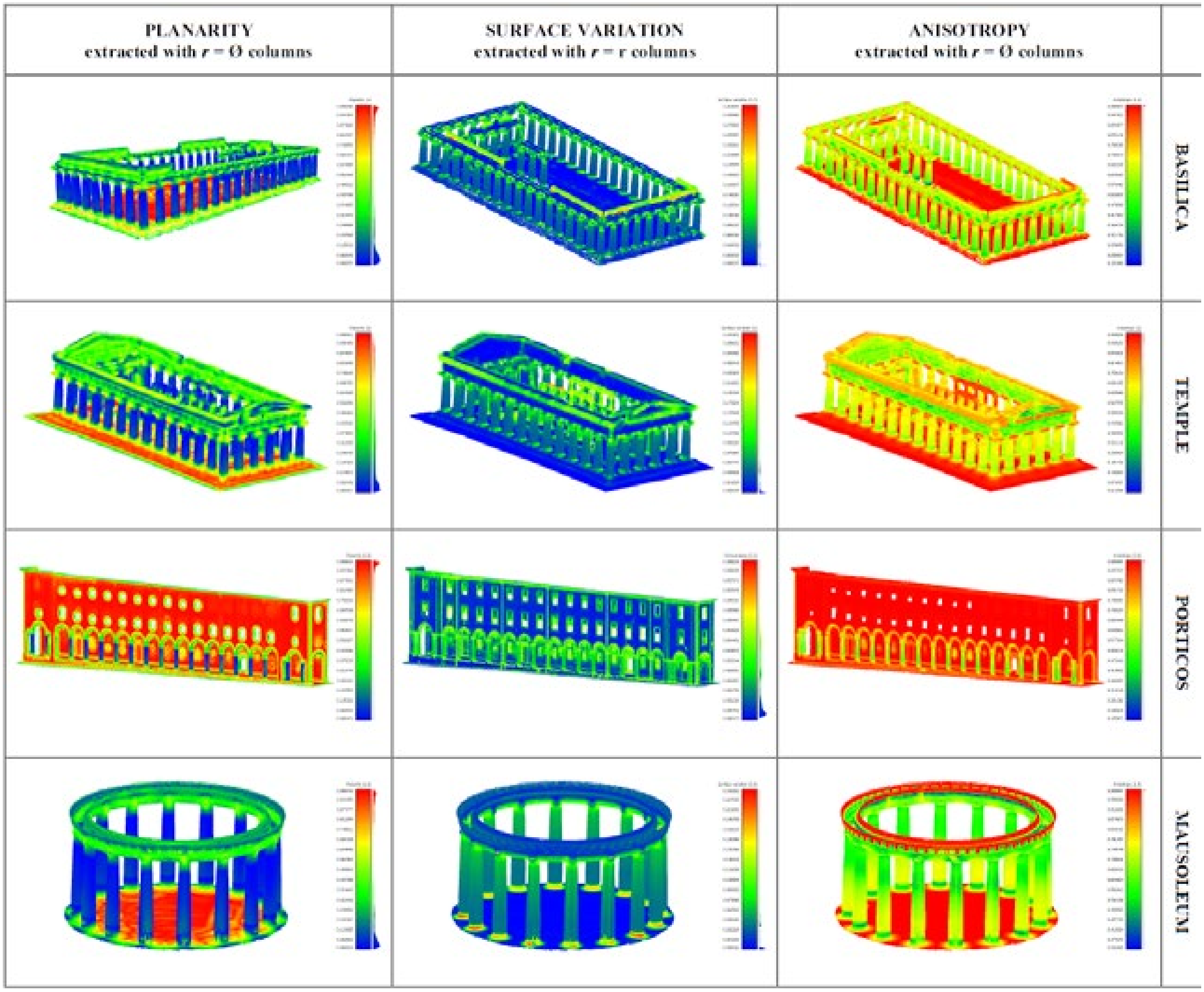


Fig. 12 | *Visual comparison of some geometric features extracted ad hoc on the different case studies. Source: Grilli et al., 2019.*

Regarding the classification phase, as mentioned above, it is carried out thanks to the Random Forest classifier. RF is a supervised classification method created by Leo Breiman (2001) that combines a group of classification trees, gets a prediction from each tree, then votes on the top candidate. To create the forest trees (as are called the processes of this method), two parameters must be set: the number of decision trees to be defined (N_{tree}), and the quantity of variables to be chosen and tested to determine the optimal split during tree growth (M_{try}) (Belgiu et al., 2016). The best F1-score calculated on the test set is taken into account when tuning the N_{tree} and M_{try} with reference to an already labeled dataset (training phase). The advantages of RF consist in being a very successful and robust method due to the presence of many decision trees. Furthermore, problems such as overfitting (typical in ML) are mitigated since the final prediction is an average of the predictions of the individual trees. RF also makes it possible to assess the actual efficiency of each feature used, thus being able to see how much a particular feature was decisive for the prediction. This provides an enormous advantage in the feature extraction/engineering phase (Grilli et Al., 2019).

The procedure ends with the evaluation phase. A small portion of the dataset under examination is selected to be manually classified. Subsequently, the classifier is applied to this portion, which is called the test set. The evaluation consists of comparing, within a confusion matrix, how many instances have been correctly classified. The rows of the matrix represent the predicted instances while the columns represent the actual instances. For each class, there are indicators that help determine the efficiency of the classification, in particular there are the precision (indicating the quality in identifying the class), recall (the completeness of the classification) and F1 score, which consists of an average of these two and provides an all-round indicator. In the context of geomatics, this indicator (F1 score) is significant for the evaluation of the final result (fig. 13, 14, 15).

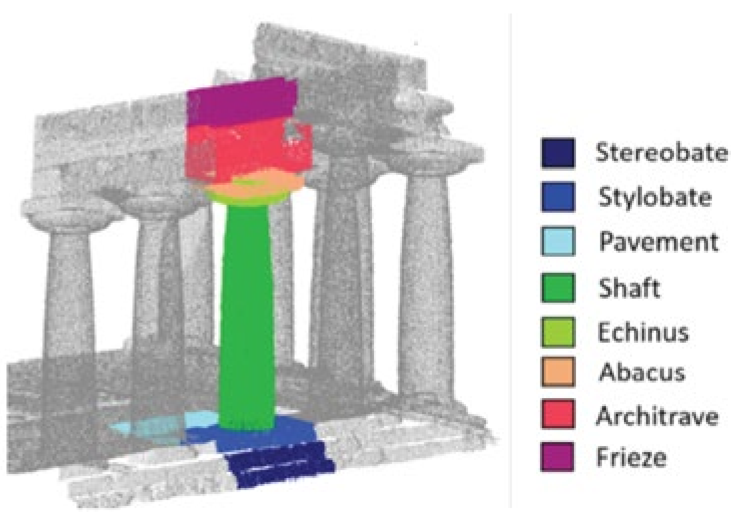
Fig. 13 | *Definitions of Precision, Recall and F1 Score. Tp = true positive, Tn = true negative, :Fp = false positive, Fn = false negative. Source: Grilli et al., 2019.*

$$Precision = \frac{Tp}{Tp + Fp}$$

$$Recall = \frac{Tp}{Tp + Fn}$$

$$F1\ score = 2 * \frac{Recall * Precision}{Recall + Precision}$$

Fig. 14 | *A portion of point cloud manually labelled with 8 classes. Source: Grilli et al., 2019.*



CLASS	Ster.	Stylob	Pav	Shaft	Echin	Abac	Archit.	Frieze	Precision	Recall	F1
Ster.	3325	427	13	0	0	0	0	0	88.31%	98.52%	93.14%
Stylob.	50	7974	312	7	0	0	0	0	95.58%	83.99%	89.41%
Pav	0	1093	11992	0	0	0	0	0	91.65%	97.36%	94.42%
Shaft	0	0	0	48490	0	0	0	0	100.00%	99.88%	99.94%
Echin	0	0	0	1	8390	1	7	0	99.89%	99.88%	99.89%
Abacus	0	0	0	50	10	6249	979	0	85.74%	99.98%	92.32%
Archit.	0	0	0	0	0	0	19380	0	100.00%	95.13%	97.50%
Frieze	0	0	0	0	0	0	7	11406	99.94%	100.00%	99.97%
							Average		95.14%	96.84%	95.82%

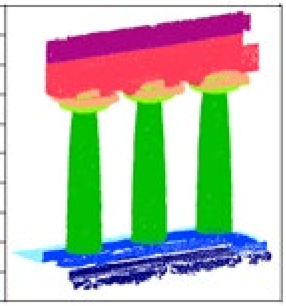


Fig. 15 | *Example of a confusion matrix obtained from a case study using 8 geometric ad hoc features plus the height information (Z coordinate). Source: Grilli et al., 2019.*

A meaningful case study for the objectives set in this research project is the classification of some porticos in the historic center of Bologna where the described methodology was applied (Remondino et Al., 2016; Grilli et Al., 2019). About 1.2 million points constitute the Bologna dataset. This point cloud incorporates a variety of geometric forms, varied materials, and numerous architectural details including mouldings and decorations. Thirteen distinct classes are selected and annotated for the categorization goal (fig. 16). In order to overcome the difficulty of the classification task, RGB values were additionally considered as essential components for the successful classification of the point cloud in addition to the 11 geometric characteristics extracted. The F1 score achieved is 79.82 %.

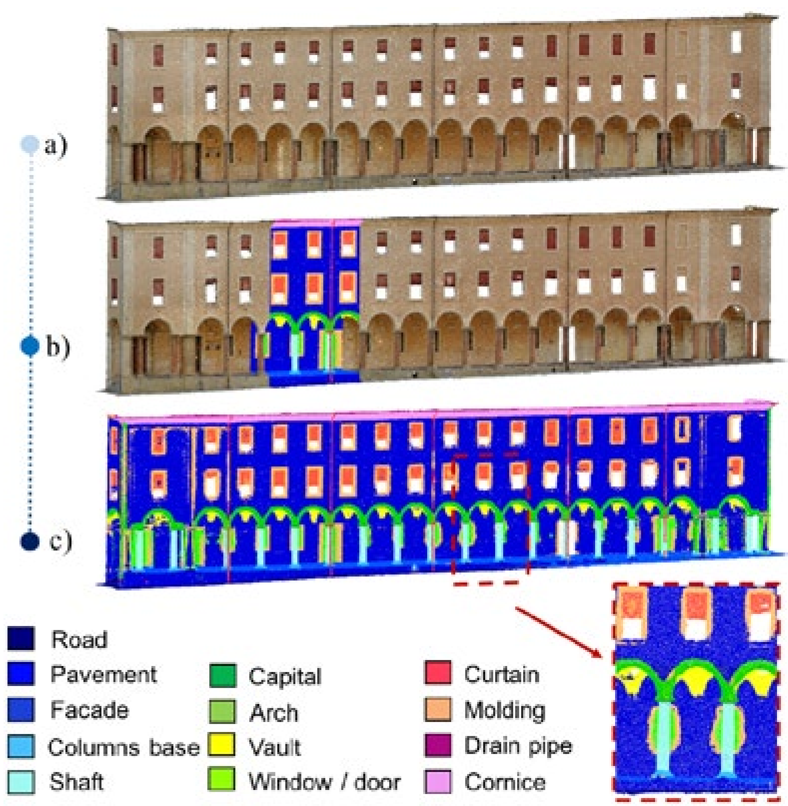


Fig. 16 | *Porticoes point cloud (a), annotated (b) and classified (c). Source: Grilli et al., 2019.*

The relevance of this case study with reference to the work presented in this research project lies in the fact that the point cloud is developed from terrestrial photogrammetry whereas in most cases this methodology is applied to airborne lidar scans. In the case study, on the other hand, the architectural features of an urban canyon in an Italian historic centre were highlighted. However, it is worth pointing out the limitations of the research. This methodology includes the possibility of taking advantage of the training done on a case study, on other objects (the so-called transfer learning). Unfortunately, the limitation lies in the uniqueness of the historical architectural heritage of cities. In fact, the covariance features and RGB values depend on the geometric and material characteristics (i.e. the architectural style) of the case study considered. For example, the same training could not be used with the same classes and the same training in the urban canyon of a modern city. Therefore, at present, this methodology, both in the architectural and urban case, must be repeated from the very beginning. On the other hand, a strong plus is that once an urban area with similar characteristics has been identified (as is the case in most historic city centers), the training developed can be reused and implemented in order to obtain better and better results in a shorter time.

2.2 Parametric Modelling

In reality capture based workflows, digital surveying is often the starting point and not the finish line. Indeed, the digital products obtained are often used as references for the creation of digital information models that are metrically accurate to the levels of detail indicated. This activity belongs comprehensively within the parametric modelling range of techniques where it is possible to generate models, generally three-dimensional, which present a semantic structure between the parts at both geometric and informative levels.

In this section, the main concepts related to parametric modelling are presented, defining its purposes and main categories (implicit and explicit), and then goes on to explore the use of Visual Programming Languages as a digital environment suitable for geometric, informative and flexible management for the creation and manipulation of urban models.

Briefly, the term 'parametric modelling' refers to the relationships existing between all the elements of a model, which allow coordination and change management operations to be performed. Relationships can be created automatically by the software or by the user. In mathematics and mechanical design CAD systems, the numbers or characteristics that define this type of relationship are called parameters. Changes made at one point are extended to the entire model (Autodesk, 2022). However, it is an oversimplification to define parametric modelling as the result of digital technologies aimed at speeding up representation processes. The very concept of 'model' and 'parametric' encompass a true theoretical revolution that has its roots in the history of architecture and representation. Migliari, on the occasion of the first digital survey of the Colosseum, revised the very concept of drawing and model:

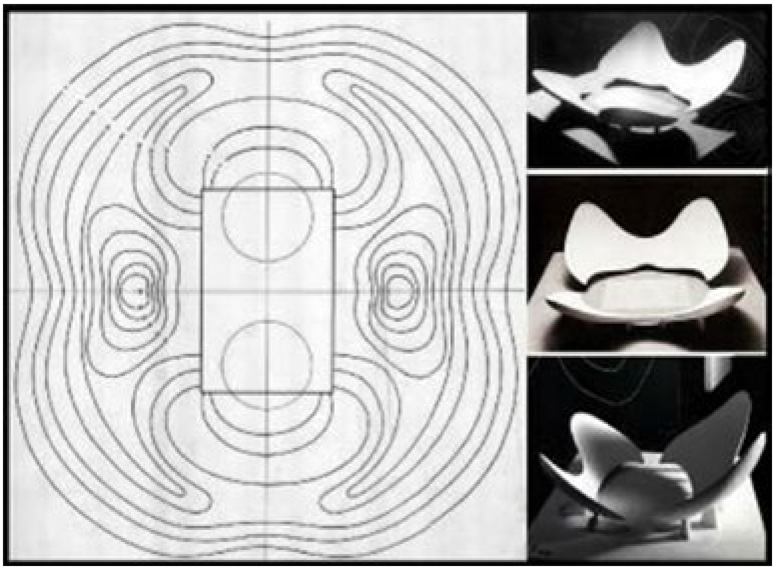
“Drawing as Model, or rather, Model, idea, which is generated in the changing forms of drawing” (Migliari, 2004).

Methodologically, drawing became more a procedure than a product, as an idea never completely defined. In this way, the result of drawing is a flexible product (thanks to digital instruments) that is constantly evolving, similar to what has already been theorised in the field of surveying disciplines (as described in section 2.1).

Today, thanks also to the contamination with other disciplines, there are new model definitions that clarify what Migliari already defined. In a lecture in 2017, Mateusz Zwierzycki defined a model as: *“a system that describes a part of reality, defining its internal relations and properties”* (Zwierzycki, 2017).

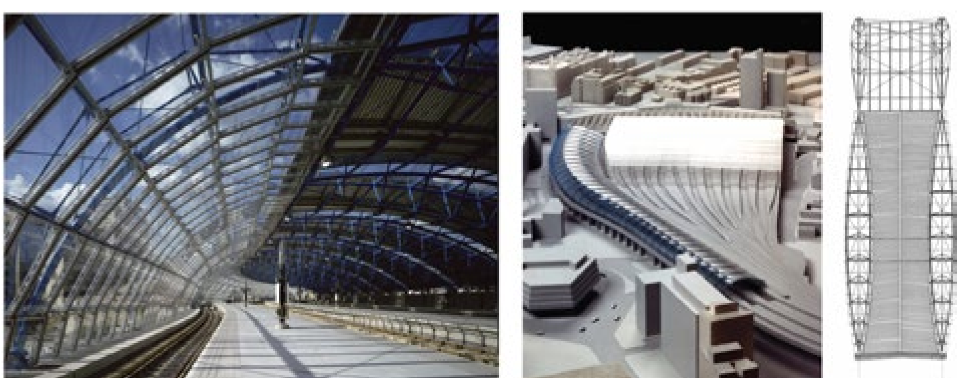
The adjective ‘parametric’ derives instead from an architectural movement that saw its beginnings in the 1940s with the definition of parametric architecture. One of its first definitions was by architect Luigi Moretti, according to whom parametric architecture is defined by: “[...] parameters and their relationships [...] the code of the new language of architecture, the 'structure' in the original sense of the term [...]"(Bucci, Mulazzani, 2006). The architectural project is no longer seen as an overlapping of sub-projects (architecture, structure, systems, etc.) but as an organic whole of functions and requirements that determine its form and function (fig. 17).

Fig. 17 | *Stadium model with isoview study, Luigi Moretti. This stadium assumes a shape that allows equal visibility for each spectator. Source: Bucci, Mulazzani, 2006.*



There is thus a move towards a more fluid concept of architecture based on two fundamental concepts: parameters and relationships. This concept, more than half a century later, will define the basic structure of all parametric information models currently available in the AEC industry (fig. 18). In conclusion, a parametric model means a system that describes a part of reality, with its attributes (both geometric and informative) and relationships, and that the model is capable of changing its properties on the basis of fixed or variable parameters (Zwierzycki, 2017).

Fig. 18 | *International Terminal Waterloo - Nicholas Grimshaw & Partners (London, 1994). One of the first parametric model realised combining first generation CAD environments and textual programming languages. The model was able to change its cross-section in relation with the size of the railway platform. Source: https://grimshaw.global/projects/international-terminal-waterloo/*



2.2.1 Implicit and Explicit Parametric Modeling

The technical evolution of parametric modelling has gone hand in hand with that of digitisation in architecture and construction. It is possible to identify three phases, or levels, through which the evolution of parametric modelling can be described (Calvano et Al., 2022). The first level consists of the use of industry-produced software that allows the user, by means of a simplified graphical interface and pre-established input rules, to construct linked architectural components. This level corresponds to the beginnings of the development of CAD systems (1950s) up to the modern Building Information Modeling (BIM) systems that implement and facilitate the three-dimensional management of both geometric and informational aspects of a building (Zabramski et Al., 2013; Eastman et Al, 2018). The potential of this system has also extended to the existing cultural heritage by developing methodologies such as Scan-to-BIM that allow manual and semi-automatic workflows in the transition from point cloud to a Historical-BIM model (HBIM) in which all building components and documents are organised in a spatial 3D database semantically defined. This methodology in particular enabled the digitasation of complex activities related to historical buildings such as documentation, conservation, management, design and maintenance (Osello et Al., 2018; López et Al., 2018; Murphy et al., 2009) (fig. 19, 20).

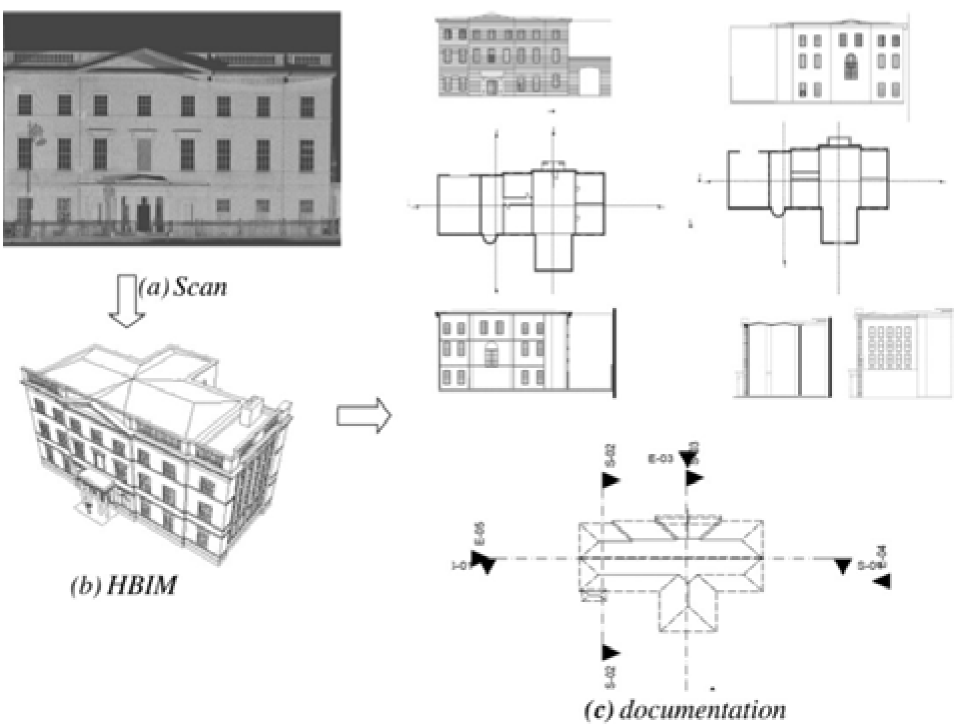


Fig. 19 | *From scan to HBIM to automated documentation.. Source: Murphy et al., 2009.*

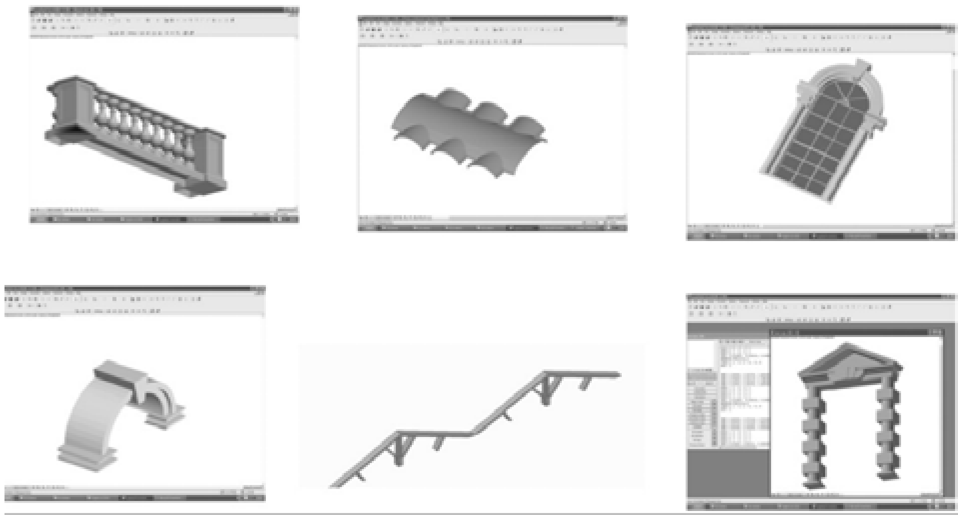


Fig. 20 | *Samples of H-BIM object library. Source: Murphy et al., 2009.*

The second level concerns parametric modelling through the use of classical Textual Programming Languages (TPL) such as C#, Python, and VBScript etc. This level, although the least used, is the oldest of all as it is the core through which software belonging to the first level has been produced since the beginnings of CAD. The limited use by architecture engineers of this level is due to the fact that it requires a high level of programming knowledge that professionals often do not possess because of their education. However, this level was the only way of modelling complex surfaces in the 1980s and 1990s and contributed greatly to the development of parametric architecture. Today this level is still adopted for research and complex task in the industry (Calvano et Al., 2022; Zwierzycki, 2017; Caetano et Al., 2020) (fig. 21).

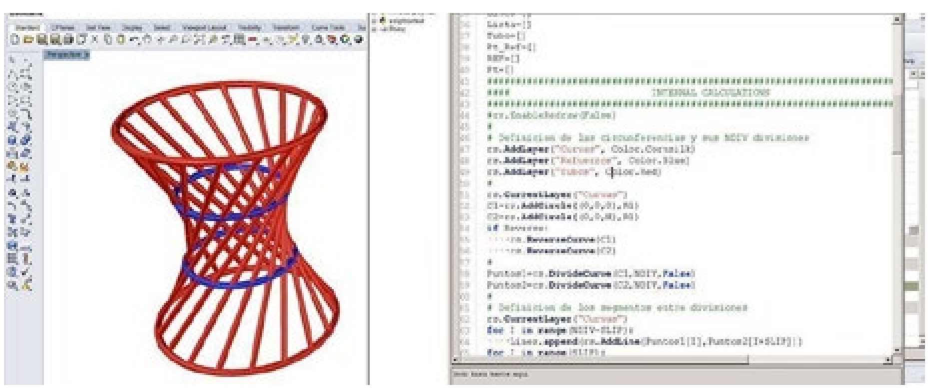


Fig. 21 | *Example of a complex geometry modelled using only Textual Programming Language. Source: https://controlmad.com/eng/formacion/curso-python/.*

The third level is a synthesis of the accessibility of the first and the potential of the second. This level, the most recent of the three, consists of the use of Visual Programming Languages (VPL) which, through the use of graphic nodes, allow even non-programmers to write code within parametric modelling software. Despite the accessibility afforded by an entirely graphic interface, the adoption of this level requires training that introduces some basic programming concepts (such as object types and data structure). The development of this level, despite the fact that it can be traced back to the very beginnings of the first CAD prototypes, only became widespread from the 2000s onwards in an attempt to enable professionals to achieve results close to those of the first CAD prototypes. (Spallone et Al., 2019; Calvano et Al., 2022) (fig. 22).

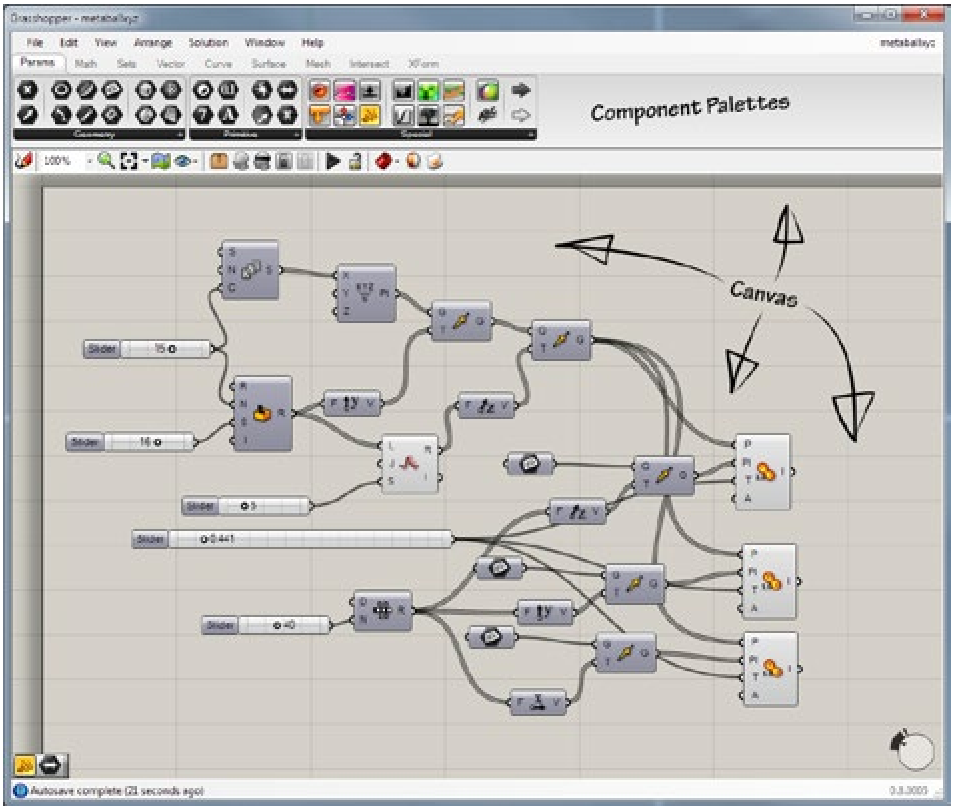


Fig. 22 | *Main window of VPL Grasshopper with some components (the fundamental algorithms) and the canvas (the place where components are placed and connected with input/output). Source: David Rutten for Wikipedia.*

Currently, the three levels just described are often combined, and depending on the level of use of the same software, it is difficult to classify which parametric modelling paradigm is being used. For this reason, it is convenient to divide parametric modelling into two macrocategories: implicit and explicit (Calvano et Al., 2022).

The focus of implicit parametric modelling is the final model in a digital environment. This model is meant to be consulted, updated and enriched over time in accordance with the scope of the model. All parametric processes are controlled by pre-set interfaces that have the ability to change the geometry and information of the model objects through numerical and data restrictions (Saggio, 2007; Turk, 2016). With the aim to situate the whole model in a wider information context, parameters are also employed to enrich objects with information attributes from other knowledge areas. The model is thought as a common database where all professionals and domain experts can share and store data. For this reason, information enrichment is greatly facilitated by the ability to view model objects in both 3D and 2D views and to make changes to their properties inside property windows that are activated by object selection. In this scenario, the modeller is asked to take into account the level of detail and information needed for each component so that he can delivers the outcome requested (Eastman et Al., 2018). Parametric modelling of first level (CAD/BIM software) is mostly included in this category.

On the contrary, the focus of explicit modelling is on how the model is obtained (the procedure) and all possible obtainable models (the results) . Thanks to explicit modelling, the user has the ability to define the hierarchy between the modelled elements by himself, thus fulfilling the design requirements of the project closely. In addition, since the user develops a code and not predefined building components, the defined procedure is always editable in its structure and responsive to the input provided. Precisely for this reason, explicit modelling is the most widely used in research and complex projects in the industy (Calvano, 2019). The major difference in comparison to implicit parametric modelling is in that, by defining objects, relationships and parameters from the very beginning, the user is not subject to the commercial choices dictated by software houses in the development of information parametric modelling software so he is free to decide which way is preferable thus lightening the computational burden and complexity required to achieve project goals. Parametric modelling of second (TPL) and third level (VPL) are labelled in this category

For the reasons stated above, the paradigm of explicit parametric modelling was chosen in this research, combining TPL and VPL when necessary. The next section will introduce a brief overview of the evolution of VPLs and its advantages in the AEC sector.

2.2.2 Visual Programming Languages: evolution and advantages

In the 1980s, there was a great diffusion of personal computers, but the average user did not have programming knowledge and this limited the impact of these technologies in different sectors. Programmers tried to improve the user interface but not always the efforts in this direction were successful. This condition led to research aimed at using graphics to facilitate programming skills, leading to the birth of Visual Programming (VP) (Halbert, 1984). By eliminating syntax, the graphical method focused on workflow, making visual programming an efficient tool even for skilled programmers. The friendliness of this method was also demonstrated by cognitive psychology, as the human brain can process visual information using two hemispheres instead of one as in other cognitive processes (Myers, 1986). In accordance with Brad Myers, VPL can be defined as a “system that allows the user to specify a program in a two (or more) dimensional fashion. Conventional textual languages are not considered two-dimensional since the compiler or interpreter processes it as a long, one-dimensional stream” (Myers, 1986). The first VPLs for geometry modeling purposes can be found In the late ’80s: Prismis (nowadays known as Houdini) and ConMan (Haeberli, 1988) (fig. 23).

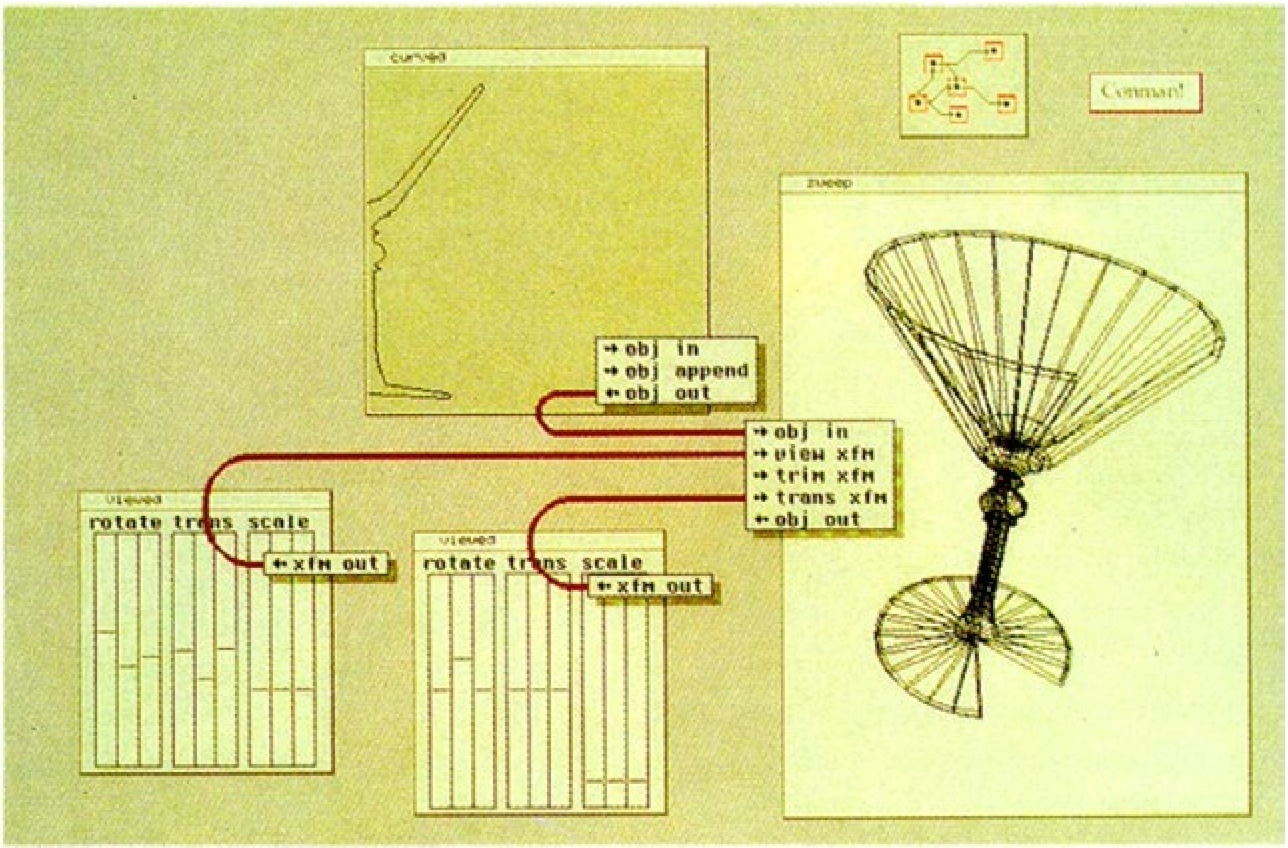


Fig. 23 | *Modelling a glass by profile revolution in ConMan (Connection Manager, 1988). Source: Halbert, 1984.*

In the 2000s there was a new success in parametric design with a subsequent spread of programming tools (ex. Grasshopper, Dynamo, Marionette) for design purposes. The applications went far beyond that, as the new VPLs allowed the management of entire workflows (and data) even between different BIM enviroments thus enabling an high level of interoperability. VPLs for architecture began to be recognized as programming languages capable of facilitating operations that designers, engineers, and architects used to carry out manually (Rutten, 2012). Together with the BIM revolution, these topics started to be included in the training of young architects (Boeykens et al., 2009) (fig. 24).

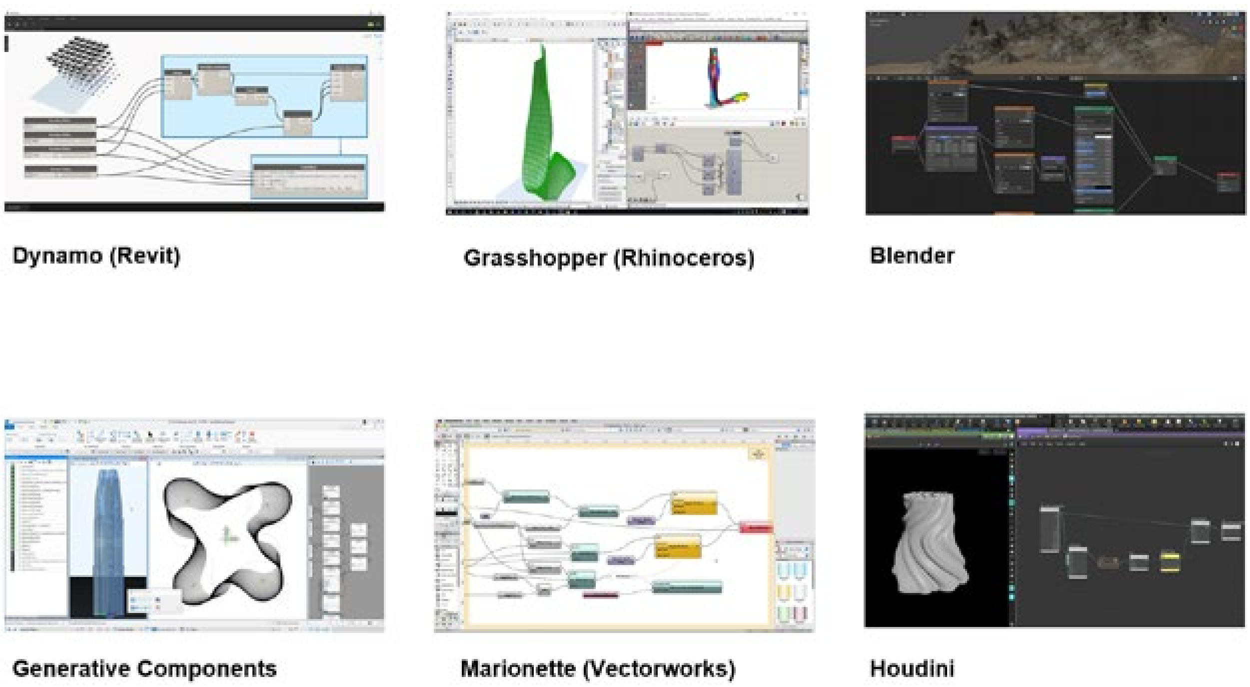


Fig. 24 | *Gallery of some of the most famous Visual Programming Languages environments. Source: author's image.*

Compared to traditional programming, visual programming has a very favorable learning curve in the short term. However, for more complex processes, VPLs are limited because they cannot keep up with traditional programming in the long term (Zwierzycki, 2017). Thanks to the community behind VPLs such as Grasshopper, it is possible to use a series of plugins that increase the potential of VPLs compared to their default setup. However, there is still a gap in the long term, even if it is smaller than the previous one. An emblematic case of this phenomenon is the introduction of Artificial Intelligence applications in the field of parametric modelling. Indeed, a variety of plugins have been created that allow the transition to these new practices within VPLs by reducing the knowledge required to apply them. These plugins enable the user to use Machine Learning and Deep Learning tools, enabling increasingly complex data processing practices. Applications range from design to optimization in production processes. Although in some applications there is no need for textual programming implementations, VPL shows limitations in the long term.

2.2.3 Grasshopper for BIM, Geomatics, Urban Modelling and FEA

The VPL Grasshopper (GH) was used for the parametric modelling applications in this research. This VPL comes with the modeling software Rhinoceros which is a software widely used in the AEC sector by professionals but also researchers. The reasons that led to this choice lie in the fact that GH is a

VPL aimed very much at NURBS-type modelling, has a data structure that lends itself to the semantic layering of elements, and is a widely used tool in the academic community and thus permits comparisons with better scientific rigor regarding the results (TUDelft TOI-Pedia, 2022).

Similar to all VPLs, Grasshopper has an interface consisting of blocks called 'components' which require both input and output for their operation. The relationships between input/output objects and components are graphically achieved through the joining of wires that connect the objects involved. This procedure reduces any kind of language syntax to a minimum, which remains only for more advanced operations related to data structuring. The foundation of grasshopper's data structure is the 'Data Tree'. This structure is articulated analogously to a tree, so a Data Tree will have, advancing in depth, 'Branches', 'Lists' and 'Items'. As an analogy to TPL, one only has to think of the nesting that occurs in JSON formats through the use of dictionaries (TUDelft TOI-Pedia, 2022). The definition of a specific structure of a Data Tree, define the semantic relationships between the parts of the parametric VPL-based model.

Another great strength of Grasshopper is the community of developers supporting it. Through a dedicated portal called 'Food4Rhino', many plug-ins developed for GH can be used. These plugins are mostly free of charge and are often products of research. At the time of writing this thesis, the portal has 1327 applications spread over various fields ranging from aerospace applications to medical applications and the various branches of engineering. In relation to the topics of this thesis, it is interesting to highlight how many apps have been developed around Grasshopper. There are 155 apps for BIM, 593 apps for Architecture, 91 apps for importing and exporting from GH, 24 apps for point clouds and reverse modelling, 80 apps for urban planning and urban modelling and 105 apps for structural engineering (Food4Rhino, 2022).

Interoperability and freedom in both geometric and informational modelling make Grasshopper an effective tool for the development of research related to survey and urban modelling. To reinforce this hypothesis, there are also several case studies in the literature, which are discussed further in section 2.4.3.

2.3 Urban Seismic Risk Assesment: the Southern Italy scenario

Although the objectives of this thesis are not directly concerned with conducting seismic safety analyses on a neighbourhood scale, but with procedures for obtaining a structural geometric model, it is nevertheless useful to investigate what procedures are adopted by local institutions and researchers at the urban scale for determining the level of seismic safety. In particular, in this section, the author will provide information on the context of these procedures in relation to the territory that hosts the sites of the case studied where the proposed methodology has been tested. Furthermore, this overview can highlight how data usually are acquired in order to speed up the analysis workflow as stated in the Introduction.

First, the schools of thought that are adopted at a national level in the study of urban seismic safety will be introduced (section 2.3.1). Secondly, some previous studies relating to the city of Catania, which is representative of typical urban scenarios in southern Italy, are briefly listed (section 2.3.2). After having defined the context of the topic, the author identifies the current methodology used for the transition from digital survey to discrete models useful for structural analysis (Cloud-to-FEM) with a comparison of the different variants (section 2.3.3). In conclusion, reference is made to some exemplary practices both in the professional world and in research that already include the use of VPL and more generally of explicit parametric modelling in the field of structural analysis (section 2.3.4).

2.3.1 School of thoughts: statistical, mechanistic, holistic

In relation to seismic vulnerability assessment at the urban scale, various research and procedures have been identified that aim to combine expeditious surveying with accuracy in assessment.

These methods differ mainly in the type of data needed and the accuracy of the analysis. In particular, an inversely proportional relationship is denoted between range of applicability and accuracy of the assessment (the more accurate the assessment, the closer to the architectural scale at the expense of the urban scale).

Among the most widely used methods for analyzing the seismic vulnerability of entire territorial districts, there are statistical analyses. These focus on determining vulnerability mainly with reference to several main features of building units (such as building/construction type) in order to analyze their distribution over the territory (fig. 25). The object of study then becomes an entire territory without considering the morphological characteristics of individual urban fabrics (at the cost of accuracy), allowing, however, an expeditious and broad assessment for the definition of emergency plans covering one or more territorial areas. The data generally used for this type of analysis are those contained in national databases such as ISTAT or from territorial bodies and institutions (such as universities or the various sections of the Civil Defense Department). The advantage of such methods lies in the fact that it is possible to apply them even in the absence of specific information on building units, assuming the most probable characteristics through the association of units with the corresponding building type. It is still possible to increase the amount of information, thereby refining the analysis at later times. Methods that refer to this category of analysis include the damage probability matrices method, the GNDT methodology, and the Risk-UE method.

Fig. 25 | *3D Map - Seismic vulnerability of residential buildings in Palermo. Source: https://coseerobe.gbvitrano.it/studio-sulla-vulnerabilita-sismica-degli-edifici-di-palermo.html*

Other analyses follow a mechanistic procedure where structural behavior is investigated in detail by simulating seismic actions on the building unit, from which limit values of the structure's strength are derived with great accuracy (fig. 26). Such an investigation requires a considerably higher level of information than statistical surveys. Geometric surveys (from the structural scheme to the internal distribution scheme), analysis of the historical chronology of interventions, and performance of on-site tests to determine mechanical and physicochemical characteristics of materials: are just some of the operations to be carried out in order to accurately determine the value of the seismic safety of a building. In the presence of historical aggregates, which are complex in terms of typological characteristics and layers of successive interventions, such analyses require more time, energy, expertise, and information than statistical methods. In spite of this, at present, these analyses are the most frequently followed procedure for achieving level 2 and 3 assessments in reference to the 2011 Italian guidelines.

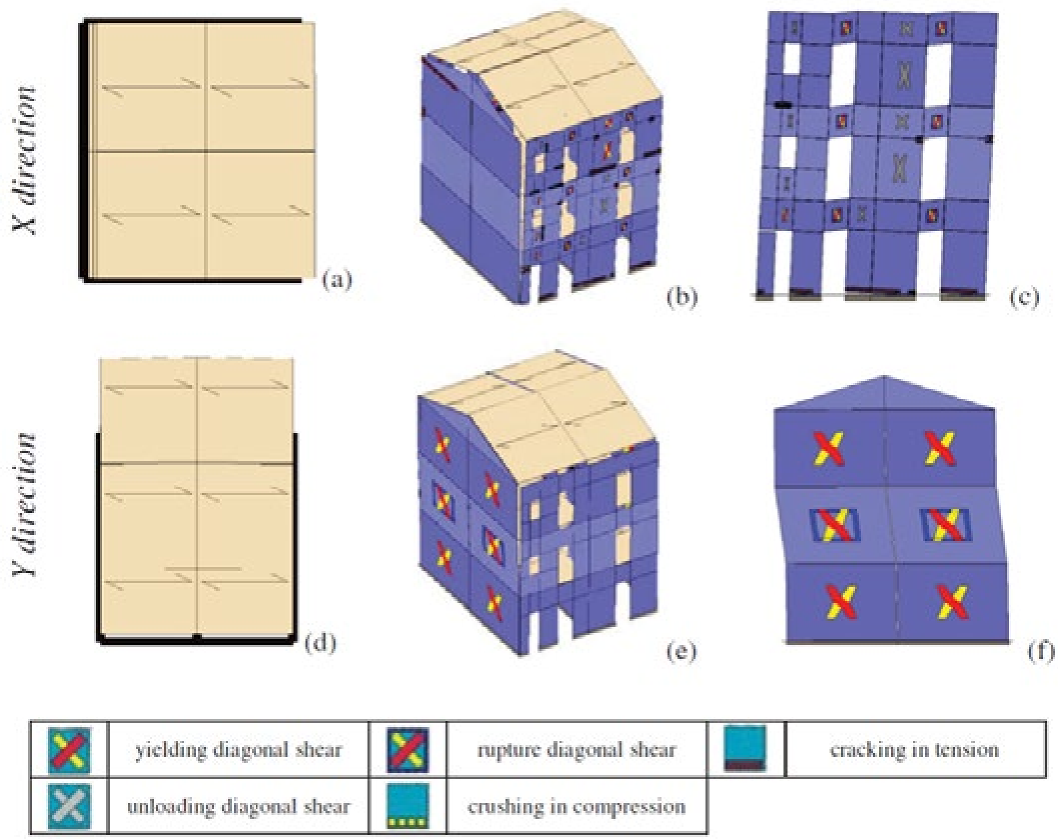


Fig. 26 | *Example of a structural model composed of macro-elements. Source: Greco A., Lombardo G., Pantò B. & Famà A., (2018): Seismic Vulnerability of Historical Masonry Aggregate Buildings in Oriental Sicily, International Journal of Architectural Heritage, pp. 517 - 540*

There is also a third way, more related to some schools of thought in the disciplines of Architectural Restoration and Conservation, which is based on an analysis by experts through a cognitive process that arranges all the characteristics of historic buildings. Specifically, this type of analysis generally begins with a survey of the urban growth of the fabric in which the building analyzed is located, proceeds through the recognition of the construction apparatus (identifying the construction techniques of the period and thus the deficiencies present), the mapping of deterioration, and the analysis of instabilities. Thereby, such a process leads toward a comprehensive and organic view of the construction, which is almost completely impossible to describe through numerical quantities and therefore makes use of descriptive tables and technical reports. This methodology is also being considered by the 2011 LLGGs, in particular, the reference goes to the level 1 assessment that takes into account these analyses where the results of these analyses can be qualitative (Predari et Al., 2019) (fig. 27).

Fig. 27 | *Analysis of a sample block in the historic center of Faenza. From top to bottom: critical survey of structural components, vulnerability and strength analysis, damage scenario analysis. Source: Carocci C.F., (2013), Conservation of wall fabric and mitigation of seismic vulnerability. Introduction to the study of aggregate buildings. In: Blasi C. (ed.), Historic architecture and earthquakes. Operational protocols for knowledge and protection. Wolters Kluwer Italy, pp. 138-153*

2.3.2 Previous studies on seismic vulnerability for the city of Catania

The city of Catania is located on the east coast of Sicily, right on the slopes of the volcano Etna. The city is among the most seismically threatened cities in all of Europe. This particular condition led the city to be repeatedly the subject of research on seismic risk topics, with several in-depth studies on the urban scale (Ciatto et al., 2018).

According to its seismic history, there is a 99% probability that an earthquake with a magnitude greater than 7 will occur in the next 150 years. An earthquake of this magnitude could repeat the historic peak that occurred in 1693 that reshaped the entire city and given the enormous urban growth that has occurred since then, the repetition of such an event in the present day would create an apocalyptic scenario in the city in accordance with what has been simulated by the National Seismic Service. In fact, the number of 'people affected' (dead and injured) exceeds 160,000 with millions of euros of damage. Also for this reason, this possible event has been renamed the 'Big One' (Ciatto, 2017).

Among the main studies conducted over the years, it is worth to mention the 'Project Catania'. This study has been carried out by the 'National Group for the Defense from Earthquakes' in the 1997 and its aim consisted in evaluating the seismeic vulnerability and safety of the building heritage of Catania. The researchers adopted a deterministic approach in two different scenarios. The first simulated the same seismic actions of the soil as in the historical earthquakes of 1169 and 1693 with an intensity of 10/11 level of the Mercalli scale and a magnitude of 7.0 - 7.4. The second scenario foresees a weaker event but with an higher frequency, closely to what happend with another significant earthquake in 1818 with an intensity of level 8 (Mercalli scale) and magnitude of 6.2. The data available for the study were mostly related to three census surveys. Some of these data were acquired from national databases, other were acquired directly with groups of social worker led by some professionals in the recognition of some basic information. A comparison of these data highlighed some inconsistency and incongruency with the data already obtainable from national databases. The study defined two main categories of building: masonry (historical) and concrete buildings. One of the main objectives of the project was to compare two different approaches for assessing of large-scale seismic damage. The first approach, the GNDT method, uses a statistical method based on the assignment of a vulnerability score and is widely used in Italy and other European countries. The assessment of vulnerability is carried out in an expeditious manner through sight analysis, a necessary requirement to have enough data on the whole city. The procedure is based on the definition of a matrix derived from the 1st and 2nd level GNDT matrices for the detection of the vulnerability of existing buildings, whose easily detectable parameters are taken into account. The survey templates are different depending on whether the buildings are with a masonry or reinforced concrete structural system. The second, more recent and mechanistic approach is based on 'displacement limit states'. This methodology, proposed by Calvi in 1999, is based on the evaluation of the displacement demand in relation to a spectrum. The spectrum depends on the site conditions and the structural type of the building. According to this approach, buildings can assume five different situations, corresponding to values from 1 to 5: substantially intact, slightly damaged, damage extensive, severely damaged, total collapse. The results obtained through the use of the two methods are similar, although a direct comparison is complicated due to the different nature with which they were developed. The results have been stored in a GIS enviroment so that these ones could be consulted (Faccioli, 2000; Liberatore et al., 2000).

Another important study is the project 'Risk-UE', which started in 2001 and covered three years under the supervision of the European Commision with the aim to define "an advanced method for earthquake risk scenarios with applications to different European cities". Catania was included, with other six cities, under this ambitious research project. The choice of Catania was made taking into account the availability of data, especially coming from the

‘Project Catania’ few years before. The project divided the city with reference to the constructive system of the buildings (masonry, concrete, steel and wood). The earthquake scenarios used for the analysis were obtained from the analysis of the seimeic history of the territory. For this reason the scenarios were the two same adopted in the ‘Project Catania’. The project took into account the city’s exposure by identifying four periods of interest (day crisis, night crisis, normal and recovery) and their exposure in accordance with the definition of homogeneous areas and parameters such as population, urban space, functional activities and services, urban activities, government activities, identity and culture and external radiance. The project defines different vulnerability indices with respect to the different objects of the analysis. There are therefore different methods of analysis with respect to residential buildings, historic and monumental buildings and infrastructure. With respect to residential buildings, the vulnerability index is established through the definition of a parameter ranging from 0 to 1. The calculation is the addition of predetermined indices related to the building type, a regional modifier and a behaviour modifier that depends on the characteristics of the building. These indices are determined on the basis of statistical information and collected through national survey campaigns. A mechanistic approach is only partially introduced for historic and monumental buildings. Indeed, the analysis of these architectures is based firstly on a territorial level taking into account the building type (statistical approach) and in the second part there is an analysis of a mechanical type. Using the earthquake response spectrum as the seismic input, capacity curves are defined that express the vulnerability of the building. However, this type of analysis concerns only 150 buildings selected for analysis, including many churches and palaces that are generally well-made with respect to the techniques used in their respective historical time periods (Faccioli, 2003).

The aforementioned research works brought national and international attention to the city of Catania, seeking to gradually integrate an approach that from being statistical and qualitative on the basis of visual surveys at the discretion of the operator’s experience, became increasingly scientific and analytical through a mechanistic approach. Unfortunately, this is no guarantee of a correct result compared to the other methods used, but it does make it possible to normalise the type of analysis and knowledge gathered from the urban environment by reducing the subjectivity of the operators and erroneous statistical trends.

The lines of research that have continued in this direction until nowdays addressed the question of how to increasingly integrate mechanistic approaches to the needs of expeditious surveying considered on a highly complex historical building heritage. In relation with the aim of this thesis, from the analysis of the state of the art has emerged a specific work that proposes an expeditious methodology aimed at structural modeling that allows the analysis of seismic vulnerability using mechanistic methods. This research project falls within the University of Catania FIR 2014 University Research Funding Program and is entitled 'Seismic Vulnerability of Historic Aggregate Buildings. New structural modeling and expeditious methodologies and approaches.' The research was conducted by a multidisciplinary team and focused on several residential areas in the historic urban center of Catania. In this work, a typological study was conducted that led to the identification of 9 distinct building types based on the amount and mode of accretion of a primary wall cell. The typologies identified were summarized into 9 archetypes used as a reference for the construction of geometric models. These models were then used to define the corresponding structural models within the software that allows the simulation of seismic actions on structures (in accordance with the procedure for 'macro-elements'). Finally, a seismic vulnerability assessment was conducted both on individual archetypes and on an ideal urban aggregate obtained by assembling several archetypes (Caddemi et Al., 2018) (Fig. 28).

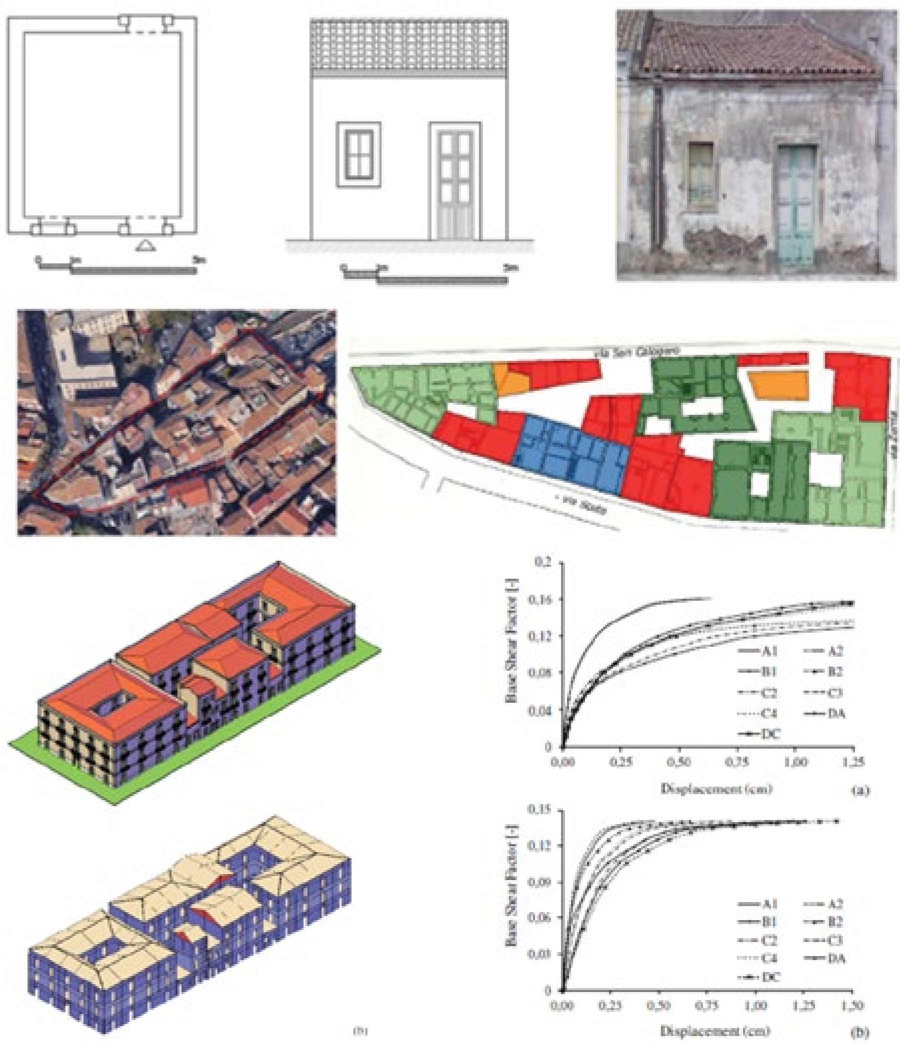


Fig. 28 | *From top to bottom: archetypal one-storey house, typological classification of building units in an aggregate of the historic center of Catania, (bottom left) geometric model and structure of an ideal representative aggregate, (bottom right) Capacity curves of structural units within the aggregate (average masonry quality) in longitudinal (a) and transverse (b) directions. Source: Greco et al., 2018.*

2.3.3 Cloud-to-FEM methods: BIM and NURBS modeling

There are research threads dedicated to the optimisation of digital workflows in an attempt to use semi-automatic and automatic methods to obtain geometric models useful for structural analysis. The topic spans two disciplines, digital surveying and structural analysis, which have apparently different requirements both conceptually and in terms of type, accuracy and quantity of data. Therefore, defining a valid approach for both means bringing together both representation and analysis necessities. In the national and international sphere, there are various researches that have attempted to bridge this gap in research by defining different approaches that are useful to take into account with respect to the experiments presented in this thesis. Given the vastness of the topic, the following is a selection of works that may be representative of the approaches currently found in the literature.

Concerning the transition from digital models to geometrical entities useful for FEA there are different approaches proposed in the last years. The evolution of geomatics methodologies allowed to acquire structures with high accuracy and to integrate in the same pipeline of work the application of BIM methodologies towards the definition of finite elements models. This procedure is known in literature as Scan-to-FEM (also Cloud-to-BIM-to-FEM) approach (Barazzetti et al., 2015; Dore et al., 2015) (fig. 29).

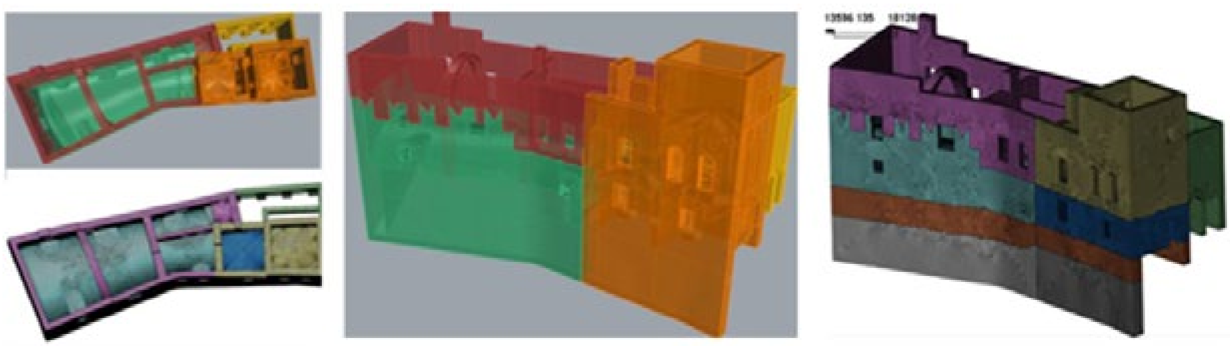


Fig. 29 | *From left to right: NURBS geometries produced in the BIM environment and converted into mesh models for FEM analysis. Source: Dore et al., 2015.*

The transition from BIM to FEM contemplated in these methodologies does not always occur straightforwardly despite the interoperability of BIM models. Moreover, FEM analyses are not univocally defined by a single model, but they vary with regards to analysis needs (Abbate et al., 2020). Other methods do not take a BIM approach and move from point cloud to manual NURBS modeling. This procedure articulates in the following steps: generation of polygonal model from point cloud, extraction of outlines coming from the slices of the model, construction of NURBS model on the basis of sections and discretization of NURBS model into mesh model for analysis in dedicated FEM software (Fortunato et al., 2017; Fang et Al., 2021). In some scenarios, the cloud would not be cross-sectioned, but after the cleaning phase of the non-structural elements, it would be converted into a closed mesh trying to obtain a mesh as smooth as possible. Most often, the mesh consists of triangular faces in order to guarantee the flatness of all elements. This mesh is then transformed into a closed NURBS polysurface within mathematical modelling software (e.g. Rhinoceros). This intermediary operation is occasionally necessary since some structural analysis software takes a closed solid polyhedron model as input. Eventually, the model provided as input to the FEA software recomputes a mesh from the mathematical model provided as input in order to optimise faces and densities with respect to the analysis to be conducted (Quattrini et Al., 2019) (fig. 30).

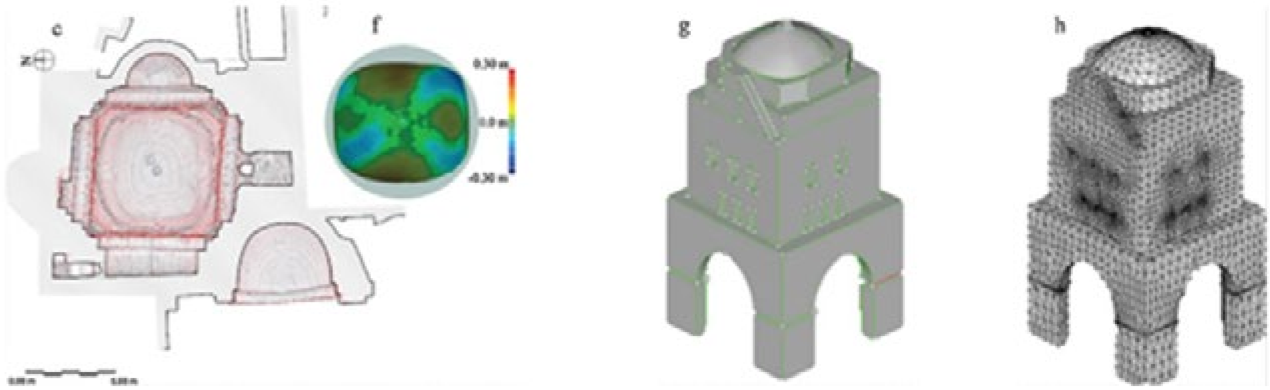


Fig. 30 | *Parametric Scan-to-FEM models. From left to right: original point cloud, generation of the parametric model, discretization into mesh model and FEM analysis. Source: Funari et al., 2021.*

In the literature it is possible to find experiences of process automation that aim to save time and overcome the criticalities present in BIM models exported for FEM analysis (mesh compatibility, local deformations and too small details) (Castellazzi et al., 2015). It is worth to mention that there are not many applications towards the adoption of computational design tools for optimising and accelerating the Scan-to-FEM pipelines (Funari et al., 2021). Another research gap can be found in the lack of applications between city blocks acquisition-modeling and a semi-automatic transition to FEA (fig. 31).

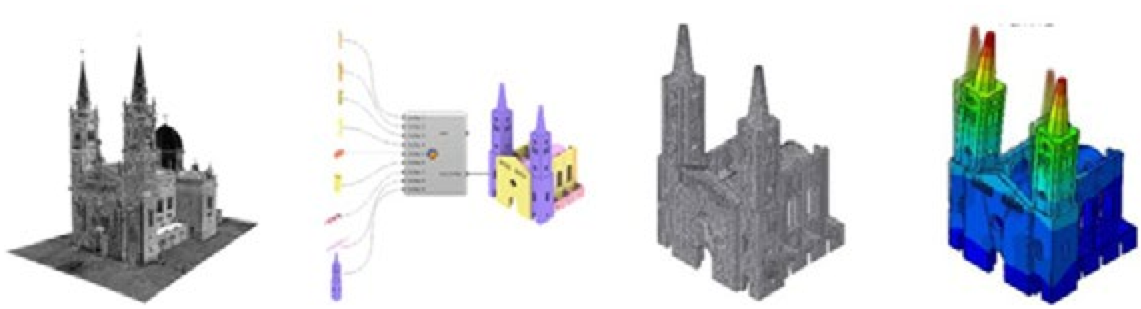


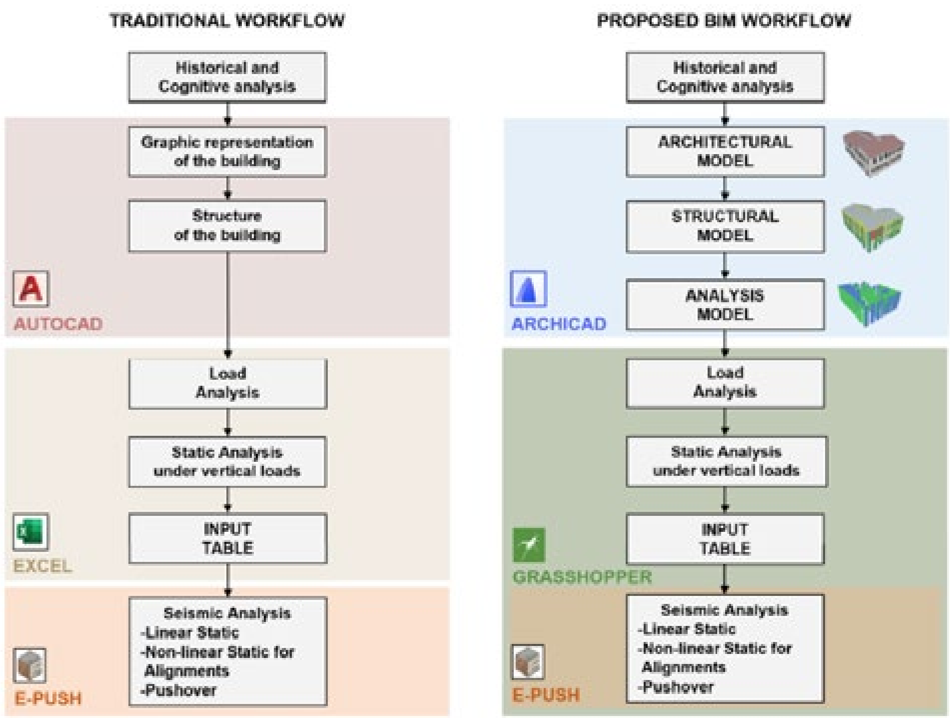
Fig. 31 | *Generation of a mesh model for FEM analysis from a NURBS mathematical model generated using point cloud cross sections. Source: Fortunato et al., 2017.*

2.3.4 Parametric and VPL based related works on structural analysis

The introduction of digital workflows from reality to structural analysis has made it possible to integrate parametric modelling solutions into the structural analysis phase itself. This phenomenon started especially in workflows that included HBIM methodologies. Indeed, this methodology often exploits the potential of VPLs to recreate components that are difficult to reproduce manually. The interoperability of BIM models with VPLs has made it possible to exploit the latter not only for modelling purposes but also for performing proper analyses. This is due both to the possibility of developing textual codes within VPLs and also due to the existence of structural engineering plugins that can directly interface with the models created (as already described in section 2.2.3). The BIM-to-FEM workflows that develop this approach initially involve a survey and study phase of the building, then BIM modelling through the point cloud-based architectural model, and finally the structural and analytical model. From the BIM environment, the analytical model is extracted using VPLs that are capable of receiving geometries and attributes of each individual component. Within the VPL environment is possible to define loads and boundary conditions. At this point, two scenarios can occur. In the first, the VPL is exploited to create the input model to an external analysis software (through the creation of a file or directly with a dedicated plugin), while in the other scenario, the analysis can take place directly within the VPL environment (through expressly defined codes or via specific plugins). Eventually, the results obtained are processed by VPL by means of which the BIM model is updated with the result of the analysis (Croce et Al., 2022; Croce et Al., 2021; Calvano et Al., 2022; Massafra et Al., 2020; Moyano et Al., 2022) (fig. 32).

In other cases, the use of VPL is useful for improving the configurations of parameters and families within BIM environments, so that models can be calibrated to directly obtain information such as the quality index of the masonry automatically through the input of appropriate indices. This approach makes the structural analysis even more intrinsic, developing it already during the HBIM modelling and information enrichment phases (Calvano et Al., 2022; Massafra et Al., 2021) (fig. 33).

Fig. 32 | *Comparison between Seismic analysis workflow CAD based and BIM based. Source: Croce et al., 2022.*



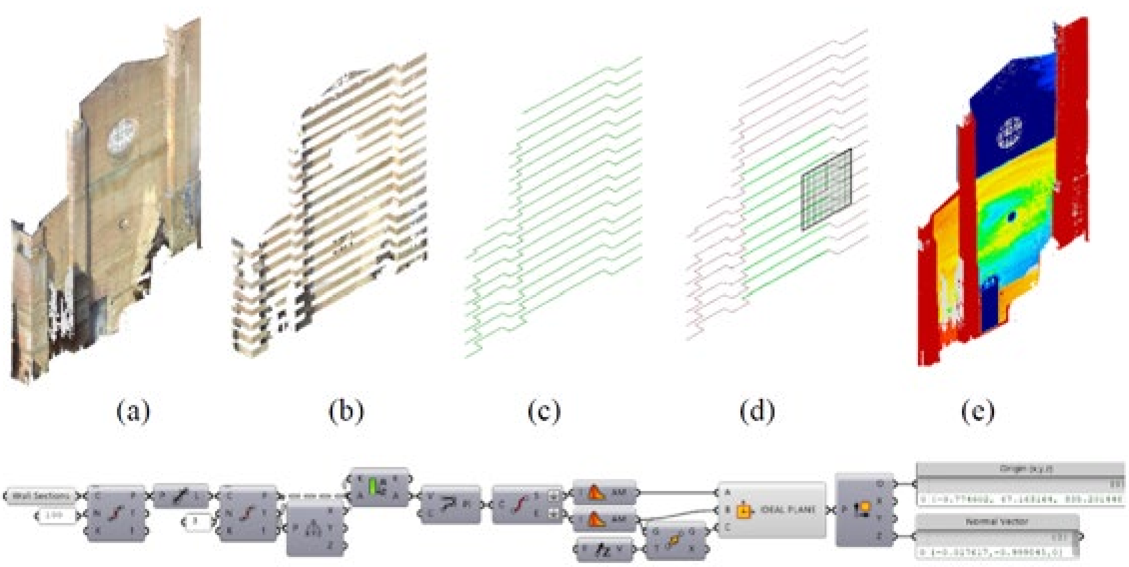


Fig. 33 | *The model generation procedure and grasshopper algorithm. (a) TLS point cloud; (b) Point cloud segmentation; (c) Vectorised cross-sections; (d) Ideal Plane; and (e) TLS point cloud-Ideal Plane comparison. (Source: Massafra et al., 2021).*

2.4 From 3D City Models to City Information Modeling

To conclude, this section introduces the topic of 3D city models. This subject, which is one of the main topics in relation to the aims of the thesis, was left for last as it is transversal to all subjects discussed and contains several points of contact with them. In particular, the definition and standards for 3D city models are introduced (section 2.4.1). This is followed by a description of City Information Modeling (section 2.4.2), the methodological paradigm in which the thesis work is embedded. Finally, a review is provided regarding the state-of-the-art of current applications in relation to City Information Modeling that are close to the topics of the research work (section 2.4.3).

2.4.1 Definition, standards and applications of 3D City Models

Currently, a 3D City model can be defined as *"a digital representation, with three-dimensional geometries, of the common objects in an urban environment, with buildings usually being the most prominent objects"* (Arroyo Ohori et Al., 2022). This virtual representation is usually adopted to store, visualize and interact with digital urban data acquired from reality that include terrain, building, vegetation as well as roads and transportation systems models. Virtual 3D city models' ability to visually integrate diverse geoinformation into a unified framework is one of its distinguishing features. As a result, they enable the creation and management of complex urban information environments (Döllner et Al., 2007; Billen et Al., 2014; Zhu et Al., 2009). The generation of 3D city models can take place from different types of acquisition and data. Examples of methods through which 3D city models can be generated are: photogrammetry (terrestrial and aerial), laser scanning, extrusions from 2D cad, CAD/BIM model conversion, procedural modelling, crowdmapped opendata, etc. Generally, 3D city models are defined with respect to a data structure and format according to the type of datasources available, the expertise of those producing them and the type of output expected. The applications of 3D city models cover almost all disciplines, so their generation and management is a topic of considerable scientific relevance. In Biljecki (2017), 29 different applications of city models are identified. These include analyses for solar irradiance estimation, energy demand estimation, inhabitant estimation, visualisation of the urban environment for navigation systems, visibility analysis, shadow studies for urban climate analyses, applications for land registry, urban planning, facility management, emergency response, etc.

In the context of this research, semantic 3D city models will be discussed. The motivation for semantic 3D city models is the fact that they allow information to be extracted from the city model (e.g. *how many inhabitants are there in a city block? or what are the years and construction techniques of its buildings?*, etc). Models that do not allow queries and/or interactions cannot be called semantic 3D city models but 3D representations of a territory (a mesh obtained from photogrammetry of an urban area cannot be defined as a semantic model since the computer does not know how to extract this information). These digital artefacts are data models where the relevant objects

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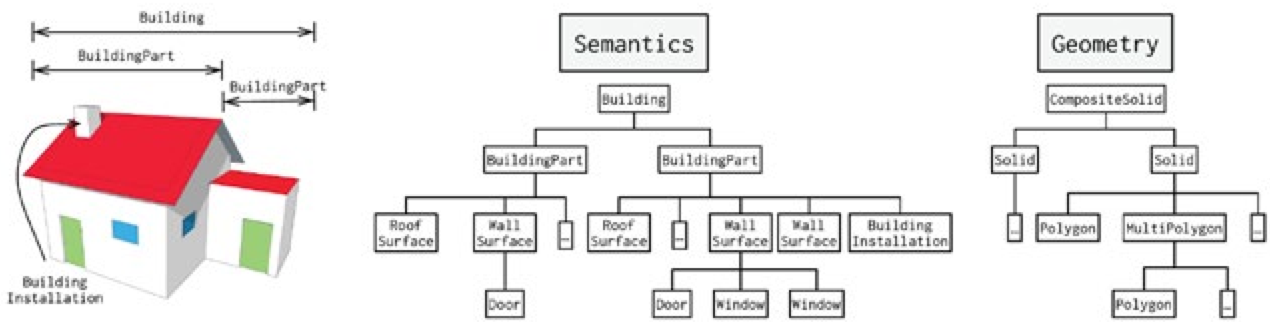


Fig. 34 | *A building is semantically decomposed into different objects, and each object is defined with geometry. (Source: Arroyo Ohori et al., 2022).*

Due to the great variety of types of 3D city models, it became necessary to define an international standard that would define the data structure from a semantic point of view so that even if models were obtained from different data and processes, they would all be constituted in the same way. The modeling standard for three-dimensional information models of cities and urban systems is the CityGML 2.0 from the Open Geospatial Consortium, which identifies five levels of detail (LOD) in the three-dimensional representation from 0 (footprint on the ground) to 4 (building modeled both internally and externally) and uses a set of classes to describe city characteristics. In the latest version of this standard, there is also mapping of IFC elements (from BIM models) to the CityGML classes (OGC CityGML 3.0 Conceptual Model) recognized by the Open Geospatial Consortium (OGC) and the ISO/TC211 technical committee. It is worth pointing out that these levels of development correspond to geometric and semantic features requirments informational requirements. The different levels of detail are discussed in more detail below.

LOD 0 - It is the two-dimensional representation of the footprint of buildings on the ground through polygons. It can also contain polygons relating to the projection of roof edges in order to facilitate the transition from 2D to 3D. It can also be in the form of 2.5 D digital terrain model (DTM), since it represents the topography of the territory under analysis on which the aerial photo is projected. In this case, the buildings are represented as 2D ground footprints projected on a 3D surface. This level is widely adopted in GIS application for territorial/country scale models.

LOD 1 - LOD 1 consists of the representation of building type objects in the form of prisms obtained from the extrusion of the LOD0 footprints on the ground. This level provides the volumetric characteristics of the urban environment at the scale of a city or settlement.

LOD 2 - This level provides a model capable of representing roof geometry with simple shapes as well as semantically breaking down buildings into their different subclasses (e.g. walls, roof, floors). This level reaches the scale of the neighbourhood, allowing for more detailed analyses due to the presence of roof geometries. Furthermore, thanks to the semantic decomposition into sub-components, this level can be said to reach the 'BIM scale' where each building component is related to the others and has geometry and attributes.

LOD 3 - LOD3 increases the detail compared to LOD2 by adding all the openings present on the envelope (doors and windows) plus other objects not comparable to LOD2 such as chimneys and roof details. The scale of this level is architectural, from 1:200 onwards.

LOD 4 - With LOD 4, the highest level of detail is achieved. In addition to the features presented in LOD3, the dimension of the interior space is added, so the LOD4 can present elements such as floors, interior walls, doors, stairs and furniture (Biljecki et Al., 2014; Biljecki et al., 2013) (fig. 35).

Fig. 35 | *The five LoDs in CityGML for the exterior of a building. (Source: Biljecki et al., 2014).*

The predominantly geometric nature of LODs is due in part to that the applications of 3D city models generally have requirements more related to geometry than to object semantics. While as far as information is concerned, it is often layered two-dimensionally through the use of GIS without a precise location. However, applications involving 3D city models have scaled down to the architectural scale requiring greater precision and more advanced management of collected geometries and attributes. Furthermore, the impossibility of some digital acquisition techniques in particular urban environments has highlighted certain drawbacks that the adoption of such LODs raises during the modelling phase (Machl, 2013; Löwner et Al., 2016; Biljecki et Al., 2016). Below is an example of some of the ambiguities involved in such LODs. Indeed, in figure x, it can be seen that the first and second models from the left correspond to LOD2. However, the first is more accurate as it is the result of an aerial and terrestrial accquisition that allowed the exact position of the roof and walls to be defined, while the second is obtained from the projection of the roof edges alone, leading to an erroneous position of the walls. Another example is the third model, where a simple addition to the building with a different height is extruded up to the maximum height (fig. 36).

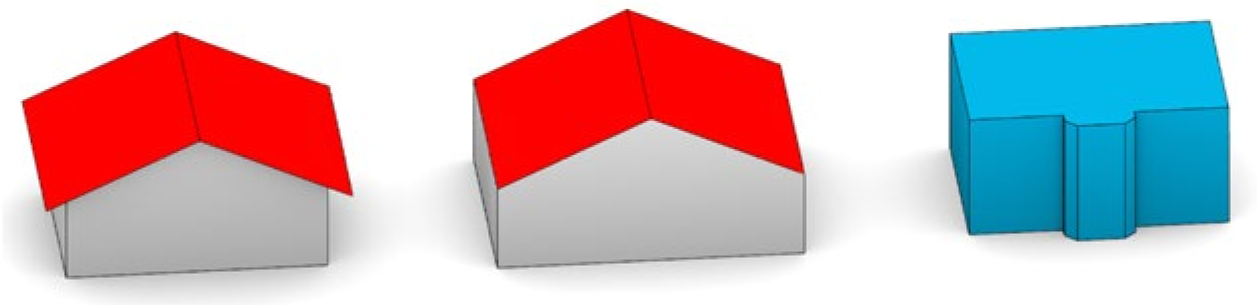


Fig. 36 | *Two variants of LOD2 and an LOD1 model exposing the shortcomings of the CityGML LOD concept, and why the computer graphics principles cannot be fully applied to GIS and 3D city modelling. . (Source: Biljecki et al., 2016).*

These ambiguities also arise from the technological advancement of acquisition and modelling techniques, which sometimes only allow for a portion of the acquired reality or already prepared and defined 3D information models. This issue is amply discussed in the literature (Guercke et al., 2011; Fan et al., 2012; Deng et al., 2016). According to Biljecki et al. (2016), one of the main problems with these ambiguities is the lack of standards that relate acquisition techniques to the models obtained, thus generating confusion over the use of nomenclature. How should be classified a building that is represented only by a prism (LOD1) but has surfaces inside it that represent floors (LOD4)? To answer these type of questions, the 3D Geoinformation Research Group at the University of Delft proposed a review of LODs. This revision consists of 16 LODs obtained by defining 4 versions for LODs ranging from 0 to 3. LOD4 is excluded, as for urban applications it is currently not used much due to the difficulty of acquiring data concerning the interior of buildings (privacy issues) (Biljecki et Al., 2016). Below is the matrix with the proposed new LODs (fig. 37).

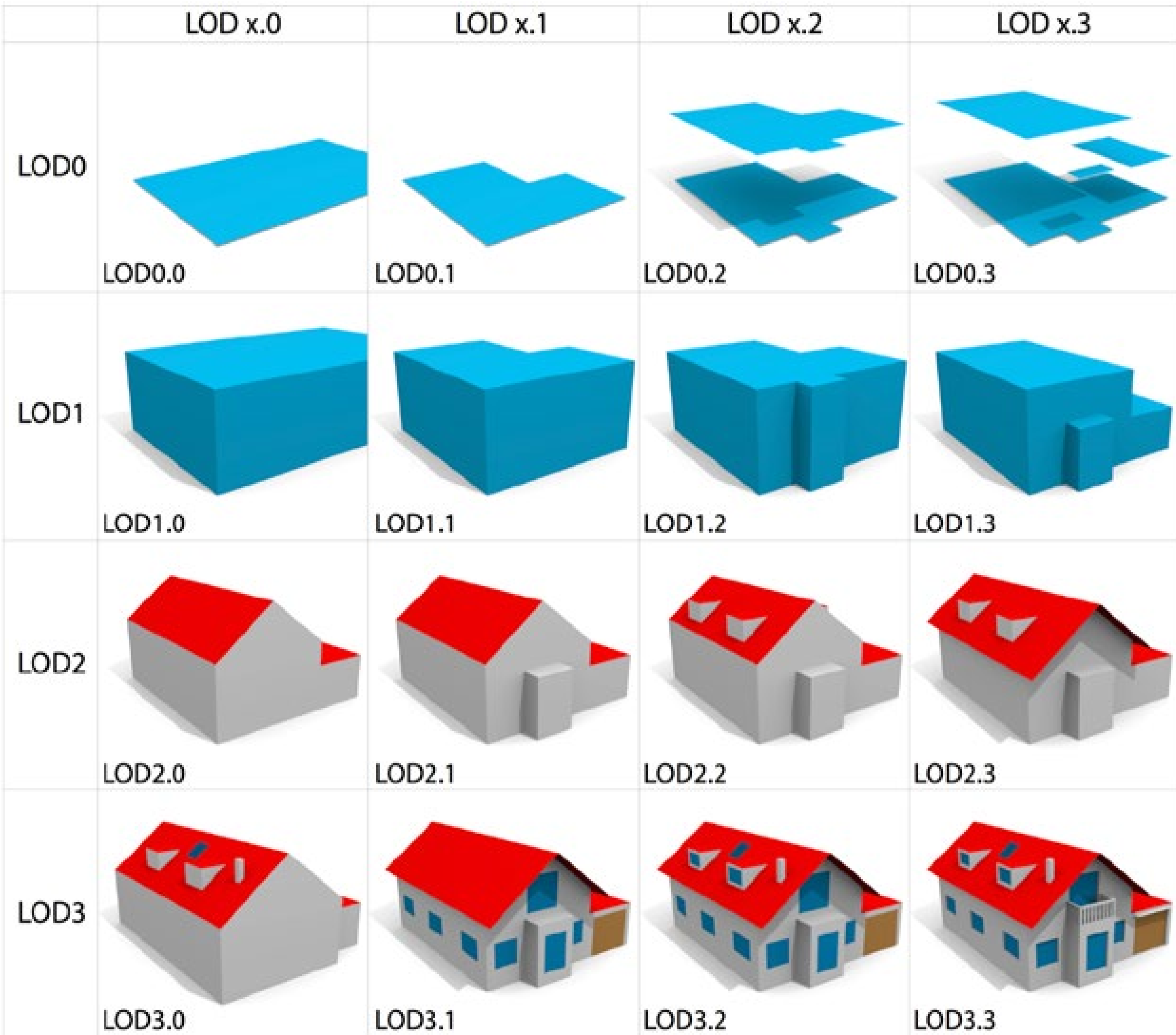


Fig. 37 | *Visual example of the refined LODs for a residential building proposed by Biljecki et al. (2016). (Source: Biljecki et al., 2016).*

This LOD allocation has also been formalised as the reference standard for the CityJSON format (recognised by the OGC), which will be introduced later. Among the various changes introduced with this LOD perspective, it is worth highlighting, with respect to the applications presented in this thesis, those concerning LOD3. Generally speaking, the acquisition of LOD3 is a very laborious process that combines different techniques. Generally, there is both terrestrial (photogrammetry or laser scanner) and airborne (photogrammetry or LIDAr) acquisition. For this reason, this level does not cover vast areas but concentrates on the size of the neighbourhood. Compared to the matrix presented in figure x, LODs 3.2 and 3.3 are intended to differentiate the level of detail of the objects in the envelope (LOD3.2 >1.0 m, LOD3.3 >0.2 m). These levels permit better classification of models obtained from BIM environments or modelled for visualisation purposes. However, some models in the literature (Franić et al., 2009; Novaković, 2011) have different LOD characteristics. Generally, such LODs, referred to as hybrids, result from differences obtained in terrestrial and/or aerial acquisition (or lack of one of them). For this reason, LOD3.0 corresponds to a model with a greater detail of roof geometries than LOD2, but in other characteristics it may fall within LOD2 (greater quality in aerial acquisition). On the other hand, LOD3.1 emphasises greater quality in terrestrial acquisition, taking into account that this type of acquisition can achieve the requirements of LOD3 except for the roof, which is often out of range (Biljecki et Al., 2016).

The official format recognised by OGC through which 3D city models can be encoded, developed and shared is CityGML with its three encodings (or sub-format) which are: XML encoding (usually called 'CityGML'), CityJSON and 3DCityDB (a database schema for PostgreSQL). The last one is not official, however is largely used around the world (Arroyo Ohori et Al., 2022).

CityGML was released in 2008 in its first version. It consists of a data model that enables the representation of semantic 3D city models. The latest version is 3.0 released in 2021. CityGML allows a description of buildings both internally and externally, in accordance with the original five LOD levels described above. The format is broken down into several modules, each of which can be described textually and via UML diagrams (Open Geospatial Consortium, 2012) (figg. 38, 39).

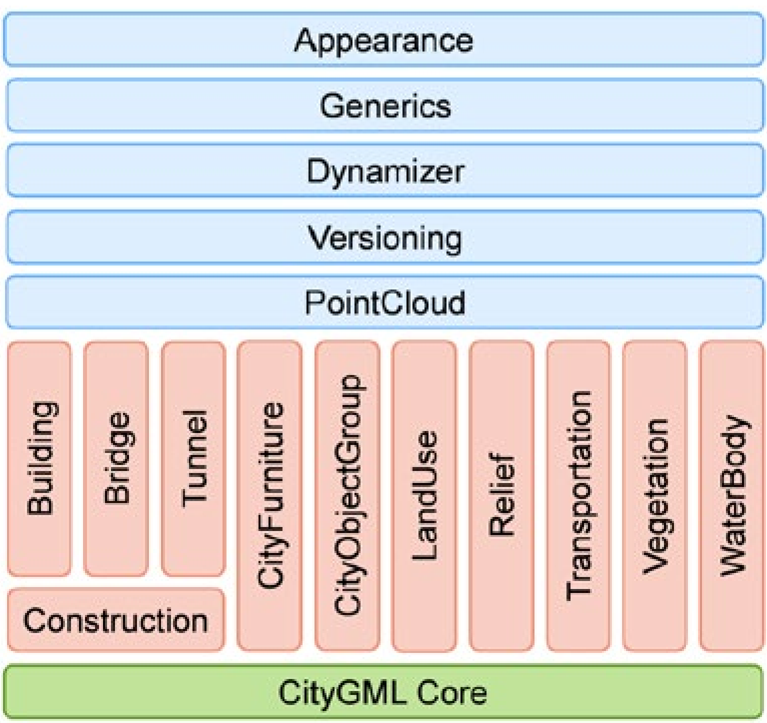


Fig. 38 | *The modules of the CityGML data model. (Source: Arroyo Ohori et al., 2022).*

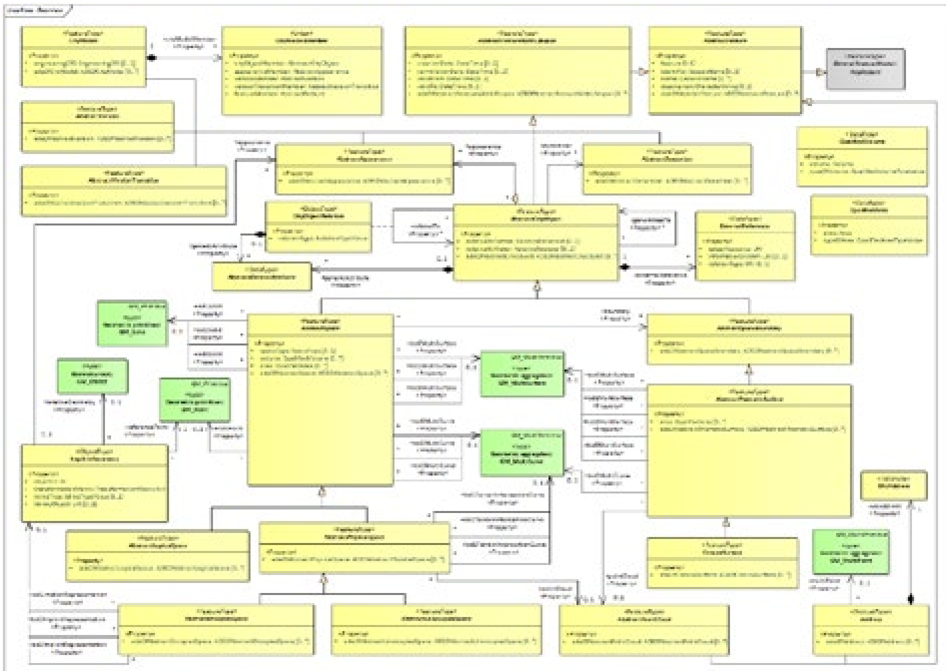


Fig. 39 | *Overview of the UML model for the core of CityGML. (Figure © 2021 Open Geospatial Consortium, Inc.) (Source: Arroyo Ohori et al., 2022).*

CityGML is encoded using GML (Geography Markup Language) via XML. Therefore, a CityGML file consists of an XML text file describing parts of the 3D city model. Unfortunately, this method of writing the file is not among the most accessible, as XML encoding is not human readable with a rigid hierarchical structure and hardly adapts to the web. This has reduced the applications of CityGML in other software, determining a reduction of the attention towards the standard itself, thus causing a proliferation of semantic 3D city models that are hardly interoperable in terms of both file and semantic structure (fig. 40).

```
<?xml version="1.0" encoding="UTF-8"?>
<CityModel xmlns:xlink="http://www.w3.org/1999/xlink"
  xmlns:gml="http://www.opengis.net/gml"
  xmlns="http://www.opengis.net/citygml/2.0"
  xmlns:bldg="http://www.opengis.net/citygml/building/2.0"
  xsi:schemaLocation="http://www.opengis.net/citygml/2.0">
  <cityObjectMember>
  <bldg:Building gml:id="9a06451677c7">
    <bldg:function>1070</bldg:function>
    <bldg:lod1Solid>
      <gml:Solid>
        <gml:exterior>
          <gml:CompositeSurface>
            <gml:surfaceMember>
              <gml:Polygon>
                <gml:exterior>
                  <gml:LinearRing>
                    <gml:pos>0.0 0.0 0.0</gml:pos>
                    <gml:pos>0.0 1.0 0.0</gml:pos>
                    <gml:pos>1.0 1.0 0.0</gml:pos>
                    <gml:pos>1.0 0.0 0.0</gml:pos>
                    <gml:pos>0.0 0.0 0.0</gml:pos>
                  </gml:LinearRing>
                </gml:exterior>
              </gml:Polygon>
            </gml:surfaceMember>
    ...
    </bldg:Building>
    <bldg:Building gml:id="jdhd76sa">
    ...
    </bldg:Building>
  </cityObjectMember>
</CityModel>
```

Fig. 40 | *Part of a CityGML file containing 2 buildings. (Source: Arroyo Ohori et al., 2022).*

For this reason, CityJSON was developed. It presents itself as an alternative to XML encoding that aims to be more user-friendly and thus improve dissemination thanks to the API support it enjoys. The current version of CityJSON is 1.1.2, released in August 2022. The adoption of JSON encoding makes this format accessible to most programmers, especially beginners. In fact, JSON files are structured from the nesting of common dictionaries and thus find easy development in both existing software and new applications. In CityJSON, the hierarchical structure is reduced to a minimum, through a division between first- and second-level CityObjects (fig. 41). All hierarchical relationships are explicitly stated within the objects in the form of attributes ("parents" and "children") and not by means of an actual semantic structure. Thus, by using the appropriate keys, the data model can be reconstructed correctly (Ledoux et a., 2019).

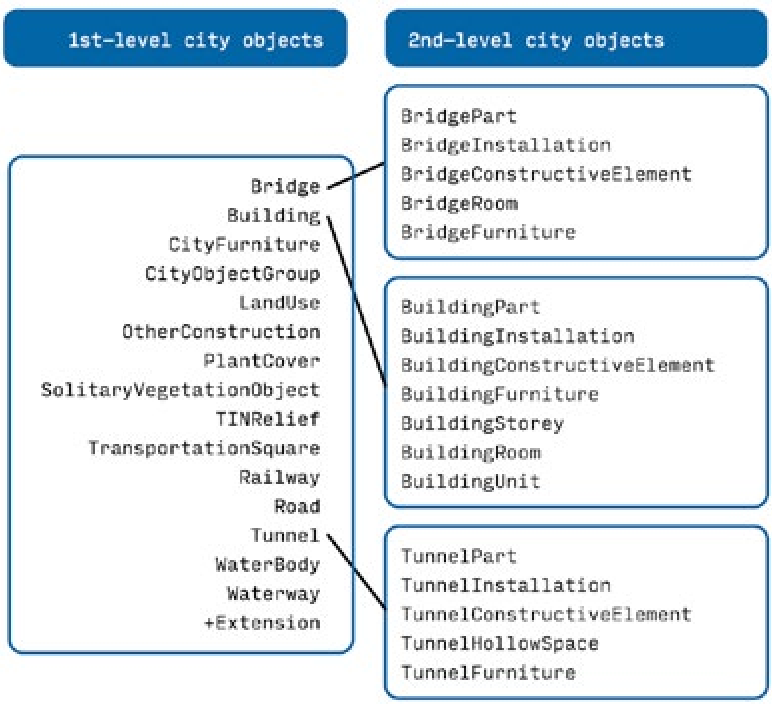


Fig. 41 | *The implemented CityJSON classes (same name as CityGML classes) are divided into 1st and 2nd levels. (Source: Arroyo Ohori et al., 2022).*

2.4.2 City Information Modeling: beyond GIS and BIM

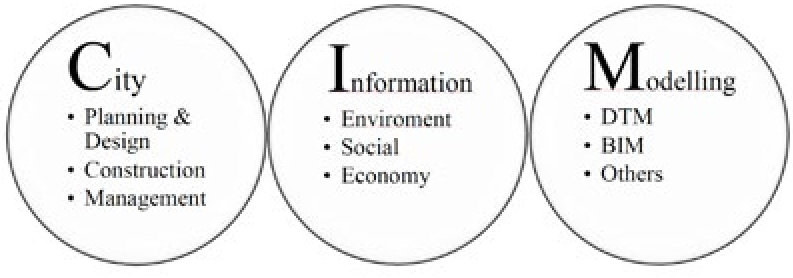
As discussed in section 2.4.1, 3D city models currently share a format that guides the definition of the semantics of city objects. However, the multitude of methods used for acquisition and modelling have made it difficult to define a methodological paradigm as has been the case for GIS and BIM systems. In the state of the art, however, a method has emerged that has become an increasingly common subject in the literature for several years now, due in part to the debate about the digital revolution in Smart Cities. It is called City Information Modeling and is considered to be the synthesis of several workflows in the branch of parametric information modelling.

The definition of City Information Modeling is an issue that has been widely debated internationally in recent years (Simonelli et al., 2018). An outlining according to information modeling standards is at least complex given the hybrid nature of the BIM and GIS environment. Therefore, it is necessary to identify what characteristics allow a CIM model to be defined as opposed to a 3D GIS or BIM extended to the urban scale. In agreement with Xue, F. et al. (2021), the meaning that the 'I' of 'Information' takes on in CIM versus GIS and BIM provides the correct key.

According to one of its first definitions, it is called the Urban Information Model which “integrate the multidimensional urban aspects like economy, society and environment with 3D urban model plus temporal dimension. Urban information model will provide comprehensive information support to various urban planning application systems” (Hamilton et al., 2005). One of the most established and recognised definitions in the literature is that a City Information Model consists of a system of urban elements represented by 2D and 3D elements containing information, linked by semantic relationships (Stojanovski, 2013). Therefore, we talk about City Information Modeling when we refer to the technologies and practices used to develop CIM models and to exploit their potential for urban and spatial analysis (Xue et al, 2021; Mozuriunaite et al., 2021) (fig. 42).

We can think of CIM models as BIM systems applied to urbanism, a 3D semantic expansion of GIS models (Stojanovski, 2013). As Xu et al. highlight (2014), the major difficulty in CIM is the information modeling since these models deal with outdoor and indoor data semantically linked. It is worth to mention that 3D city models developed on BIM environments and then visualized in GIS (and vice versa) cannot fulfil the definition of CIM since geometries and information are not able to modify and interact to each other beyond visualisation and queries purposes. This type of 3D city models, also known as ‘GeoBIM’ (Noardo et al., 2020), is mainly focused on interoperability between BIM and GIS standard formats (IFC and CityGML) (Sun et al., 2020).

Fig. 42 | *Concept diagram of the definition of City Information Modeling. (Source: Mozuriunaite et al., 2021)*



The first developments of CIM can be identified in applications aimed at overlapping point clouds obtained through instrumental surveys (laser scanning, photogrammetry) and geo-referenced 3D models obtained in a GIS environment (Julin et al., 2018) (fig. 43).

Fig. 43 | *View of the three-dimensional information system Helsinki 3D+. It is possible to consult the system both as a CIM (created from geodata, BIM models and laser scanner point clouds) and as a 'Reality Mesh model' (polygonal photogrammetric model obtained from aerial photographs of the entire city). Source: Helsinki 3D+ Information Model. Link: https://kartta.hel.fi/3d/*

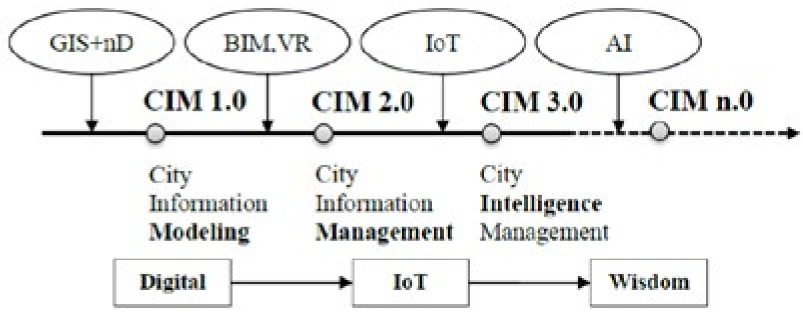
In these models, information was (and still is) stratified by layers within one- and two-dimensional geometries (Goodchild 1991; Lu et al., 2018). The first substantial difference between GIS and CIM emerges: the latter considers urban scenarios such as flow analysis, energy simulations, and construction techniques that relate to each other through cause-and-effect relationships (similar to what happens in BIM) and not only by the adjacency of georeferenced locations. A 3D (semantically defined) model developed within GIS software can thus be considered a specific subcategory of CIM (Xu et al., 2014a; Liu et al., 2017).

As for BIM, it concerns all the information at the architectural scale that is functional for the design, management, and preservation of a given architecture (Lo Turco, 2015; Osello, 2015). In CIM, however, the relationships between the individual architectural unit and the information related to the three-dimensional urban context intervene (Xu et al., 2014a). Based on these relationships, in CIM, the semantic enrichment of the architectural units themselves is defined (e.g., the identification of the main front with respect to the street).

Currently, one of the challenges in City Information Modeling is the integration of Geographic Information Systems (GIS) and Building Information Modeling (BIM) into a single model that allows for the investigation of different scales of detail (in terms of geometry and information) in a given urban area for different purposes (Ying et al. 2020; Jovanovic et al. 2020). Thus, there are on the one hand systems that implement data describing the area and/or the city predominantly in the two dimensions, and on the other hand systems that describe in detail, both in terms of geometry and information, the individual building and its construction components.

In Mozuriunaite et al. (2021), the different stages of evolution of CIM systems are described in four stages. In the first phase, there is the combination of GIS and digital modelling technologies with the aim of creating a single, coherent urban information model (such as GeoBIM models). The second phase deals with improving the interaction with these models through the introduction of technologies such as Augmented and Virtual Reality in order to allow more effective consultation, both on-site and in the office, even for non-experts. The third phase, on the other hand, consists of the integration of the Internet of Things, in order to embrace the concept of a city-wide Digital Twin. The fourth phase, the one whose evolution is currently in progress, consists of the application of AI mechanisms in order to further improve the creation, management and maintenance of the CIM, reducing costs and increasing the quality of output (fig. 44).

Fig. 44 | *Stages of CIM's development and application. (Source: Mozuriunaite et al., 2021)*



2.4.3 3D City Modelling significant case studies close to CIM for seismic risk assessment and management

Nowadays, there is a wide range of CIM applications covering different disciplines (Xue et al., 2021; Xu et al., 2014). It is possible to distinguish three main approaches for developing CIM models: bottom-up, top-down and parametric.

The first one (or BIM-based) focuses more on remote sensing on site acquisition (close- and mid- range laser scanning and photogrammetry) with subsequent manual and semi-automatic modeling processes in BIM and CAD environments (Pelliccio et al., 2017; Zhang et al, 2021; Avena et al., 2021; Parrinello et al., 2020). These procedures often merge BIM and GIS data enabling the users to make queries and display models on web-based platform. In these models Computational Design is applied, through Visual Programming Languages (VPL), to link, sort and merge metadata between models and environments but not for modeling purposes (fig. 45).

The top-down procedures deal mainly with long-range remote sensing techniques (e.g., Airborne LiDAR data) and geodata (coming from online open-data sources or datasets held by local institutions) which are further developed inside GIS-based procedural modeling digital environment (Biljecki et al, 2015; Nys et al., 2020; Wang et al., 2018, Pârvu et al., 2018). Top-down models usually don't need any further integration (unlike bottom-up models) with exception for indoor data that are inserted via the conversion of IFC files into CityGML objects (Biljecki et al, 2021). These models are closer to the

Fig. 45 | *Example of BIM-based 3D city model for risk assesment. The methodology applied was called Historical Town - BIM. (Source: Pelliccio et al., 2017)*

definition of CIM since they are based on CityGML standard where the city is treated as a whole system composed by different objects with geometries and metadata (OGC CityGML 3.0, 2012). In these models, CD is applied by using traditional textual programming languages for creating algorithms that, starting from point clouds segmentations, allow to obtain building geometries. The development paradigms for CIM presented so far are very expensive in terms of technologies and expertise needed. Therefore, they are not sustainable except for large cities, leaving small and medium centres excluded from the potential utility of CIM for emergency management (fig. 46).

Fig. 46 | *CityJSON Building Generation from Airborne LiDAR 3D Point Clouds. (Source: Nys et al., 2020)*

In this context there is a third approach used for generating CIM model often called ‘parametric urbanism’ (De Jesus et al., 2018). This approach is characterized by Computational Design workflows that often interoperate with open-data and remote sensing products. The main work environments are VPLs connected with CAD software. In particular, the VPL Grasshopper, thanks to several plugins dedicated to 3D city modeling, has supported the development of several research activities related to the CIM paradigm (De Jesus et al., 2018; Calvano et al., 2019; Fink & Koenig, 2019; La Russa & Genovese, 2021). The parametric approach relates to the previous ones regarding responsiveness between files of different nature (ex. IFC and SHP), interaction with digital survey products and standards for 3D city models (CityGML) (fig. 47).

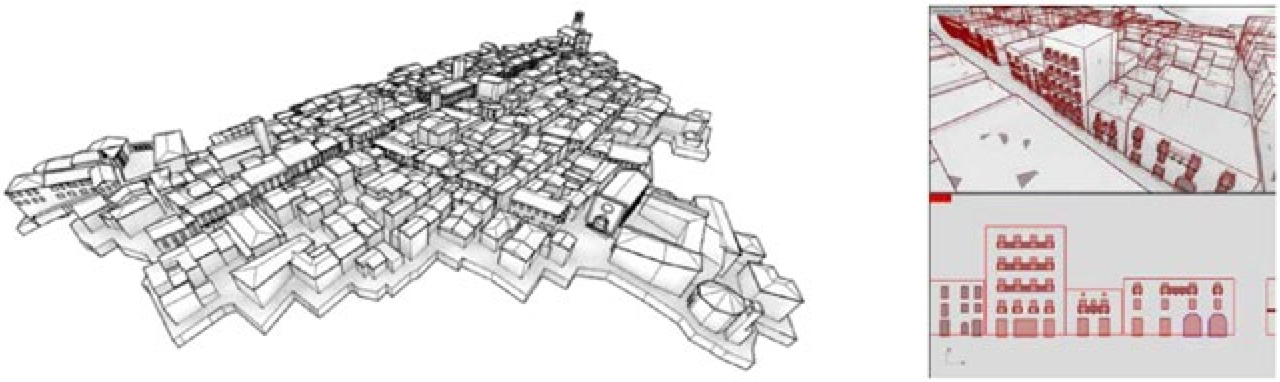


Fig. 47 | *3D reconstrution of the city of Amatrice using Grasshopper and opendata. (Source: Calvano et al., 2019)*

As regards the Italian scenario, Italy's architectural heritage has been the focus of study, documentation and research campaigns for the design of plans of measures aimed at risk assessment and mitigation. Several studies have been conducted aimed at the creation of integrated systems for documenting historic centers in order to implement conservation and transformation policies (Parrinello et al., 2019), in which the issue of interoperability between GIS and BIM becomes fundamental (Cecchini, 2019) or addressed to the creation of a methodology for the management of prevention and reconstruction related to natural disasters (Calvano et al., 2019). These strategies can be divided according to the approach to modeling from the architectural to the urban/territorial scale and vice versa. Thus, there is a top-down approach (treatment of geodata for the development of primitive geometries developed up to the architectural scale) and a bottom-up approach (on-site instrumental surveys with subsequent reverse-modeling of the surveyed objects with the progressive abstraction of the geometries). This also determines the ease of the creation of information databases to be linked to CIM. In fact, in top-down processes, it is assumed that there is an upstream source of geodata through which to initiate modeling by semantically differentiating the geometries produced while in the bottom-up approach the information database is obtained downstream by first having to segment the geometries obtained from the initial instrumental survey.

The choice of these approaches is related to the objectives of the applications. For example, it may be necessary for the short term to possess a point cloud functional for visual inspections that determine the start of a bottom-up workflow. Some case studies carried out by Italian research groups are presented below. Both approaches can be found in the works identified although there is always a higher tendency toward one of the two, even if only at the methodological level.

In this context, the project promoted by the joint LS3D Landscape, Survey and Design (University of Florence) and Dada Lab (University of Pavia) laboratories, having as object of study the city of Pavia, dealt with the creation of digital databases for the preservation of urban heritage (De Marco et al., 2018). Further research conducted by the Pavia group responds to the need to define operational strategies for the experimentation of documentation systems useful for the development of tools for the management and enhancement of historical heritage. In particular, the research is part of an Italy-Israel international cooperation project for city knowledge (Parrinello et al., 2019) (fig. 48).

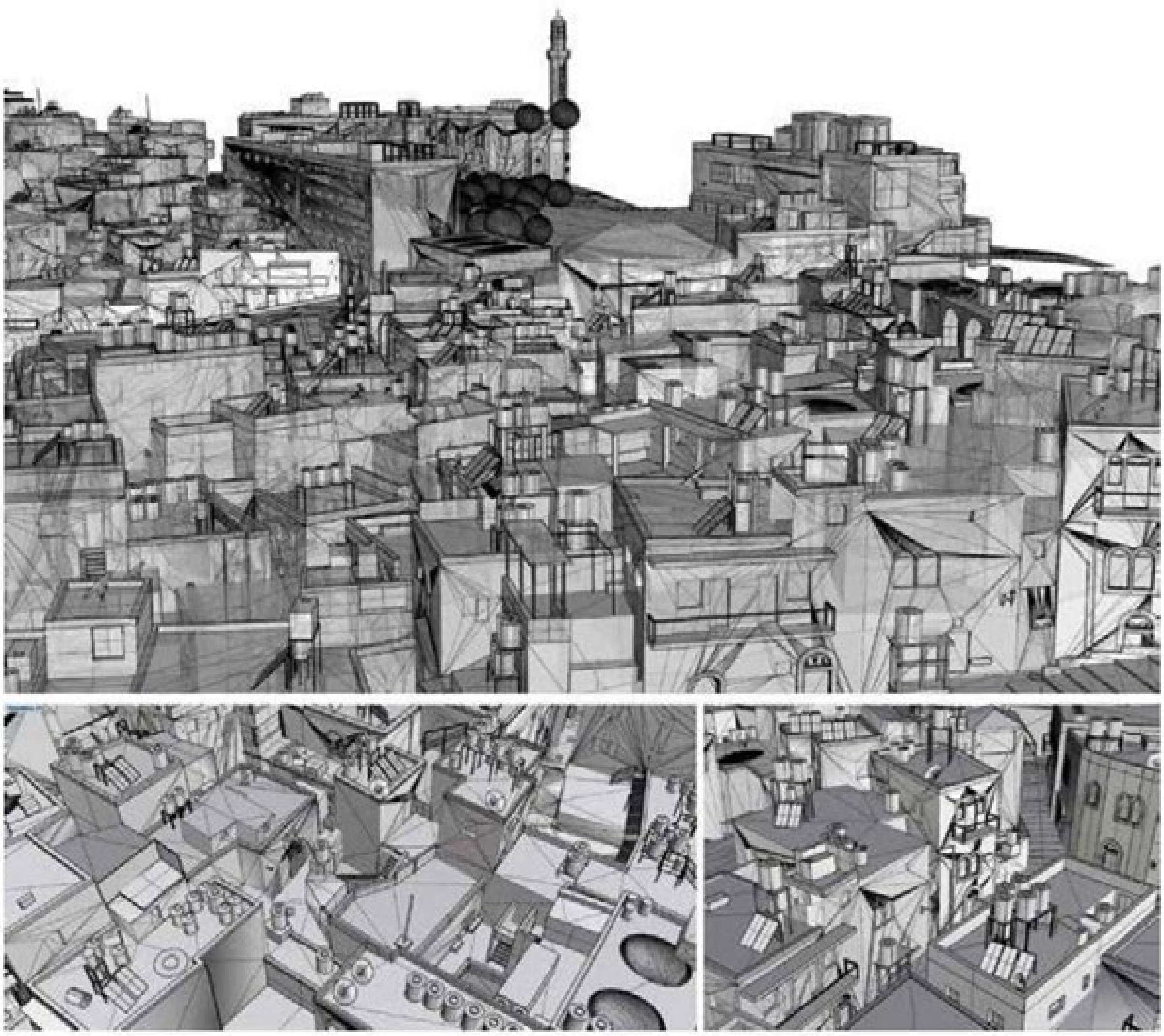


Fig. 48 | *3DBethlehem. Urban growth management and control for heritage development and life improvement in the city of Bethlehem. (Source: Parrinello et al., 2020)*

If the experiments of the Pavia group are more oriented toward the development of 3D GIS systems in the field of architectural heritage management in urban contexts, which is useful for a mapping of the territory in a pre-earthquake scenario, the METRICS project of the Built Heritage Innovation Laboratory of CNR-Itabc shifts the focus to the documentation and description through BIM systems of sites affected by the earthquake. It constitutes the first industrial research project to develop innovative methodologies and technologies for sustainability and safety in historic centers (METRICS, 2021). Also developed in a BIM environment, the methodological proposal of HT_BIM (Historical Town Building Information Modeling) for risk analysis in historic centers (Pelliccio et al., 2017) extends established practices in BIM digitization of historic heritage to the urban scale (fig. 49).

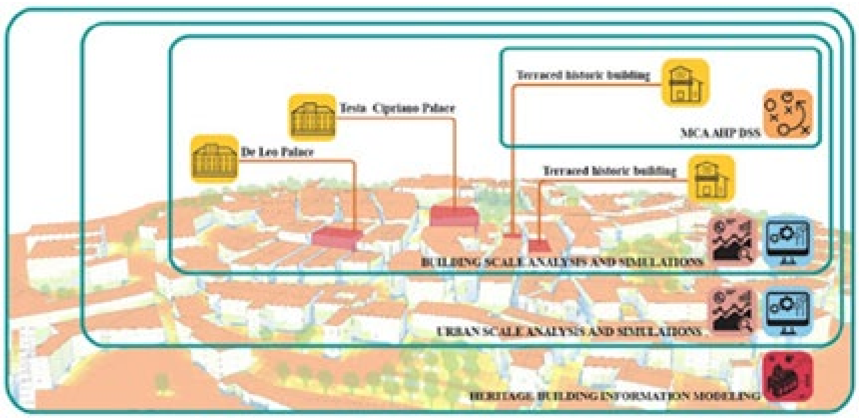


Fig. 49 | *METRICS project of the CNR-Itabc Built Heritage Innovation Laboratory. (Source: METRICS., 2021)*

It is also worth highlighting the procedures adopted by local institutions spread across the territory to counter seismic risk historic cities. Generally, these procedures are based on the compilation of geodatabases useful for establishing risk exposure values for urban centres but also for managing the post-emergency scenario. In these activities, territorial institutions face the difficulty of being able to populate these geodatabases with data that can be updated over the medium and long term. For this reason, opendata have been increasingly considered by public institutions in recent years. Indeed, the use of open source data such as geographic-spatial data from OpenStreetMap (OSM) can facilitate this process. In this direction, the Civil Defense's ERIKUS system (Regione Piemonte, 2018) (fig. 4) also made use of data from OSM, a crowd mapping platform used by so-called 'digital humanitarians,' volunteers who provide digital mapping data. In 2010 following the Haiti earthquake, the Humanitarian OpenStreetMap Team (HOT) was formed to coordinate volunteer mappers during crisis scenarios or in support of specific mapping projects (Minghini et al, 2017). Even during the last dramatic earthquakes in Italy, L'Aquila 2009 and central Italy 2016, and the most recent explosion in the port of Beirut (OpenStreetMap Wiki, 2020), OSM communities helped collect and produce data (fig. 50).

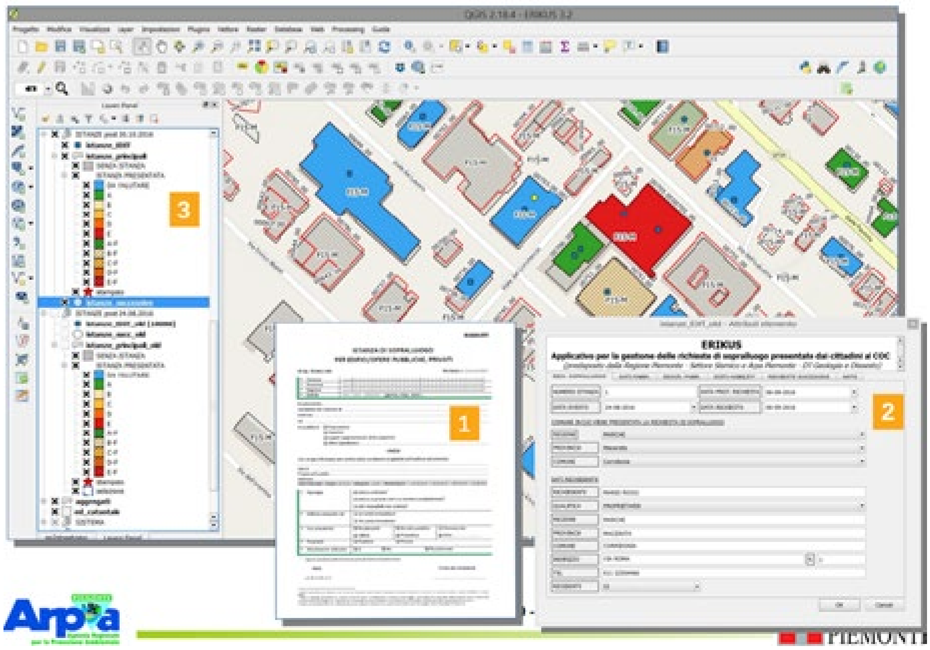
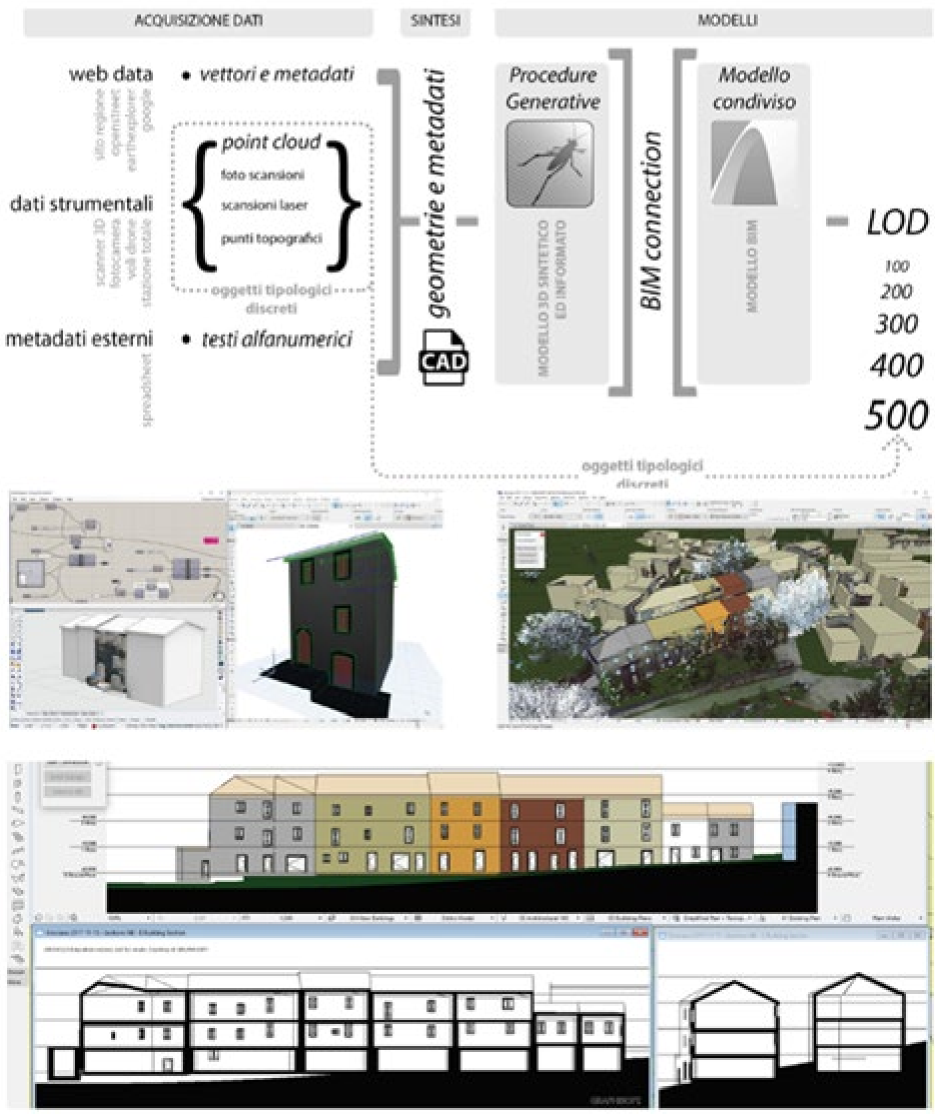


Fig. 50 | *Operational interfaces of the GIS-based ERIKUS system. Source: "ERIKUS the earthquake damage census. An overview of what is possible with GFOSS tools" by Luca Lanteri, Erika Ceriana Mayneri and Stefano Campus during QGIS Day 2019, Florence.*

In the literature there are applications that use data from OSM to create city models that visualize environmental data and allow simulations to be operated (Hadimlioglu and King, 2019). However, as pointed out by Wang and Zipf (2017), when working with crowdsourced data it is necessary to verify its reliability, define guidelines for mappers, and data validation forms.

Among the applications that are most interesting for the purposes of this thesis work is “Urban/territorial restoration and seismic risk prevention: a methodology. Learning and experimenting from the case of 2016 Central Italy earthquake”. This research project is part of the activity within the ‘Grande Ricerca di Ateneo della Sapienza Università di Roma (Empler, 2017)’ and is conducted by the team of the research unit “Urban Seismic Risk: Prevention and Reconstruction” of the Department of History Design Restoration Architecture of La Sapienza University of Rome. The focus goes to a specific section of the project: “ARIM (Assessment Recontrucion Information Modeling) Procedure Applied to Reconstruction” which proposed the ARIM methodology (Calvano et al, 2019) developed in the context of the 2016 Central Italy earthquake. This methodology attempts to manage the complexity of urban aggregates of minor centers from the urban spatial scale (represented by geodata) to the architectural scale (through visual survey and instrumental survey). For the development of the different prototypes, the team used VPLs that allow for the processing and management of heterogeneous data (geometric, historical, etc.) to be used for modeling and analyzing at the urban scale. The workflow to generate the model can be summarized in two phases: the first in which a general three-dimensional model of the urban aggregate is generated (‘synthetic model’) representing the main volumes and roofs, while in the second phase this model is transferred to the BIM environment for further development, geometric and informative, of the individual building units. In the latter stage, the product of instrumental surveys such as georeferenced point clouds obtained through integrated survey methods (terrestrial laser scanner, aerial drone shots, SFM photogrammetry) is also integrated (fig. 51).

Fig. 51 | *Workflow and modelling environments of the ARIM procedure. Source: Calvano et al., 2019.*



2.5 Conclusion and research challenges

The common theme that emerges from the state of the art is a major digital innovation in the approaches used in the different fields (urban survey, parametric modelling, structural analysis, 3D city models) where the skills required by engineers and architects are pushing towards programming and computer science knowledge.

Another common point in the different fields is the search for greater flexibility in the choice of approach towards the object of the work. There are many attempts to disengage from black-box processes dictated by software houses in order to try to create increasingly dynamic and open digital working environments for interdisciplinary teams.

This leads to another important point, which is the customisation of workflows. This is especially the case in the field of 3D City Models where, unlike other workflows in other disciplines, the standard formats provide a certain semantic structure to be respected, but do not impose a certain workflow on the way to achieve it, thus leaving researchers and practitioners to decide on the best way of working.

The research gaps that arise with regard to the different topics discussed are the following:

1. In the field of digital surveying, there are works that can speed up acquisition times, however the technologies used often require a lot of resources in terms of both equipment and expertise and permits from local institutions (as in the case of airborne digital surveying). The issue of sustainability and scalability of urban surveying does not seem to be comprehensively addressed except for a few low-cost applications related to urban-scale 360 photogrammetry.
2. Concerning parametric modelling, the use of explicit parametric modelling for urban modelling purposes was adopted mostly for visualisation purposes and/or interoperability with BIM environments. Furthermore, in the present works, there is no adherence to the semantics required by 3D city model formats (CityGML/CityJSON). It is also worth mentioning that urban modelling practices using VPL, in particular Grasshopper, are becoming more widespread. Nevertheless, the semantic treatment through data trees[2] for urban systems is not discussed in depth or comprehensively. In addition, workflows that (semi-)automate urban modelling do not seem to propose solutions that take into account the use of VPLs despite the fact that VPLs are already being used in HBIM in monumental architectures.
3. With regards to expeditious seismic analyses at the urban level, the processes to apply the mechanistic approach seem to be very time and resource consuming. However, the adoption of parametric modelling in the workflow of these analyses seems to be promising in terms of both optimisation and results. It is therefore interesting to expand these applications to the urban domain by facilitating modelling operations even to very large and complex objects such as entire blocks.

[2] Data Trees are semantic relationships between data inside Grasshopper. These objects define its data structure.

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03.

METHODOLOGY

The present chapter describes an innovative approach that allows the execution of expeditious digital urban surveys to generate parametric City Information Models by taking advantage of a Visual Programming Language environment for developing digital models useful for Finite Element Methods analysis.

Firstly, the main steps of the methodology will be introduced with reference to the modeling standards adopted (section 3.1). This section describes the main modeling steps in relation to the semantic handling of geometries. Finally, it proposes a new format called CityGH. The aim of this novel format is to facilitate the dissemination/conversion/creation of 3D city models also through parametric environments, thus making the applications open to a larger and also non-specialist user base. This goal is pursued by mapping the native Grasshopper data structure in accordance with the guidelines of the CityJSON format for 3D city models.

In the following subsection, two main workflows developed with respect to the assumed starting scenarios are described. The first, called *"Survey-to-CIM"* takes into account a scenario similar to that of smaller urban centers, where resources and expertise are often limited but there is the possibility of accessing databases of geodata (complete or partial) describing the existing built heritage and the availability of technicians (volunteers and/or professionals) which can carry out expeditious sight/direct/instrumental surveying campaigns (in situ or remotely) of the urban center under analysis (section 3.1.1).

The second workflow is the direct evolution of the first. Indeed, it attempts to replace the cognitive effort of recognition, classification, and instance segmentation of openings on building envelopes through the application of Machine Learning on the point cloud produced by the digital survey campaign. This workflow referred to as *"Scan-to-CIM"*, is designed to be effective in the case of medium to large city centers that can rely on more resources (section 3.1.2).

Once the workflows have been described, the author defines the method (CIM-to-FEM) by which, in both cases, the CIM models (generated by means of NURBS geometries) are discretized in order to obtain meshes that can be used within FEM analysis software (section 3.1.3).

In conclusion, the sites of the applications are briefly described in order to provide their urban and territorial context as well as the reasons for their choice (section 3.2).

3.1 3DCityGH: a parametric CIM-based methodology for 3D City Models

This section states the reasons and choices that led to the adoption of the parametric paradigm for the construction of a CIM for the purpose of seismic assessment at the urban scale via FEM analysis. The objective of this work is to develop a sustainable and expeditious methodology that allows professionals in any territory to have a simple but effective tool that leads to the development of functional CIMs for FEM analysis. As described in Section 2.4.3, top-down and bottom-up CIM models require many resources for their development, in terms of technology and expertise. In the methodology described below, it was decided to adopt the parametric paradigm because it allows to develop through VPL a code that is easier to manage for non-experts (unlike top-down models) and that limits the effort of users to the acquisition of data in situ (unlike the tasks required in bottom-up models). The potential of the parametric paradigm lies in the automation and scalability of the process. It is possible to include algorithms that automatically optimize the transition to the polygonal model for FEM analysis. In addition, the versatility of the VPL code allows for the development and integration of solutions like bottom-up and top-down methods, thus ensuring interoperability (De Jesus et al., 2018).

The methodology proposed in this research takes its background from the ARIM methodology (see section 2.4.3) and the FIR 2014 project entitled *"The seismic vulnerability of historic aggregate buildings. New methodologies and structural modeling approaches"* (section 2.3.2). Compared to this methodology, this thesis advances by proposing a speditive and parametric approach that, through the City Information Modeling approach, allows the development of semantic 3D city models. In addition, it is possible to extract the geometric models required for FEM analysis from the parametric CIM models developed (fig. 1).

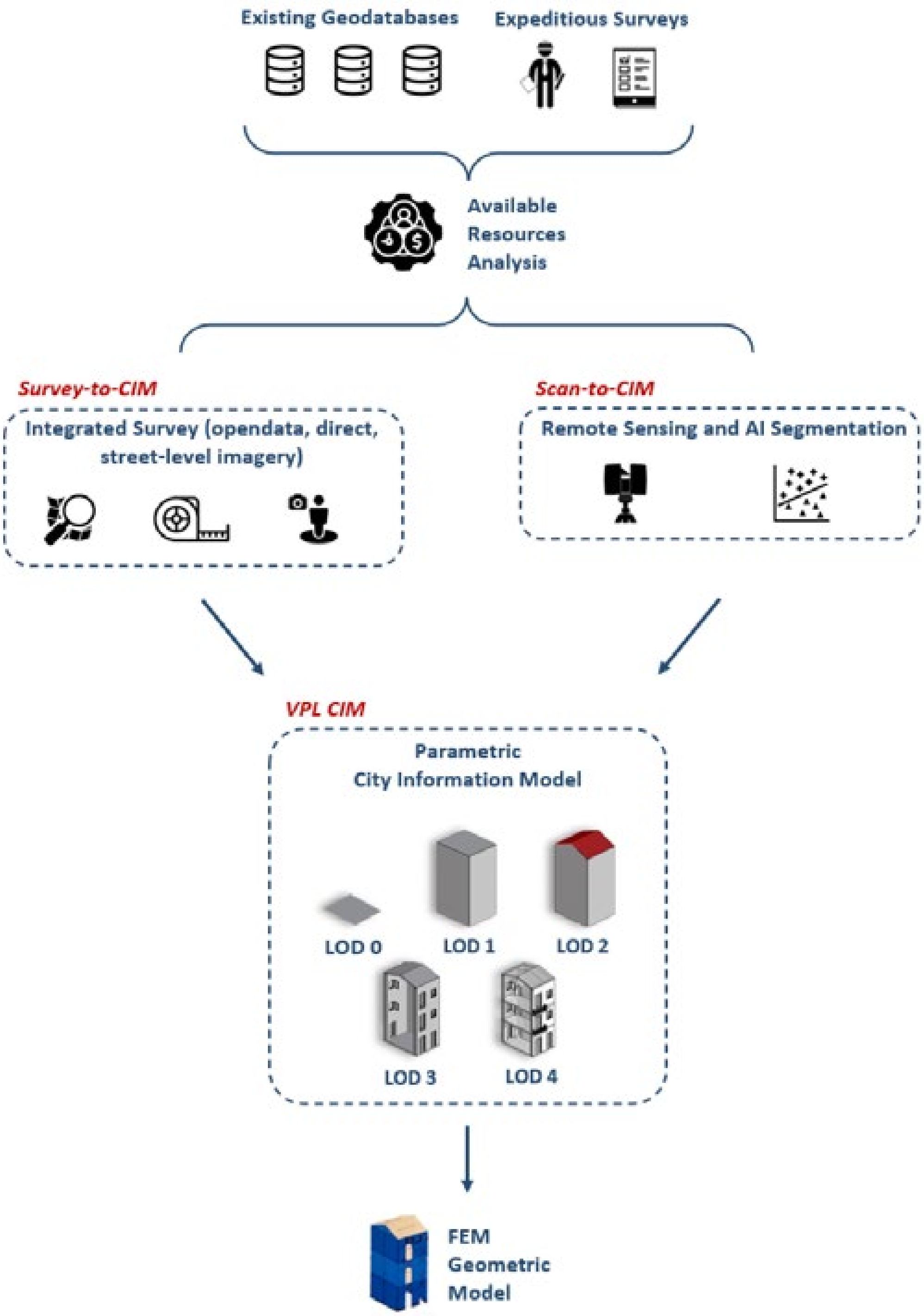

Fig. 1 | *Conceptual outline of the proposed methodology.*

The methodology is composed of several progressive phases that can be pursued through two methods *(Survey-to-CIM and Scan-to-CIM)*. The choice of which method to adopt depends on the availability of project resources and the type of urban center to be modeled. Both methods lead to the definition of a City Information Modeling system capable of managing the territorial and urban scale, the data related to each building unit both as attributes and metadata associated with the single unit and as sub-components. The system, by means of VPL modeling possibilities, can lead up to the automated generation of geometrical structural output for each building unit. Each phase can be conducted independently of the other and also in parallel, depending on the needs of the project.

Phase 1 | *Data input and CIM model at territorial/urban scale*

The first preliminary step in the construction of the parametric CIM consists in the retrieval of geodata according to the spatial area of interest. Such data may be Open Data as in the case of OpenStreetMap or come from databases of the national institutions present in the territory. In many cases these data are not exhaustive of the geometric-technological characteristics of the urban areas under analysis, therefore it is necessary to integrate them through the implementation of the tables of contents associated with each geometric entity present in the geodata acquired. These include the number of elevations, average inter-story height, building type, roof geometry, types of materials, etc. For this purpose, any previous studies that have mapped the territory can speed up the operation. In the case of the scenario in southern Italy, the many campaigns to compile GNDT (pre-emergency survey campaign) or AeDES (post-emergency survey campaign) constitute geodatabases often in the possession of local civil protection institutions.

The input data deficiency can be filled in two main ways. The surveyor inspects the uncompleted object directly or indirectly. Directly implies a site survey in order to note the main dimensions and features by adopting analog surveying techniques with also the possibility of using rectified metric scaled photos to obtain summary measurements of heights. Indirectly, on the other hand, it takes into account the vast presence of street-level imagery web platforms that allow for a digital visual inspection of various locations (even in this case, the possibility of acquiring summed heights by straightening scaled screenshots).

Once data has been collected, it is necessary to map it in accordance with a specific data table designed for the development of the CIM from territorial to district scale. The previously mentioned data table is associated with an area-type geometry that represents the footprint on the ground of the building being modeled. Therefore, this phase takes place within GIS environments that are widely used and known in many municipalities around the world. These operations do not require any specific expertise or additional costs as they are database management operations that each institution is called upon to perform autonomously.

CIM modeling is done in a semi-automatic manner by exploiting the potential of VPLs that allows, within specific digital modeling environments, parametric, responsive, and informative geometry management. Unlike BIM models or structural geometric models defined within dedicated software, the use of algorithms for model creation (procedural modeling) eliminates all manual steps required even for the first modeling stages. Therefore, the logic is to create a one-time algorithm that can be used many times for the generation of CIM models at the urban scale. In this way, the only effort required by the proposed methodology is the retrieval and normalization of input data. If the input data are stored in a database with a well-defined and documented data structure (such as OpenStreetMap) these steps can be further speeded up by reducing the actions required by the user who changes his role from being a manual modeler to being a supervisor of a responsive data flow.

For the creation of the parametric CIM, the levels of detail (LODs) provided by the international standard CityGML (see section 2.4.1) were taken as a reference. In addition, the improved LOD specifications proposed in Biljecki et al. (2016) (described in section 2.4.1) were also taken into account as they were officially considered according to the CityJSON 1.1.2 guidelines.

However, despite the LOD specifications of Biljecki et al. (2016), some of the modeling LODs developed in this thesis cannot be found in a standard reference LOD. In particular, the difficulty relies on LOD2 because, in the applications presented in Chapter 4, there are scenarios for LOD2 buildings without/with roof geometry and internal surfaces (floors) even if these building components fall under LOD4. Therefore, in order to facilitate international discussion regarding these scenarios, it was decided to call these levels of detail LOD2.5 and LOD2.6 respectively.

This results in the following workflow:

- **LOD 0** (spatial/landscape scale): this is a 2.5 D digital terrain model (DTM), on which an aerial photo is inserted and which represents the topography of the area under study; the buildings are represented as a 2D ground imprint projected onto a 3D surface;
- **LOD 1** (city or urban settlement scale): consists of the representation of buildings as prisms; an indication of height (as eaves height or number of floors) is required, thus delineating the volumetric relations of the urban scene;
- **LOD 2/2.5/2.6** (neighborhood scale). LOD2: compared to LOD 1, the geometry and typology of the roofs are defined as well as the hierarchization of the vertical and horizontal surfaces (identification of the main façade and the different horizontal closures). LOD2.5: the building is semantically decomposed as in LOD2 but there is not roof geometry and floors are present[1]. LOD2.6: it is the same as LOD2.5 but, in this

[1] LOD2.5 can be thought as a LOD3.1 unless for openings. See section 2.4.1.

case, the roof geometry is defined. At this scale, it appears useful to be in possession of floor geometries as it may already be useful for the generation of BIM models to be implemented or to visualize seismic vulnerabilities such as those of the misalignment of adjacent floors.

Phase 2 | *Knowledge of urban fabric and construction techniques*

This is a specific study phase on the area to be described by the CIM model. Chronologically it is placed at the second step as it determines the initial conditions to proceed to LOD 3 and 4 (interior and exterior architectural scale). However, this phase, depending on the level of detail required (but also depending on the time and resources required) may be at the beginning of the entire work if a level of detail higher than LOD 2 is planned from the beginning.

In this phase, it is determined which digital or analogical acquisition techniques (it depends on the availability of both expertise and technologies) allow sufficient and expeditious coverage to represent the actual state of the urban object under analysis. This activity is preparatory to the LOD 3 modeling phase where all elements of the envelope such as openings are identified.

This analysis is associated with the study of the typical building types of historic town centers, in particular the evolution from the simplest single-storey types to the most complex ones composed of several residential units on several levels. This study lays the foundations for the informative enrichment of the building components that constitute the city blocks under analysis. In addition, this study is relevant for the prediction of missing data that can be deduced from the literature regarding the construction ages of the blocks to be modeled. For example, mostly through visual analysis, it is possible to identify the construction techniques of the external façade but nothing is known about the internal partitions or the staircase system (techniques, thicknesses, etc.). Furthermore, such a study also includes the collection of historical documents such as cadastral maps, archive plans and cartographies to help define internal elements that are very difficult to detect for privacy reasons, especially at urban scale. This knowledge phase is relevant to achieve a minimum level of LOD 4 development that can be really meaningful in regard to expeditious vulnerability analysis at the urban scale.

The study of typical building types can definitely help in the calibration of the modeling VPL code even at LOD 1 and 2 since some data can be assumed with a reasonable possibility of success on the basis of previous studies or due to similarities with other buildings of the same era in the same urban fabric. A practical example is the slope of pitched roofs (a feature related to LOD 2), which is often difficult to detect. At first, this can be assumed by exploiting sources in the literature, and after the digital acquisition phase that allows accurate verification, it is possible to confirm the assumptions or correct them with the appropriate values.

Phase 3 | *Architectural Scale Model*

The result of the previous phase is expressed in the definition of LODs 3 and 4, which respectively concern:

- **LOD 3/3.1** (architectural scale - exteriors). LOD3: the walls, openings and their fixtures are defined and the detail is increased where possible in the external building components (e.g. roofs); at this level of detail, sub-component hierarchies are started to be used, allowing initial and semantically coherent information enrichment; LOD3.1: it is the same as LOD3 with the exception of the absence of roof geometry.
- **LOD 4** (architectural scale - interior): interior elements (floors, stairs, interior partitions and doors) are added to the model; at this level the recognition of the building unit's structural equipment is sufficiently detailed to complete the information enrichment of the individual building units.

At this last level of detail, the CIM model described so far allows for the management of individual units as independent systems where it is possible to consult and intervene in the individual building components that constitute single building units.

It is worth pointing out that the CIM model, as is already the case with BIM models, is not likely to have the same level of detail for all units. In fact, just as in BIM the level of development of the components can be diversified with respect to objectives and available knowledge (ReverseLoD) (Banfi, 2016) also in CIM the level of detail can be variable in the different building units represented. This not only allows for greater operational flexibility of the model (modeling tasks can be performed immediately depending on the data available) but is also compatible with the responsive nature of parametric VPL models, which recompute the model every time the input data is updated without further effort on the part of the user. Therefore, it is possible to have CIM models with a land dimension but also specific city blocks at an architectural scale.

Phase 4 | *Data Structure and Semantics*

The proposed methodology was developed using the VPL Grasshopper as the main explicit parametric modeling environment. The choice of this environment is not only due to its modeling potential (already extensively discussed in Sections 2.2.2 and 2.2.3), but because of the robustness of the semantic data structure which allows for management during the modeling phases. In the workflows presented below, the geometric and informative results were achieved thanks to the management of the data trees present in Grasshopper, thus making it possible to uniformly define both the origin and the level of semantic depth of each geometry.

As an example, in LOD1 the buildings are represented as prisms so each of them is a tree with only one branch (they contain only themselves). LOD2, which requires the semantic division between the parts of the building, consists of deconstructing the prisms generated in LOD1. The objects obtained from this deconstruction will have as their first index, the index of the starting parent prism, and the second index proper to the second depth level reached (fig. 2).

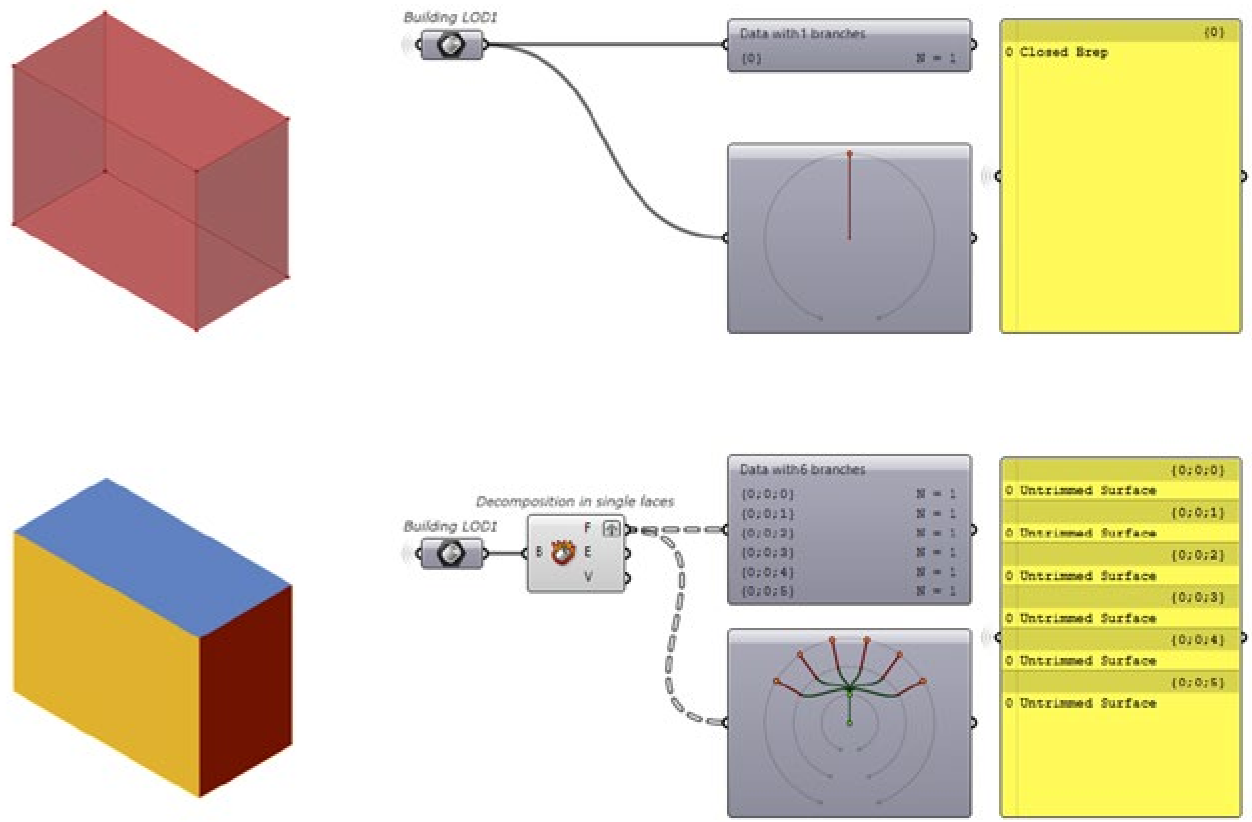

Fig. 2 | *Example of the semantic decomposition of a prism (building LOD1) to obtain the data structure of LOD2 within Grasshopper.*

This semantic mechanism was maintained in all modeling phases. However, despite the fact that this approach makes it possible to trace all the necessary semantic levels of detail, this system does not take into account the standard CityGML data structure and becomes limited to the experience of this research.

An innovative outcome of this thesis is the development of a novel data format within Grasshopper, called *CityGH*, that would semantically incorporate the same data structure as in CityJSON in order to standardize the modeling semantics. Currently, in the landscape of parametric 3D city models, there seems to be no codified method of semantic data structuring. This reduces the potential of developed 3D city models as it limits interoperability and application to different domains. In this thesis, *CityGH* will allow attributes to be stored for each individual building component, thus facilitating FEM analysis operations that can be increasingly automated.

The normalization of this new semantic structure is intended to be at the end of modeling operations so as to leave each user free to define a free modeling workflow. The aim is to create an interchangeable format within Grasshopper given the extensive use of VPL for urban modeling purposes. The description of the development of this parametric format is detailed in section 4.4.

3.1.1 Survey-to-CIM

Bearing in mind the main methodology defined in the previous section, one of the first stages of the research investigated the sustainability of urban parametric modeling. The objective was to define a methodological approach that would focus on data available and implementable over time while limiting the resources required in order to achieve a level of detail at least equal to LOD2. A study of the literature revealed the potential of Open Data, which, together with parametric modeling techniques, makes it possible to create models capable of evolving over time. This has led to the definition of the *Survey-to-CIM* workflow where the definition and development of the CIM model over time is an operation that takes advantage of various direct and indirect sources and makes particular use of existing databases and territory mapping operations in various platforms (both institutional and crowd-mapping volunteer).

Indeed, OpenData represents a huge potential for applications in various sectors and, in particular, in territorial government. To date, OpenStreetMap (OSM) is the largest collection of open-licensed geospatial data. These data can be used to create and implement 3D city models that represent digital twins (DT) of real cities. In the conceptualization of DT, its effectiveness is closely linked to the sensor network from where it acquires data (Batty, 2018).

The Digital Twin concept, in the creation of city models for the management of urban and territorial risks, is particularly useful in those fields of application where the quantity and quality of collected data can change significantly. Emblematic cases are the seismic risk scenarios in minor historical centers where the amount of data is limited and usually their quality is not high. The realization of responsive three-dimensional urban models, starting from OSM data collected by VGI, allows therefore to have informed models updated quickly. These models can be used and consulted both in the ordinary periods (for analysis, forecasting, and planning activities) and during the alert and/or emergency period for crisis management (e.g. as a support database for the activities of verification of usability of building units).

However, OSM data have an average accuracy sufficient for the territorial scale but too low for the architectural scale (Wang et al., 2017). In the method proposed in this research, it was integrated the use of data from OSM with direct surveys (visual survey, laser scanning, SFM photogrammetry) in order to identify significant metric deviations (for example, the correct definition of the ground footprint of building units) and then correcting upstream data on OSM.

The choice of the working environment has been mainly driven by the need to preserve the starting information without changing the work environment as well as to combine data coming from GIS systems (at the territorial scale) with tools that could manage the geometries and allow the evolution into real BIM components (architectural scale). Visual Program Languages (VPL) like Grasshopper (GH), thanks to their wide range of plug-ins, allow you to customize and choose all the tools needed to manage and create both GIS (ex. @ it, Elk, Gismo, Urbano, LaunchBox, Heron, DeCodingSpaces to name a few) and BIM (VisualARQ, Rhino-inside-Revit) data. In this research, it has been decided to use GISMO plugin (2022) for the insertion of geodata from OSM.

The information enrichment phase has envisaged the entry of references to materials and construction techniques. For the definition of the model from LOD 0 to 2 indirect sources have been mainly used, while from LOD 3 to 4 mostly direct sources have been considered (georeferenced digital survey).

In particular, for LOD 3 and 4 modeling phases, were defined the following steps:

- Knowledge phase: determination of the urban curtain of interest and analysis of the urban pattern (development and morphology);
- Data collection and classification of architectural components in the urban scene;
- Acquisition of geo-referenced metric data carried out via instrumental survey (laser scanning);
- BIM families design and parametric modeling of architectural façade elements;
- BIM modeling of the facades of the designated urban canyon;
- Informative enrichment of the architectural components of the model.

The transition to the architectural scale was managed in the same working environment (Rhinoceros and Grasshopper) used for the territorial scale. The transduction of the LOD 2 geometries into BIM objects was carried out through the use of the VisualARQ plugin for Rhinoceros. This allowed the BIM-like processing and management of the geometries obtained through Grasshopper. This combination optimizes the workflow and allows to export and consult the model in other BIM environments through the IFC file format (fig. 3).

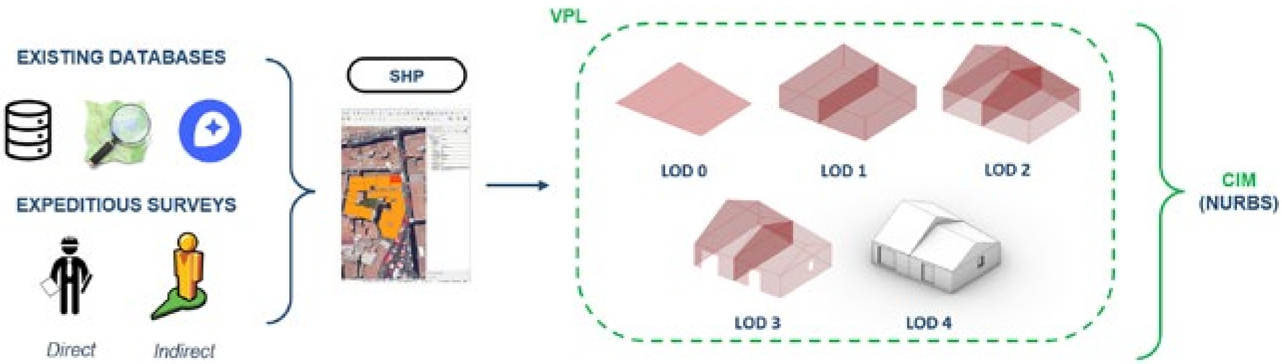

Fig. 3 | *Conceptual outline of the Survey-to-CIM method.*

3.1.2 Scan-to-CIM AI-based workflow

The *Survey-to-CIM* workflow introduced in the previous section is effective for long-term urban survey campaigns, especially in smaller urban centers. However, this approach applied to historic city centers may prove too time-consuming. The time required to obtain the necessary information for LOD 3 (openings and elements on the envelope) through visual analysis is very long though effective. Considering that medium to large cities are assumed as a scenario in this case, it is reasonable to assume a greater use of resources both in terms of sensors (terrestrial laser scanners, drones, etc.) and in terms of the skills of the technicians involved.

For these reasons, a second workflow was defined called *Scan-to-CIM*, designed to handle the greater complexity of historic city centers in major cities within a territory. The innovation of this workflow is that it allows LOD 1, 2.5 and 3.1 to be obtained directly from the point cloud at the same time in very short times. It also allows the development of LOD4 through a semi-automatic procedure. Similarly to the rest of the methodology, this workflow considers cities in southern Italy as a worst-case scenario. However, the workflow has been sufficiently generalized to be flexible and also reusable in cities with different urban morphology and architectural characteristics.

Scan-to-CIM can be considered as a readaptation of the *Scan-to-BIM* methodology to a CIM model. The difference between the two lies in the management of information since even if it is possible to apply the Scan-to-BIM methodology to the urban scale, the final model management and also its structure do not appear to conform to the semantics typical of 3D City models. Therefore, the model produced with a *Scan-to-BIM* process in an urban context is generally a BIM macro-model with semantics typical of the architectural scale where, apart from the objects of specific interest, the rest of the urban context does not benefit from relationships and/or information enrichment (as already discussed in section 2.4.2).

The concept behind *Scan-to-CIM* is to automate the cognitive operations of interpreting and retrieving survey data performed by the surveyor. This task is performed by an Artificial Intelligence system that uses Machine Learning techniques (in particular *Random Forest*) to detect the same architectural and geometric features on the basis of which the surveyor is able to define the input data.

Hence, in this workflow, the first step is the digital survey campaign as the goal is to achieve and manage the CIM model at a LOD of not less than 3 (envelope with openings). The digital survey conducted is predominantly terrestrial since there may be many limitations to the use of drones within urban centers. An exemplary case is the historical center of Catania which, due to the proximity of the airport, has a large area where drone overflight is prohibited. The survey is therefore conducted using active sensor technologies that allow a sufficient degree of geometric detail in the point cloud produced. In order to achieve rapid acquisition times and effective geometric feature recognition with Random Forest, it is preferable for the survey to be conducted with easily transportable laser scanners, with the possibility of pre-alignment on site thus optimizing both acquisition and registration operations at the laboratory. A specific comparison has been carried out with the aim to compare different urban digital acquisitions with the aim to exploit the best use in relation of the approach adopted (see Section 4.2). The final point cloud should be georeferenced in the same coordinate reference system of the digital cartography available.

Once the point cloud cleaning and registration operations have been completed, the Random Forest workflow described in section 2.1.2 is undertaken. Then, facade components useful for the identification of planes and openings are annotated in the point cloud and assigned to a specific class (e.g. walls, windows, etc.). This is the only manual operation in the Machine Learning process since once the training phase is finished, the cloud is classified and divided into as many sub-clouds as there are classes identified in the training phase.

These sub-clouds, together with the footprints on the ground in the cartography, become the input data of the parametric CIM modeling VPL code. The code developed in this research produces a model with a level of detail equal to LOD 3.1 (exterior architectural level without roof geometry). The algorithm also provides for the export of lower-level models meaning that LOD 1 and LOD 2.5 (without roofs but with semantic subdivision and interior floors) are available simultaneously. The only manual operations at this stage are the calibration of the parameters for instance segmentation of the components identified in the Machine Learning phase. The clustering of the cloud is managed within Grasshopper's VPL environment thanks to dedicated plugins.

At this stage, LOD 4 is developed. Currently, this research presents two solutions for this LOD. The first is manual and consists of the two-dimensional restitution within the three-dimensional models of the lines that define the main internal walls. These lines are interpreted by the algorithm that subdivides them by level and extrudes them defining the mean plane of the septa. This solution is particularly effective when documents can be found that describe the internal layout (at least of the ground floor), but it is also useful in the case of complex-shaped buildings for which it is difficult to define a construction rule for the internal layout. The second solution is automated but depends on the presence of a specific building type. In fact, the literature review shows that in some building types, patterns of internal layouts are repeated very regularly. This makes it possible to construct shape grammar rules capable of predicting the internal layout of the building under analysis (fig. 4).

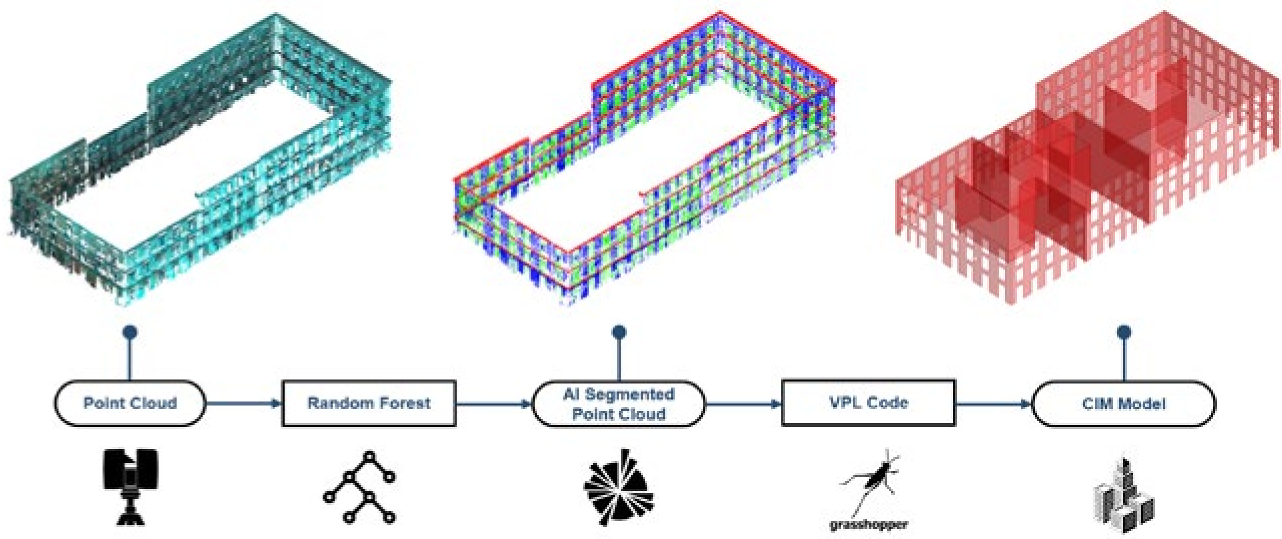

Fig. 4 | *Conceptual outline of the Scan-to-CIM method.*

3.1.3 CIM-to-FEM

The CIM models obtained through *Survey-to-CIM* and *Scan-to-CIM* workflows are developed through the VPL Grasshopper (GH). GH shares the same three-dimensional modeling tools as Rhinoceros, so it is possible to handle NURBS-type mathematical modeling or MESH-type discrete modeling. In order to be able to conduct modeling operations with maximum flexibility, CIM models are developed with NURBS geometries. This choice allows the models obtained to be discretized into mesh objects with different densities according to modeling requirements. This approach is particularly useful when exporting a digital geometric model to be used in structural analysis software, as it makes it possible to determine, according to the specific analysis requirements, what type of model to obtain, whether more approximate or more detailed.

Once the CIM models are obtained, the proposed methodology involves the export of digital geometric models that can be used for structural analyses. Within the VPL environment, there are four possibilities for structural analysis:

1. the first consists of using plug-ins already developed to export the models obtained from GH within structural analysis software;
2. the second concerns if no specific plugins exist for conversion: GH allows textual programming codes to be written in Python, C# and Visual Basic that can be used to create output files with reference to the target FEM software;
3. the third is to run the structural FEM analysis directly within the VPL using specific plugins that allow the definition of the structural model, analysis and display of the results; examples of these plugins for Grasshopper are Karamba3D and Alpaca4D (based on OpenSees);
4. the fourth exploits the possibility of manually writing calculation code within the VPL through the textual programming languages that are available.

In this research, the methodology adopts the first, second, and third ways, as the focus of the research is aimed at generating usable geometric models rather than performing structural analyses which fall outside the field of knowledge presented here. Therefore, the *CIM-to-FEM* transition is achieved either by discretizing NURBS geometric models into quadrangular face mesh models (due to the analysis requirements of different FEM analysis software) or by using NURBS models. In the applications described below (Chapter 4), there are examples of both modes, which vary depending on the type of model accepted by the FEM analysis software.

This flexibility provided by the VPL environment makes it possible to create automated workflows specific to the analysis software to be used. This way, the structural engineering specialist is freed from the task of modeling and can concentrate directly on designing the dynamic analysis to be conducted.

3.2 Experimental context and choice of case studies

With the aim of testing the main methodology and workflows proposed in this research, two main scenarios were identified for the proposed applications.

The first scenario concerns smaller urban centers. These urban settlements are numerous in the area below the volcano and are often the most exposed and vulnerable areas. The research focused on Fleri, a village in the municipality of Zafferana Etnea in the province of Catania, which has been damaged by a seismic event of magnitude 4.9 on the Richter scale that occurred on the night of December 26th in 2018. The earthquake collapsed and damaged several buildings that are still uninhabitable. The event highlighted the fragility of the Etnean territory and the difficulty of managing a crisis in contexts where the urban clusters on the territory are widespread and with uneven density. Fleri becomes significant as a case study in order to test a methodology scalable and replicable in other Etnean urban centers (fig. 5).

Fig. 5 | *From left to right: view of Fleri area in the context of Etna, satellite image with the perimeter of the town highlighted, urban canyon under study highlighted in the cartography. Source: Google Earth 2022 and La Russa, Genovese, 2021.*

The second scenario concerns historic urban centers of larger cities such as Catania. The high complexity of Catania's historic city center allows for different urban survey scenarios that may put the technologies under stress. For this reason, the focus was on a northeastern area in the historic city center built in the late 19th century in a preexisting medieval urban context. This mixture of eras allows for a diversified environment with very different urban canyons. Indeed, it is possible to find building types similar to those of smaller urban centers, but also several regular blocks defined in a chessboard pattern according to late 19th century urban planning practices. This area, therefore, allowed the application of both the proposed workflows *(Survey-to-CIM and Scan-to-CIM)* and also the comparison of some urban digital survey techniques allowing the proposed technologies to be put under stress (fig. 6).

Fig. 6 | *Bird's eye (top) and top (bottom) view of the urban area of the historical center of Catania under study.*

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04.

CASE STUDIES

This chapter describes the applications conducted to test the methodology proposed in Chapter 3. In particular, the applications are grouped with reference to the scenario in which they are carried out: minor urban centers (section 4.1) and major urban centers (section 4.2). The applications in section 4.1 take into account the shortage of resources and therefore present more sustainable solutions that can be implemented by the small communities in these villages. On the other hand, the experiences described in section 4.2 involve the use of more resources, thus presenting more sophisticated and expensive solutions than the ones in 4.1. However, the experiences described show how it is possible to create expeditious workflows appropriate for the urban complexity of the historic centers of large cities.

4.1 Minor urban center scenario: the territorial scale

This section describes the first attempt to develop a parametric City Information Model within this research work. Taking the sequence of LODs defined by CityGML as a reference, the aim of this work was to construct a City Information Model capable of describing the territorial dimension.

The territory around Etna presents a multitude of small villages, with urban blocks developed along the main communication roads with the larger urban centers. Among all the villages, Fleri (a fraction of Zafferana Etnea) took the greatest interest since it was severely hit by an earthquake during Christmas 2018, so at the time of the thesis work, the village was in a post-emergency scenario. Moreover, due to the calamity, a significant increase in data on OpenStreetMap was noticed. These conditions created the ideal research context to develop a parametric CIM model that would not only meet the research objectives (in this case the development of the VPL code) but also be useful for post-earthquake management purposes. For this reason, this work also investigated the interoperability possibilities that the CIM model realized allowed, integrating a *Scan-to-BIM* methodology (see section 2.2.1) that allowed LOD 3 and 4 to be achieved. Geometries and attributes developed still remain useful for structural analysis according to the research goal of this thesis.

4.1.1 An Anti-Fragile City Information Model for Fleri

This case study investigates the application of the concept of Antifragility in City Information Modeling (CIM). Exploring the potential of a responsive City Information Model (CIM) for seismic risk management, the objective is to create a three-dimensional information system that allows the consultation of data useful for the compilation of data forms related to seismic prevention (such as GNDT II level seismic assessment forms) but also those necessary during crisis scenarios (AeDES forms). In accordance with the concept of Antifragility (Taleb, 2012), the model is able to take advantage of possible emergency events by acquiring data directly and almost in real time. This is possible thanks to the activation of Volunteer Geographic Information (VGI) communities that, in addition to the constant mapping actions on the local territory, are also active during calamitous events by mapping the damaged areas and, acting as “human sensors” (Foody et al., 2017), supporting local governments in the management of the emergency. At the same time, they populate the CIM (proposed) model with data. The methodology adopted in this application is the Survey-to-CIM approach described in section 3.1.1. Below is showed a conceptual scheme of the pipeline of work adopted (fig.1).

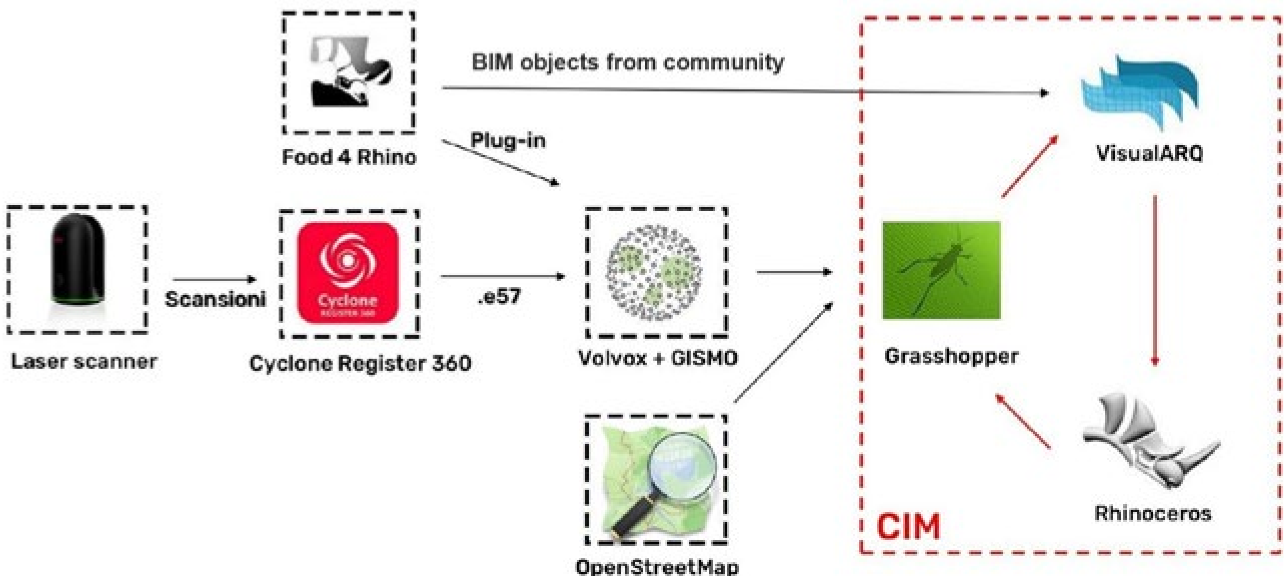


Fig. 1 | *Scheme of the workflow adopted in this case study.*

The methodology has been applied to Fleri, a village in the municipality of Zafferana Etnea in the territory of Catania, which has been damaged by a seismic event of magnitude 4.9 on the Richter scale that occurred on the night of December 26th in 2018. The earthquake collapsed and damaged several buildings that are still uninhabitable.

The event highlighted the fragility of the Etnean territory and the difficulty of managing a crisis in contexts where the urban clusters on the territory are widespread and with uneven density. The choice of Fleri as a case study becomes significant to test a methodology scalable and replicable in other Etnean urban centers.

The LOD 0 is the representation of the topography of the considered territory. Through the TerrainGenerator component of GISMO (GH plugin) the DTM of the area of interest can be downloaded. To define the area, it is sufficient to indicate the name of the location and, through the online tool Nominatim of OSM, the corresponding coordinates will be extracted in WGS84. If the location cannot be clearly identified by toponymy, the area can be indicated directly on OSM. The extension of the area is determined by indicating a radius as a horizontal distance from the origin. In the presented case, the radius is 750 m; the total area considered is 225 ha. The data source used for DTM extraction is SRTMGL1 (NASA). Other sources are AW3D30 or GMRT. It is possible to insert contour lines defined in an interval.

The result of this operation is a NURBS surface on which it is already possible to perform morphological and hydrological analysis. This surface has been converted into a mesh in order to project the corresponding satellite image through the plugin Human. To obtain the correct dimensions of the image, the georeferenced coordinates of the vertices of the area of interest have been extracted using GISMO.

LOD 0 has been completed by using the OSMshapes component in relation to the area of interest. In this way, all the data present on OSM about that specific area are already available inside the model. In this phase, it is possible to access the data contained for each polygon and put them in relation to the corresponding geometries. Then the polygons corresponding to the footprints of the buildings have been extracted to project them on the DTM 3D surface (figg. 2, 3)

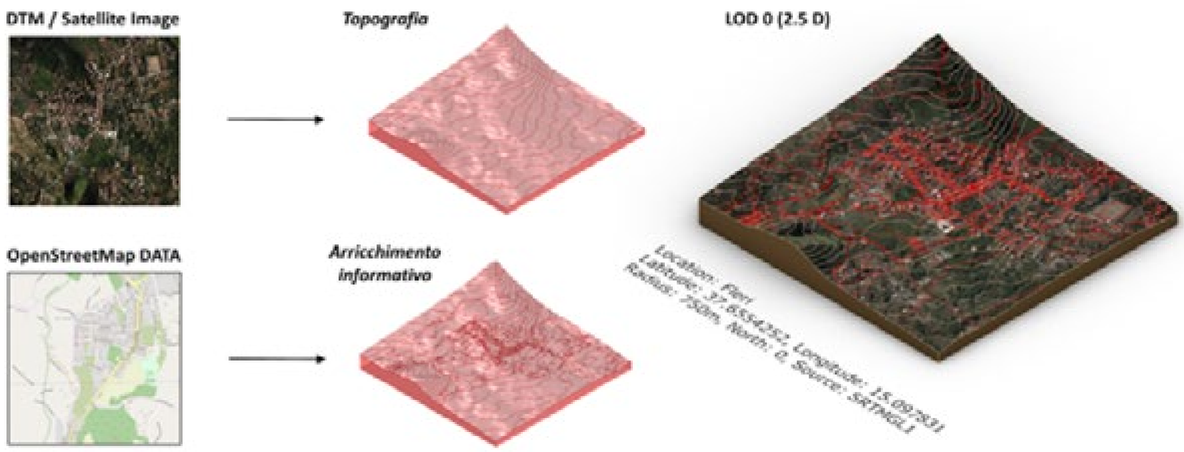


Fig. 2 | *OpenData treatment for model definition at LOD*

Fig. 3 | *1) OpenStreetMap data consultation inside Grasshopper; 2) GISMO plugin tools; 3) OpenStreetMap on Fleri area.*

In LOD 1 the buildings have been modeled in the form of blocks. GISMO allows performing this operation through the OSM3D component that reads the OSM file and linearly extrudes the polygons according to the height value (Elevation) assigned for each of them. The component has been designed to give a result even in those cases where the height of each building from OSM is not known. In particular, it allows to indicate a domain of possible heights that will be assigned randomly for the realization of the volumes; or to indicate the average height for each elevation of each unit (reading the Levels value in the OSM file). In the case of Fleri no building shape had values related to height or number of elevations. In order to have a first synthetic model, a range of probable heights (from 3 to 6 meters) was assigned for all the buildings in the study area except for those of the urban canyon of Via Vittorio Emanuele. For the latter, the number of elevations was indicated within OSM; once the model was updated, it was possible to attribute an average floor-to-floor height (equal to 3 meters) and therefore to have a representation closer to the urban aggregate.

In addition, different color has been assigned to highlight the volumes to which a random height has been attributed from those in which the number of elevations has been given (Fig. 4).

Afterward, the surfaces of the volumes were differentiated, thus allowing the modeling of the roofs and the identification of the facades (LOD 2).

Fig. 4 | *Bird's eye view of the model at LOD1. In white the buildings with a known number of floors, in gray the buildings with assumed height.*

The classification of the surfaces is possible through the deconstruction of the volumes (Deconstruct BRep) into faces. Through the analysis of the coordinates of the barycenters of the faces, it is possible to determine which are the highest and therefore the planes of the roofs. Despite GISMO allows the modeling of roofs, it was chosen to use VisualARQ (VA) since it allows the information enrichment of geometries; this way the roof type information extracted from the OSM file has been directly connected to VA via GH. Similarly, the identification of facades is done by evaluating the distance of the barycenters of the vertical surfaces from the axis of the pertinent road (fig. 5).

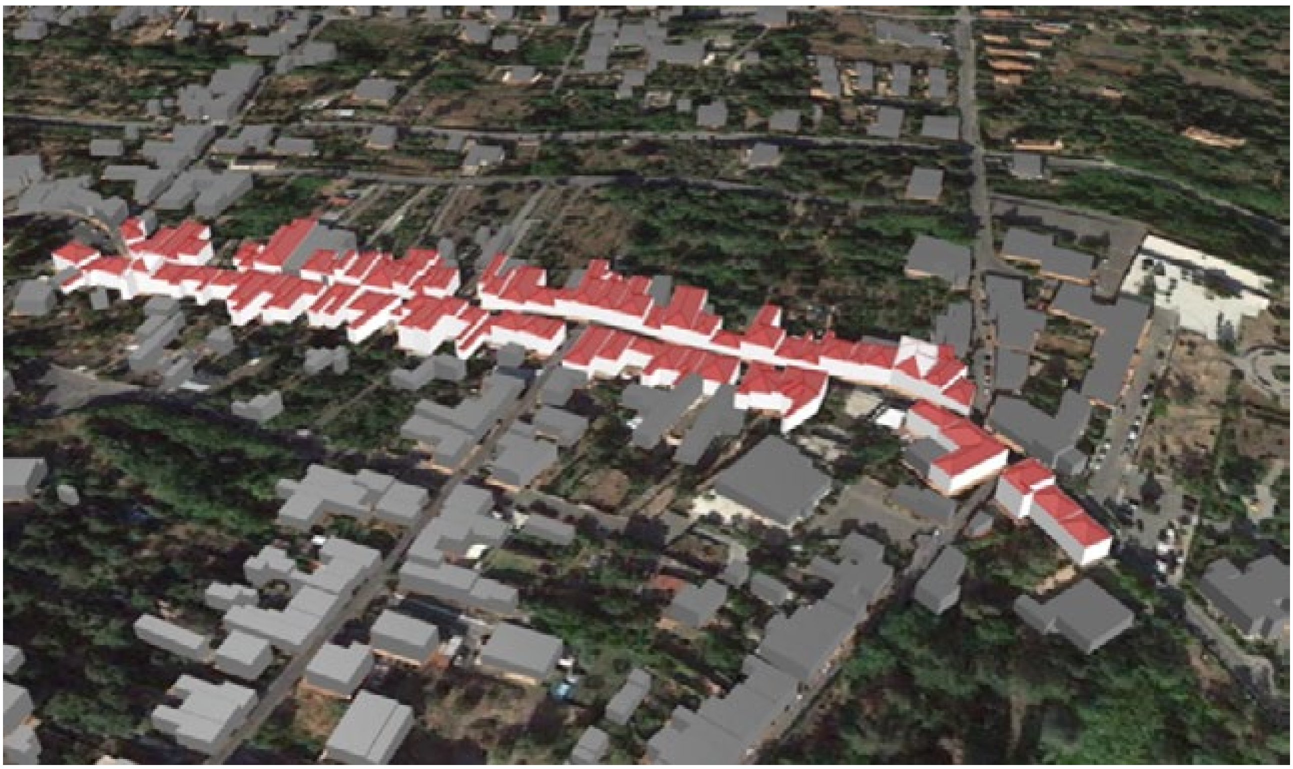
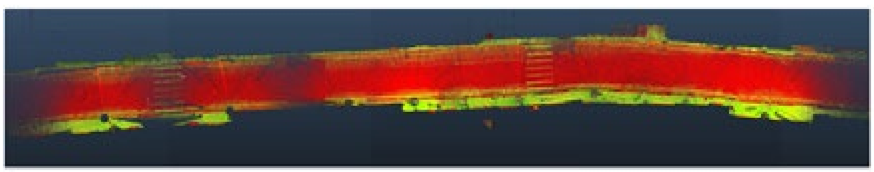


Fig. 5 | *Bird's eye view of the model at LOD2.*

LOD 3 and 4 are obtained through instrumental survey on site. 11 scans were conducted with a terrestrial laser scanner (Leica BLK360) on a portion of the urban canyon object of analysis for a total of 423,213,499 points acquired. At the same time, Ground Control Points have been acquired by a GPS receiver to allow the georeferencing of the cloud according to the reference system WGS 84 - EPSG: 4326 (fig. 6). GISMO uses the same reference system but re-projects the coordinates of the initial location from the origin of the Rhinoceros model space (thus avoiding display problems due to the distance from the origin). Once georeferencing has been performed on Cyclone, the cloud was exported as .E57 and imported into GH using the Volvox plugin. Finally, the cloud has been aligned to the model through a rigid translation using a displacement vector defined by two points (Vector2Pt): the starting point is a target used for georeferencing in UTM - WGS 84 coordinates while the arrival point is the same point projected in the GISMO local reference system starting from the coordinates in decimal degrees (LocationToXY) (fig. 7).

1



2

3

LIBRETTO GPS

File: fle5.GPO

N.Gruppo: 1

Nome Gruppo: fle5

Descrizione:

Commento:

Data: 25/8/2020

Codice punto	Nome punto	Latitudine	Longitudine	Elev.
-2 metri	1	37°39'34.68417	15°05'51.64475"E	568.714
-2 metri	2	37°39'27.09846	15°05'54.31941"E	576.204
-2 metri	3	37°39'27.09837	15°05'54.31938"E	576.167
-2 metri	4	37°39'25.69742	15°05'54.17209"E	579.343
-2 metri	5	37°39'25.61293	15°05'54.36717"E	579.584
-2 metri	6	37°39'24.45414	15°05'54.09187"E	581.677
-2 metri	7	37°39'24.42526	15°05'54.36130"E	581.606
-2 metri	8	37°39'24.20444	15°05'54.04420"E	582.185
-2 metri	9	37°39'27.22048	15°05'54.16992"E	576.301
-2 metri	10	37°39'27.47533	15°05'54.36923"E	576.717
-2 metri	11	37°39'32.69261	15°05'53.43058"E	564.558

4

5

Fig. 6 | *Laser scanner survey: 1) view of the point cloud aligned in RGB; 2) orthophoto of the point cloud in false colors; 3) GPS points set; 4) table of geo-referenced points in UTM - WGS84; 5) view of the KML file inside Google Earth.*

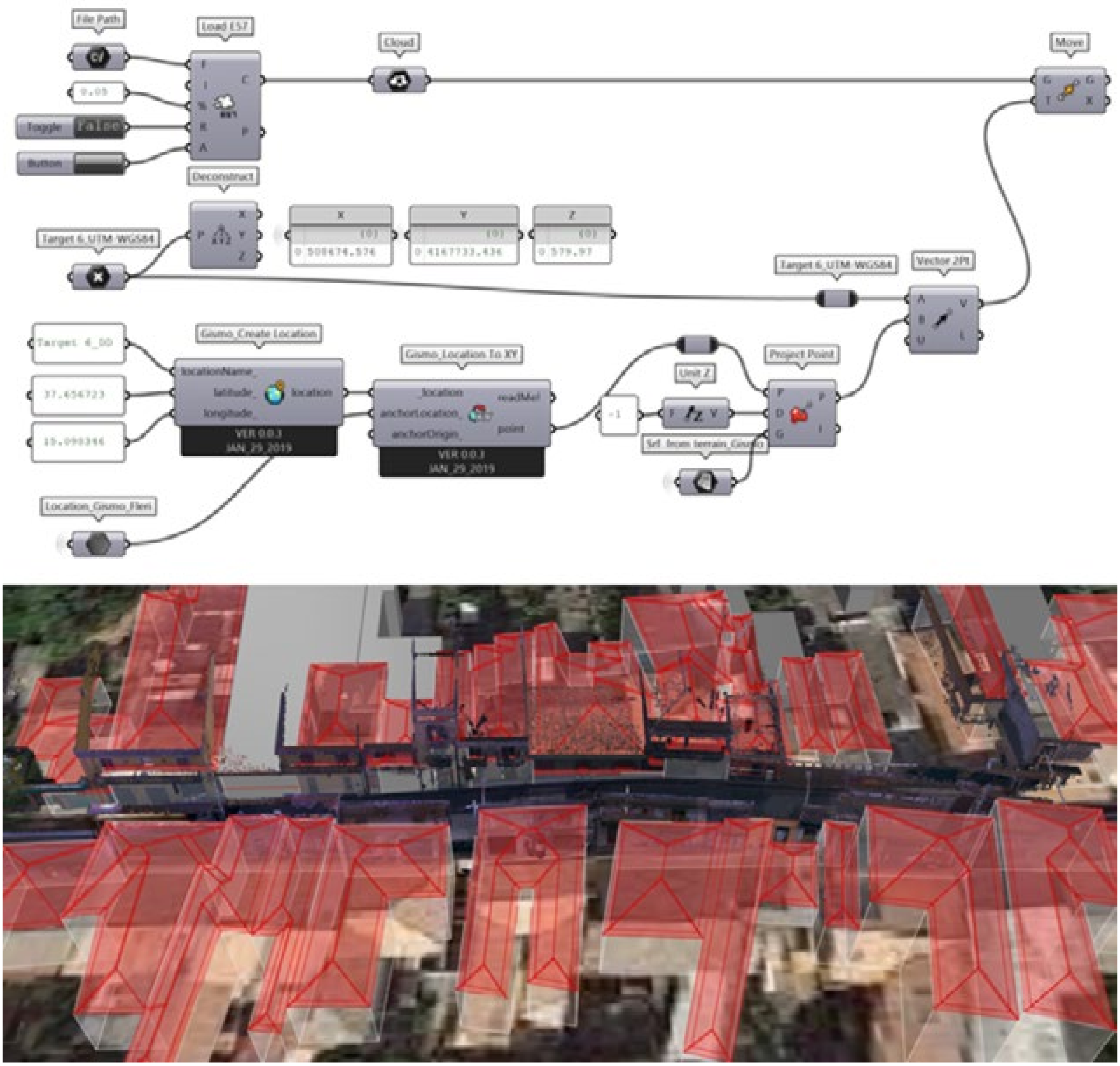
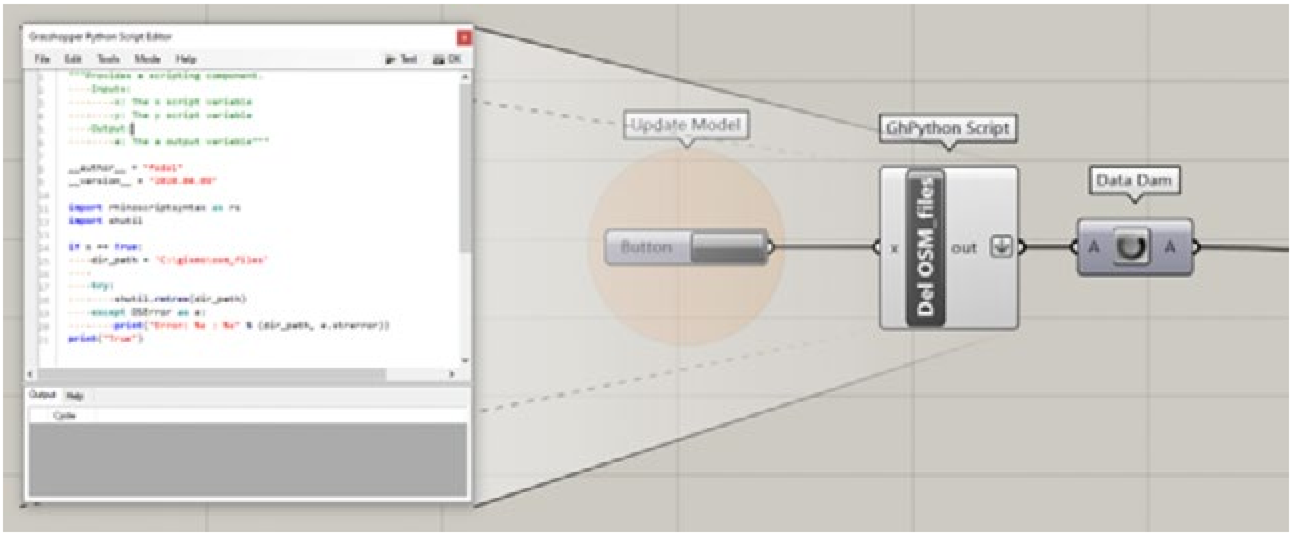


Fig. 7 | *Georeferencing of the point cloud within Grasshopper.*

In this way it is possible to evaluate the metric deviations between the model developed so far and the point cloud. A code in Python language has been written (thanks to GhPython) that automates the operation of updating OpenStreetMap data by reducing the whole operation to the execution of a Button in GH. This operation usually involves the manual deletion of the file from the directory defined by GISMO and the recomputing of the code. In this way it is possible to work on OSM (iD editor or JOSM) and see, at the same time, the CIM model quickly updated (fig. 8).



With regard to the application concerning LOD 3 and 4, it was decided to focus the experimentation on the urban curtain relating to Via Vittorio Emanuele III (main north-south axis) between numbers 142 - 178 after a phase of historical investigation on the urban evolution of Fleri (fig. 9).

Fig. 8 | *Code in GhPython for the automation of the model update from OpenStreetMap.*

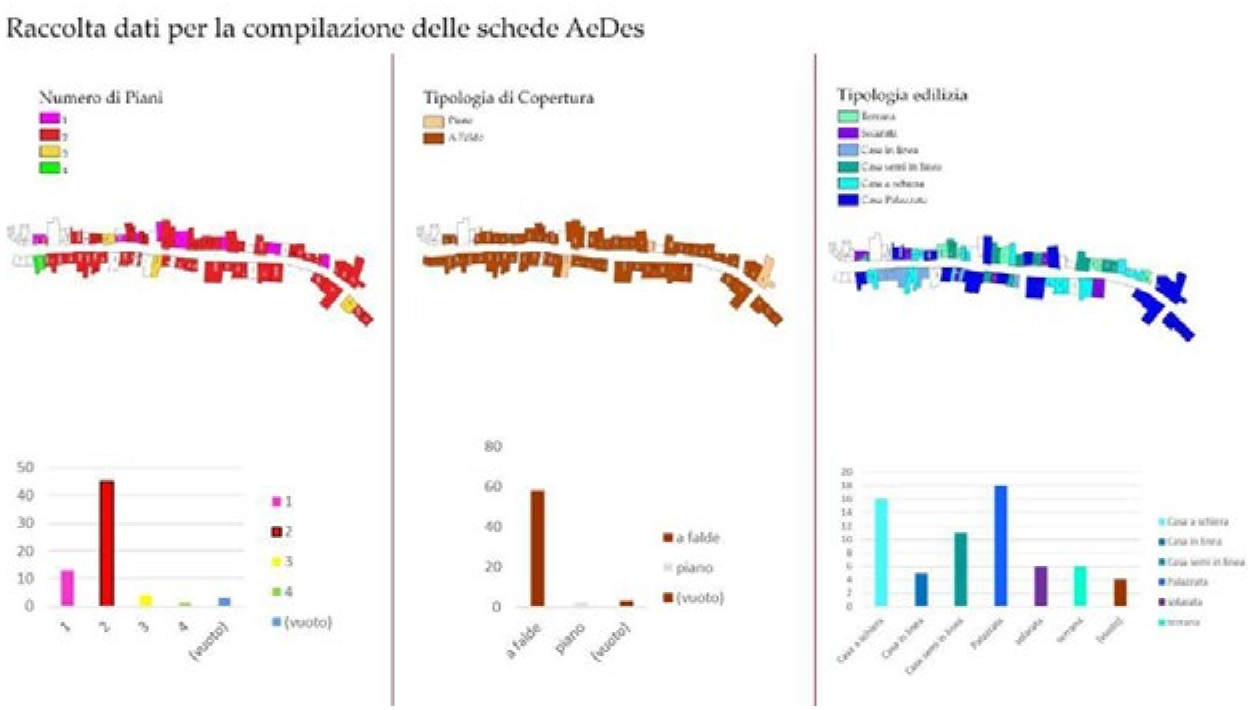


Fig. 9 | *Analysis of the urban curtain under study.*

The urban scene showed many heterogeneous features related not only to the building types and construction techniques but especially to the elements on the facades.

After the identification of the urban block, the geometric data were acquired through laser scanning for a total of 11 scans, which were subsequently aligned and georeferenced. Finally, the overall point cloud was edited to obtain orthographic images useful for the study of the building openings (fig. 10).

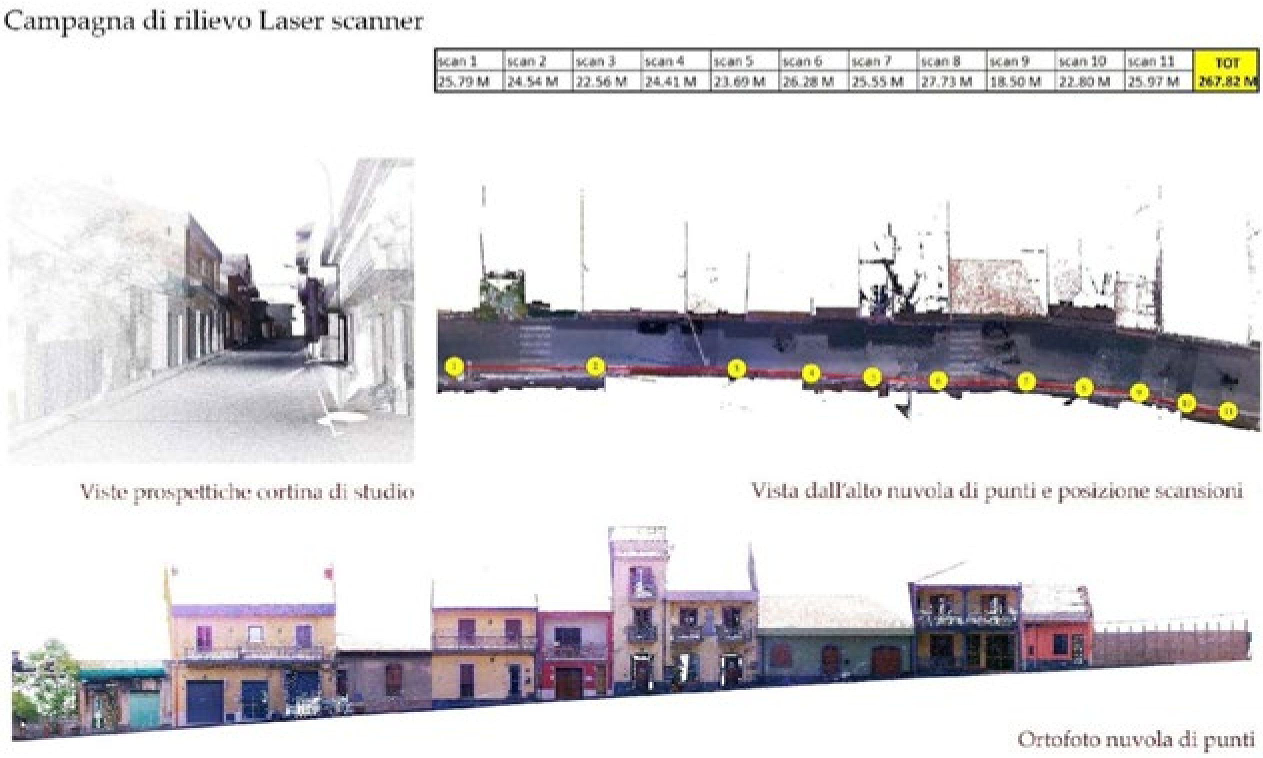


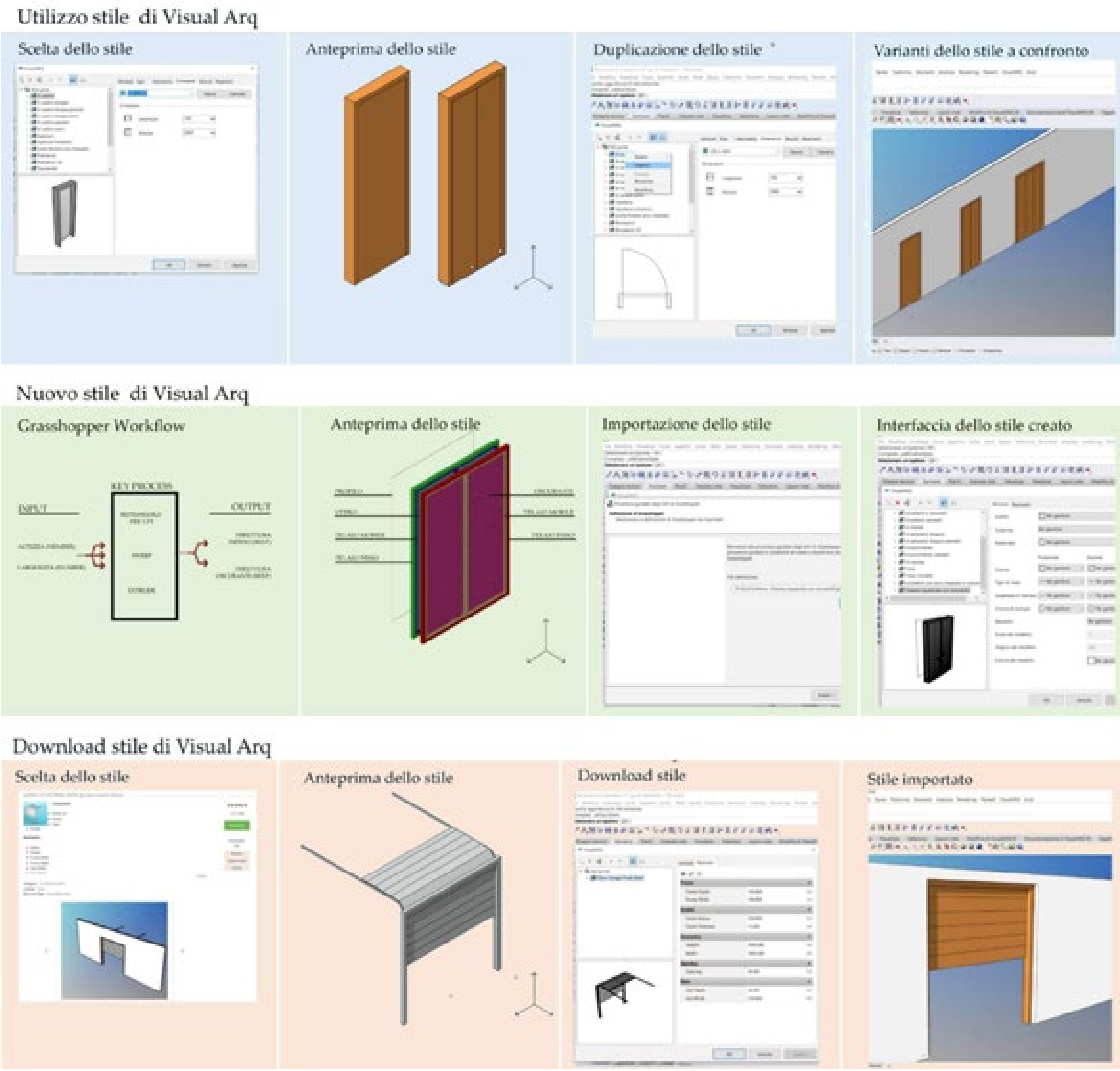
Fig. 10 | *Perspective view, top view and orthophotos of fronts from cloud of points (TLS).*

The point cloud was then imported into the modeling environment using Volvox. This tool provided a basis for the modeling operations that led to the creation of LOD 3. The study of the facade elements focused on the openings, which were analyzed both from the metric and the material point of view. This way variants and invariants of the different building components have been identified. These considerations allowed the cataloging of the elements in styles (analogous to the Autodesk Revit families), functional to the informative enrichment of the final 3D model of the urban canyon. The objective was to create a library of windows and doors incorporating, within the model, the results of the analyses carried out initially (type of opening, material, geometry, etc.). This library of BIM objects facilitates the modeling operations on the entire urban canyon and constituted a database of objects that could be reused in similar contexts.

The creation of styles required three possible methods. The first was to modify the predefined VisualARQ styles. However, in many cases these were not flexible enough, so an alternative was to consult the styles produced by other users and shared online in the Food4Rhino web portal. Finally, if even in this scenario the style did not meet the modeling requirements, the specific style was developed using Grasshopper.

In this last case, it was necessary to code a definition divided into input data (Boolean conditions, number sliders, texts) and output data (Breps). The first ones corresponded to the geometric and informative parameters that the style would possess, while the second ones concerned the geometric models (fig. 11).

Fig. 11 | *Techniques for modelling styles in VisualARQ.*



Following the finalization of the library of styles needed to describe the facades of the urban canyon studied, there is the transduction of the parameterized geometries into editable BIM objects.

The objective is to achieve LOD 3 which describes perimeter walls, roofs, openings, balustrades, and balconies. Walls, overhangs, balconies, loggias were modelled and then identified the position of the openings previously developed in Grasshopper or chosen from the VisualARQ libraries. Afterwards, the modelling of the building roofs was updated on the basis of the point cloud. For the correct perimeter of the roofs with reference to the buildings, the cartography overlapping the satellite image was used (fig. 12).

Fig. 12 | *Implementation of the parametric model into a BIM model.*

The lack of access to the rear of the buildings did not allow a direct survey of the geometries. Therefore, it was necessary to carry out a photographic survey to represent the rear of the buildings as faithfully as possible by means of photo-straightening. This allowed to complete the modelling phase (figg. 13-14).

Fig. 13 | *View of the CIM model in LOD 3.*

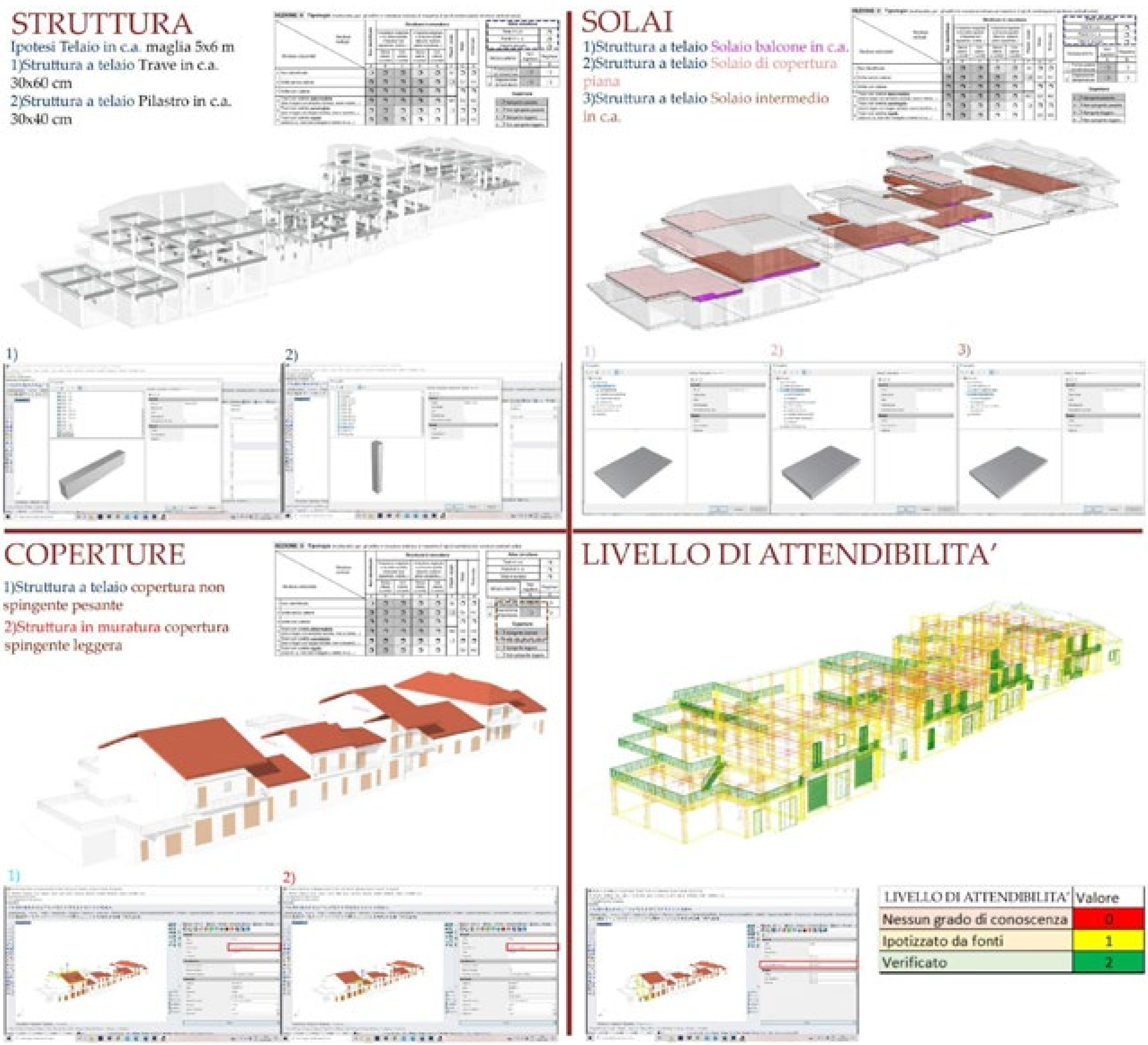
Fig. 14 | *Perspective view of the georeferenced point cloud aligned to the CIM model (LOD 3).*

The building components were then informed with the information gathered during on-site survey. The use of VisualARQ styles for modelling the urban curtain wall has permitted the enrichment of the model with geometric and material information as well as with additional customized parameters in the styles or as a modification of the internal geometry (in terms of representation of the stratigraphy of elements such as floors and walls). The analyses conducted on the urban block during the post-emergency phase of the 2018 earthquake referred to the AeDes sheets. The advantage of the CIM model consists in depositing directly the data collected on that occasion in the building components of each unit. For this reason, more attention was paid to section 3 of the AeDes sheets in which the type of structure both of the building and its roof is described.

The data collected indicate a miscellaneous presence of masonry buildings and reinforced concrete frame structures. The recognition of these typologies allowed the definition of hypotheses regarding the internal layout of the buildings, useful for a first representation of the interior spaces. In the case of the

Fig. 15 | *Thematic insights in relation to the AeDes sheets of the parameters associated with VisualARQ styles.*

reinforced concrete frame structures, a rectangular 5x6 m layout with 30x40 cm profile pillars and 30x60 cm profile beams was assumed. The BIM-based approach allows to update and easily modify these geometries as soon as new data is available, verified through the acquisition of cadastral plans and/or site surveys (fig. 15).



Data collection on building components is not always successful, in some cases missing data can be assumed, and in others, there will be information lacking. It is therefore recommended to explicit the different levels of reliability of the data incorporated for information enrichment through the definition of an appropriate parameter. In the literature can be found contributions that propose a classification of the level of reliability on the basis of a scoring evaluation using special matrices that take into account the process of data recognition and acquisition (Bianchini et al., 2018). Another approach focuses on the classification of the consulted documentary sources' reliability (Parisi et al., 2019). These approaches have been developed mainly at the architectural scale in order to describe and explicate the reliability of HBIM models. However, in a post-emergency scenario, the definition of reliability levels must take into account the urban scale of the information system adopted (CIM) and is closely related to the project's finality. Therefore, for the purposes of this research, three reliability levels have been defined, simplifying what is already present in the literature (Nicastro, 2017). A new style parameter in VisualARQ was associated with these three levels for each object style inserted in the model.

This parameter, which can also be changed in the individual instance, allows the user to easily identify components with less reliable information and thus to undertake specific investigations.

The three levels of reliability are defined as follows:

- 0 - not recorded;
- 1 - assumed by literature sources;
- 2 - verified by survey[1].

The introduction of this parameter guarantees the correct use of the data and also supports the scheduling of updates to the CIM model as more accurate analyses of the urban area are conducted.

In the specific case study, the hypothesised frame structure belongs to grade 0 as there were no data concerning the internal layouts of the buildings but only information from the visual investigation on site. Level1 is given to the internal layers of floors and walls, as they are assumed from literature sources. Openings and roofs, on the other hand, belong to level 2 because they were verified by the visual metric survey performed during the survey campaign (fig. 16).

[1] The survey campaign includes geometric surveys, recognition of the construction equipment, consultation of archive documents, material characterisation and diagnostic investigations.

Fig. 16 | *View of the final model with supposed internal elements and aligned point cloud.*

4.2 Major urban center scenario: the district scale

This section concerns with a more densely urban environment such as the historical center of Catania. The applications presented in this section were developed on the basis of the results obtained through research work applied to the minor urban center (section 4.1) and represent the advancement in relation to the state of the art according to the objectives of the thesis. Three main subjects are discussed next.

The first concerns a comparison of urban digital capture techniques with respect to some urban canyons in the historic center of Catania that are representative of those found in many historic Mediterranean cities. This comparison focuses on a historical city block in the center of Catania, which presents a high morphological complexity and thus can be used as a stress test of the presented methodologies (section 4.2.1). As case studyan emblematic area of the city of Catania (Italy) was chosen, the ex “extra moenia” district of Rinazzo (made up of narrow, twisting streets and one/two-floor buildings) which in 1881 was affected by the opening of a new road. This intervention has dismembered the area into two parts. The city blocks include different morphological characteristics (urban canyon ratios) and building typologies, that range from high-level residential buildings (palatial houses) to spontaneous buildings (one- or two-storey cells), which are still characterised by socio-cultural degradation.

The second subject is the Survey-to-Cim methodology applied to the city block object of the previous comparison (section 4.2.2). In this experience, a procedure is developed to obtain models up to LOD 3 and 4 by defining a protocol that allows the data collected manually by the surveyors to be encoded into data input that can be used by the VPL algorithm to model the block under study. Furthermore, the transition from the CIM model to the FEM model is also implemented in this experiment through the use of existing plugins and the development of new ones, in accordance with the methodology proposed in section 3.1.3.

The third subject is the Scan-to-CIM methodology, which presents an application of AI segmentation applied to a point cloud from a terrestrial laser scanner that entirely describes a late-eighteenth-century block in the historical center of Catania. The block under study reflects architectural and geometric characteristics typical of southern Italy. In this research work, an innovative method is presented regarding the urban scale for automatic modeling from the point cloud to the CIM model (hybrid LOD 3.1) using Grasshopper's parametric VPL environment. Also in this experiment, the final CIM model is converted into structural geometric models (both single units and entire blocks) and imported into different FEM software for validating the proposed workflow (section 4.2.2).

4.2.1 Comparison of Digital Urban survey terrestrial techniques for CIM generation

Historical centers represent the outcome of transformations and stratifications of the cities across the centuries. The knowledge of a historical urban environment requires an analytical methodology articulated on several interconnected levels of investigation to model a multi-layered complexity that encompasses the geometric and stylistic features of places (blocks irregularities, narrow streets, stratified buildings), the accessibility (pedestrian zone, no-fly zone), the use of existing data (GIS, cartographies). Today the challenge for historical centers is dual: on the one side to make use of expeditious technologies to acquire data, and on the other one to create 3D city models that allow managing, visualizing, enquiring, and using these data in a unique digital ecosystem. This research work deals with multi-sensor data acquisition, evaluation, and integration with the aim of creating informed and responsive 3D city models (CIM) that constitute a synthesis of the survey conducted and become the support for simulations in seismic risk analysis software environment.

This research work focuses on the experimental field survey phase with the comparison of different techniques (TLS, spherical photogrammetry, SLAM) in order to evaluate their efficacy and the possibility of integration in similar urban configurations. The use of UAVs has not been contemplated in order to simulate contexts with no-fly zones or where it is impossible to fly the drone at sight due to the volumetric complexity of the blocks considered. Following this, the sensors used for comparison are described.

The BLK2GO is a small dual axis LiDAR. Its core technology - the GrandSlam - is based partially on the SLAM technology, simultaneously combining high-speed dual axis LiDAR, Multicamera Vision System (MVS) and an inertial measurement unit that makes the instrument selfnavigating. The MVS include an integrated camera plus three panoramic cameras for visual navigation via SLAM. The generated point cloud has RGB attribute. The BLK2GO Live app allows to view essential data while scanning is in progress. To improve self-registration during data acquisition it is preferable to define closed paths that start and end by the same "docking base". This is useful to prevent and detect drift errors, optimize cloud registration and reduce alignment error. Figure 17 summarizes the specifications of the instrument. For SFM acquisitions a GOPRO Fusion 360 action camera was used. It has a CMOS 1 /2.3" sensor with two 9 Megapixel lenses with a 180° angle of view which permit the acquisition of spherical photos and immersive videos. Its small size (74 x 75 x 40 mm) and light weight (220 g) make it excellent for moving around city blocks.

Fig. 17 | *Specifications of SLAM mobile sensor BLK2GO and 360 camera GoPro Fusion 360.*

The case study under examination deals with a spontaneous building fabric of the historical center of Catania the Santa Caterina al Rinazzo district, which is located in the north-east area of the eighteenth-century *extra-moenia* expansion of the city. In 1881 it was decided the tracing of a new road axis, located close to the entrance to the Public Villa on the main street (Via Etnea) and directed toward the sea. The construction of the new Via Umberto I will strongly break the continuity of the existing building tissue, interrupting the morphological unity of the site. The superimposition of the new road axis will dismember the spaces since it will lead to the demolition of parts or entire buildings and the plano-altimetric reconnection of the involved urban environment. The new structure will worsen the sanitary conditions of the place, so as to charge in 1888 the engineer Gentile Cusa for the drafting of the "Master Plan of rehabilitation and expansion" of Catania (Gentile Cusa, 1888). The plan foresees the opening of Via Mangano (now Via Filippo Corridoni) and the new Via Santa Caterina, never built, in order to ventilate the blocks often below street level. As a matter of fact, behind the new nineteenth-century road axis characterized by the scenes of the palaces of the new middle class, narrow alleys and courtyards, legacy of the Mediterranean culture, find space in the micro building tissue (Restuccia et al, 2011). The district originally developed at different heights and had non-homogeneous blocks with shapeless lots, narrow courtyards and streets of penetration. This determined a poor ventilation in addition to health and hygiene problems caused by the lack of networks of rainwater drainage. The block examined is part of this urban renewal and is located near Piazza Carlo Alberto, historic seat of the municipal market called "Fera u Luni", and defined by a tract of the ancient via Santa Caterina, via Spampinato and via Grotte Bianche. The high level of complexity of the city block is due to the spontaneous evolution of various building typologies. The building pattern still largely retains the features of the Rinazzo district. This heritage is threatened by renovation operations that eliminate the typological and formal characteristics of the original buildings in the neighbourhood. The buildings, ground-floor houses or maximum two/three-storey houses, stand on enclosed and corner plots, with narrow, low fronts defined by simple corner stones and mostly covered by pitched roofs. Only in a few cases, such as the building at the end of the road between via Grotte Bianche/piazza Carlo Alberto/via Santa Caterina, there are multi-family buildings on several floors, with small courtyards from which the inner rooms are illuminated (figg. 18, 19).

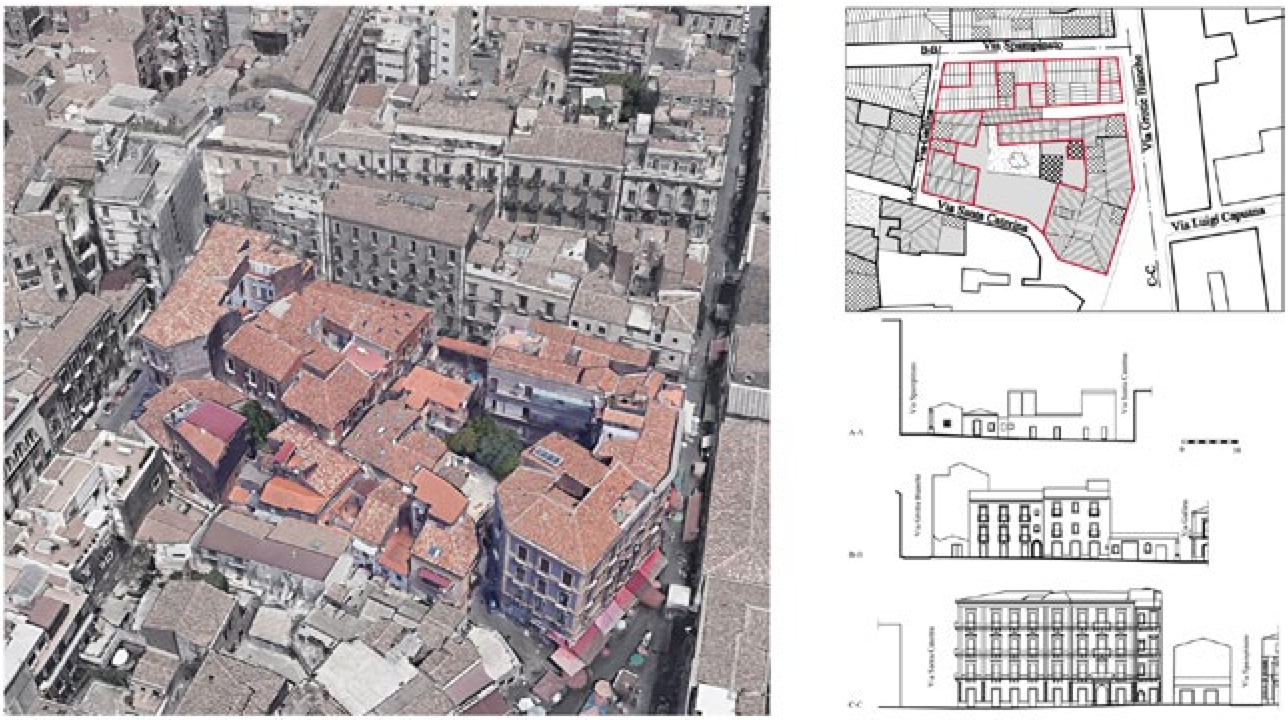


Fig. 18 | *Urban area examined in the case study (left). View of the investigated area and metric drawings along the streets which highlight the narrowness of the alleys and the different building typologies (right).*

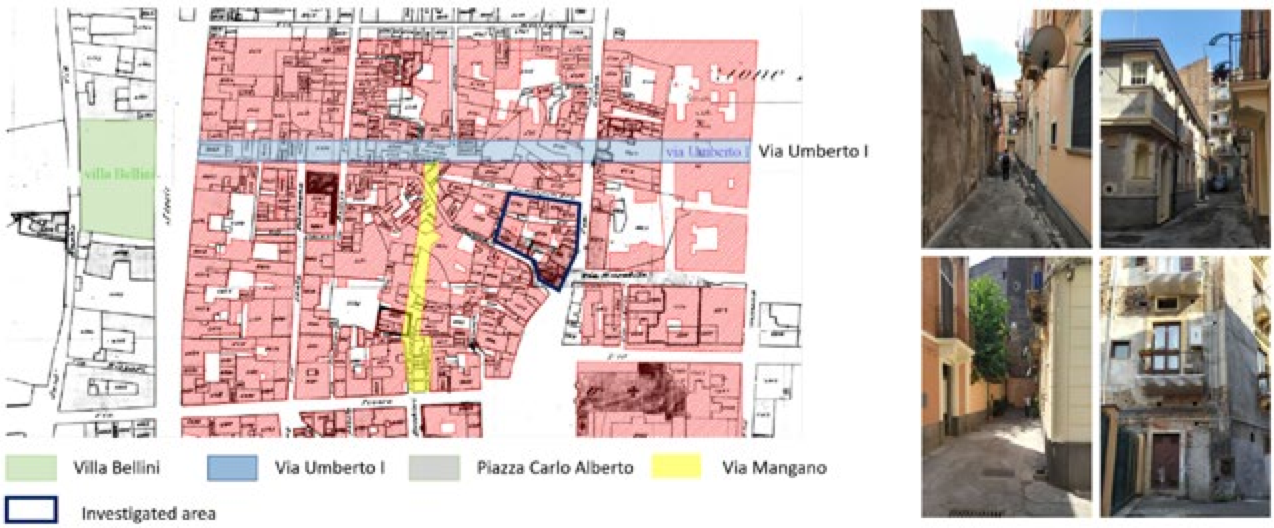


Fig. 19 | *Overlapping between current urban fabric (in red) and the cadastral map of 1876 (left). Pictures of the urban canyons considered (right).*

In order to be able to compare the results from the two survey methodologies adopted, photogrammetry from 360° images and iMMS via SLAM, a TLS-based survey has been used as a reference. BLK360 by Leica Geosystem has been used for SLAM scans. The scanner, which is particularly light and modest in size, permitted the acquisition of 20 scans along the entire perimeter of the block under severe conditions of vehicular and pedestrian traffic. In order to make the final point cloud more uniform, a high-resolution acquisition was carried out only in the presence of considerable heights and open spaces. In this way, the on-site acquisition phase lasted less than 1 hour. The clouds were pre-aligned on-site via the Field360 app. This reduced the time needed for the cloud registration phase within Register360.

The spherical photos needed for the SFM procedure were acquired on the move, holding the 360 camera through the support pole at a height of about 2 m above the ground. A sequenced image mode was selected, setting an interval of 2 seconds and leaving the shooting parameters in automatic. Walking at a normal pace around the block for about 200 meters (slowing down near the corners) 144 spherical photos were acquired with a resolution of 5760x2880 pixels in 4 minutes and 44 seconds. During the acquisition phase the axes of the two lenses were kept perpendicular to the axis of the road in order to avoid excessive deformation of the photos near the fronts of the buildings. Through the software Fusion Studio, the 360 photos have been extracted after stitching operations between the front camera and the rear camera. In addition, images were post processed in relation to shadows, highlights and exposure with the aim to reduce radiometric differences due to lighting conditions. The result is a dataset of equirectangular images that were imported into Agisoft Metashape for the processing phase. First, during the automatic alignment phase, all images were correctly aligned. Once this step was completed, a sparse cloud of 144,009 points was obtained with

‘High’ as level of accuracy (fig. 4). Afterwards, the dense cloud was reconstructed in ‘High’ quality and with the ‘Moderate’ depth filtering. The latter was preferred to the ‘Aggressive’ one to avoid relevant loss of data during the reconstruction. The final dense cloud consists of 43,422,818 points. The entire pipeline, from acquisition to processing and cleaning phase, required about 3 hours and 15 minutes. The final weight of the point cloud is equal to 639 Mb (fig. 20).

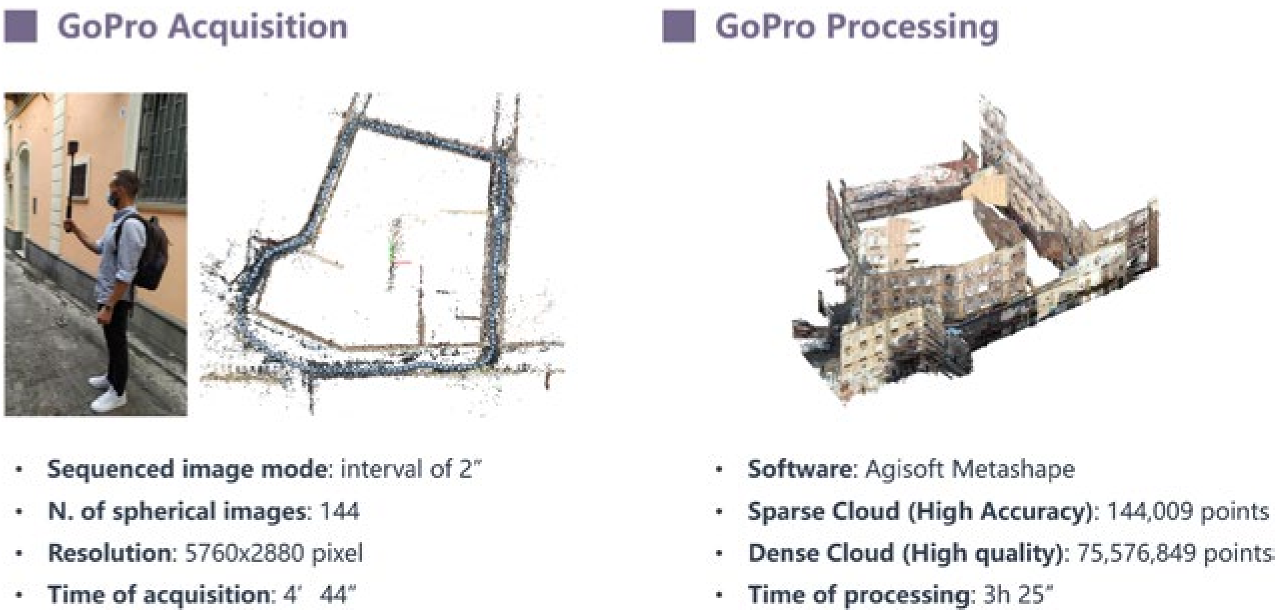
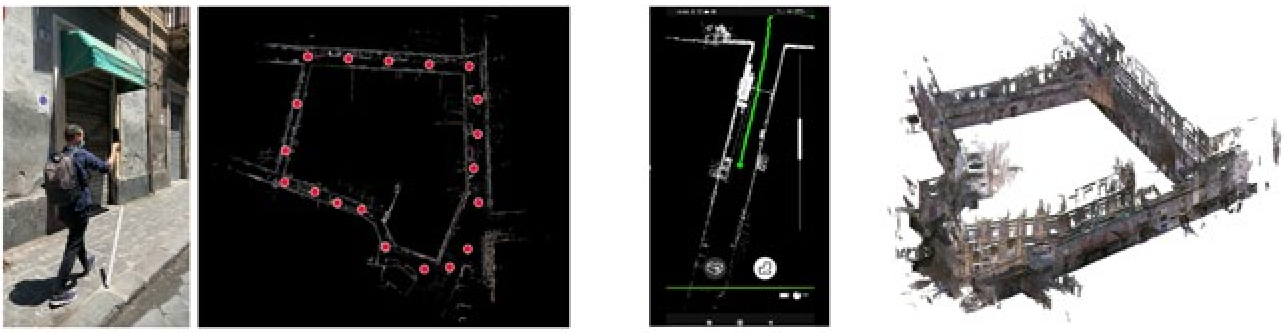


Fig. 20 | *GOPRO Fusion 360 on site during acquisition and sparse cloud with points of acquisition inside Metashape (left). Dense Cloud obtained (right).*

Regarding the SLAM survey, the new BLK2GO sensor from Leica Geosystem was chosen. As already mentioned in paragraph 3, the characteristics of the sensor determine a specific procedure for using the instrument. In particular, great care must be taken during the initialization phase of the sensor, since lifting it too suddenly from the ground or in the presence of heavy vehicular/pedestrian traffic may interfere with the start of the acquisition. The same path was covered as with the GOPRO Fusion except for obstacles caused by intense vehicular traffic. The perimeter of the block was covered in 7 minutes and 34 seconds. The operator was particularly careful when changing direction, decreasing the speed of the walk and rigidly rotating the torso in the chosen direction to avoid sudden movements during data acquisition. At this point, the raw data from the instrument was imported into Register360 and the noise reduction filter was applied. The resulting cloud consists of 13,477,837 points. The entire data acquisition and processing operation took less than 30 minutes with a data size of 246 Mb (figg. 21, 22).

BLK2GO Acquisition

BLK2GO Processing



- **Points/Second**: 420.000
- **Acquisition Range**: ca. 10 m (in this case study)
- **Relative accuracy**: 6 to15 mm
- **Time of acquisition**: 7’ 34”

- **Software**: Leica Register 360
- **Registered Point Cloud**: 13.477.837
- **Time of processing**: 20’

Fig. 21 | *BLK2GO on site during acquisition and imported point cloud in Register360 (left). Screen shot of the of the mobile app preview of the cloud and finel registered point cloud (right).*

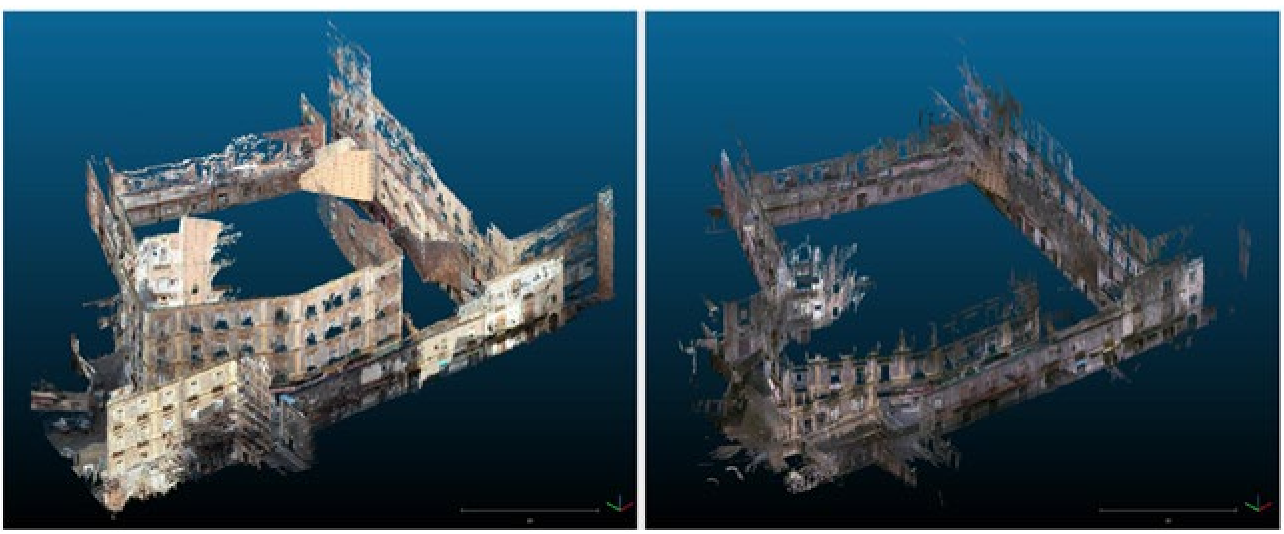


Fig. 22 | *Visual comparison between 360 SFM (GOPRO Fusion 360) cloud (left) and SLAM (BLK2GO) cloud (right).*

The accuracy evaluation dealt with the geometric features of the point clouds produced and their ability to describe reality. In particular, the approach proposed by Sammartano et al (2021) and Tucci et al. (2018) was followed. An analysis of the global accuracy of SFM and SLAM point clouds compared to TLS cloud was conducted. This was followed by an analysis of the local accuracy on a portion of the cloud representative of the building types present in the historical Italian urban centers. These two analyses are necessary because, as indicated in 2.3 section, over wide distances the point clouds produced by SLAM can be affected by drift errors while locally they closely reproduce the built environment. Afterward, specific analyses were carried out on geometric characteristics such as: planarity, density, roughness, and curvature of both point clouds. All the analyses were conducted using the algorithms provided by the opensource software CloudCompare (CC).

To assess the global accuracy, SLAM and SFM scans have been aligned with TLS scan which was used as reference. This was done by locating 15 points distributed along the perimeter in areas common to both SLAM and SFM data. For the global analysis, the M3C2 algorithm was chosen. This algorithm allows a faster analysis than the traditional Cloud-to-Cloud (C2C) method and is less sensitive to noise. M3C2 initially calculates the evolution of the mean surface with respect to a scale that takes into account the roughness of the scan. It then evaluates its trend with respect to the normals calculated with respect to a significant point (in the case study, the barycentre was used) using a subset of points (corepoints) to speed up the analysis. Compared to C2C, it does not require the computation of a mesh and therefore reduces inaccuracy due to cloud roughness. The result of the analysis can be directly represented on the point cloud used as a reference (TLS). Therefore a colour scale was applied to display the deviations in a range from -30 cm to +30 cm. For the SFM scan analysis, a mean deviation of 3.3 cm and a higher standard deviation of 1.05 m were calculated (fig. 23).

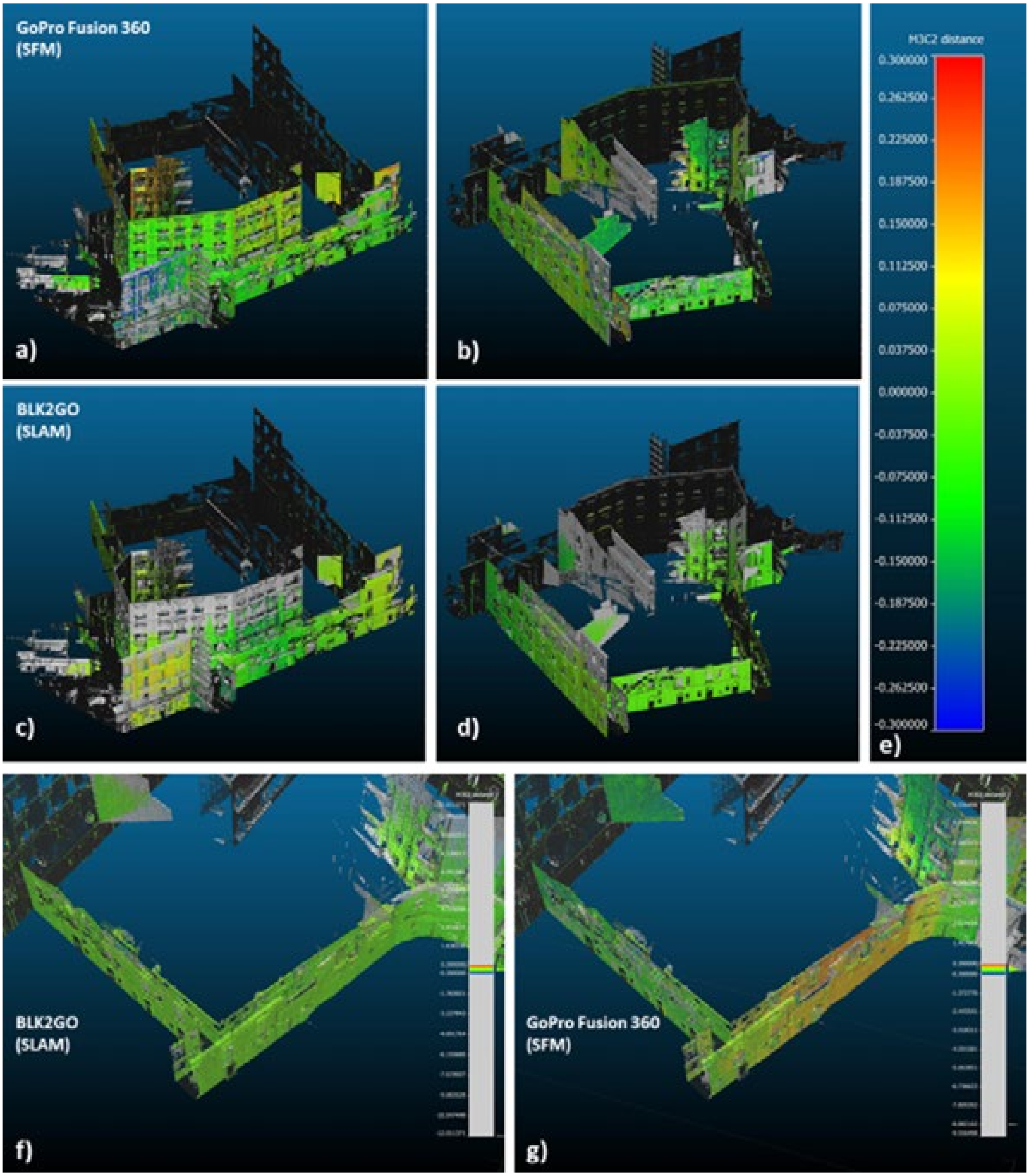
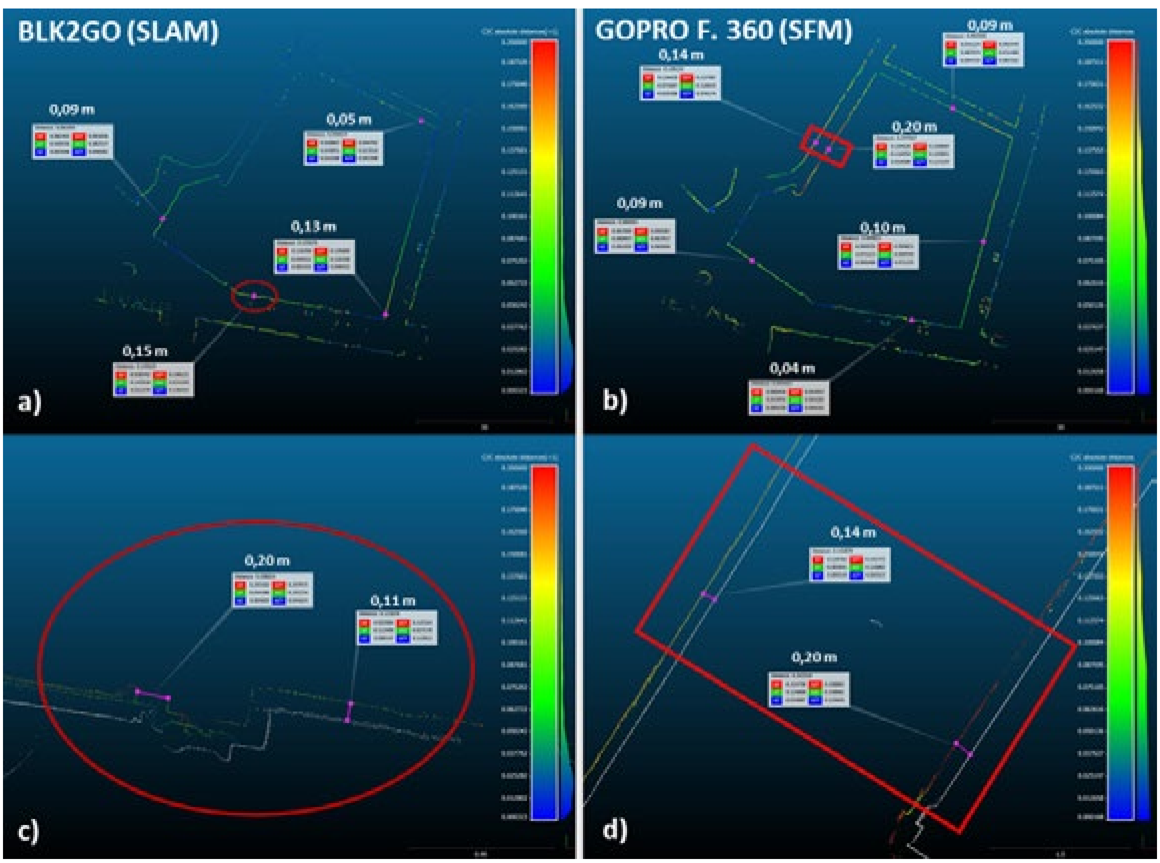


Fig. 23 | *M3C2 global analyses of SFM cloud (a, b) and SLAM cloud (c, d). The scalar field (e) ranges from blue (-30 cm) to red (+30 cm). Focus on differences in narrow streets between SLAM (f) and 360 SFM (g).*

From the visual analysis of the comparison, it is possible to notice higher deviation values near the ledges, in the noisiest areas and in the upper part of the facades (22.5 to 30 cm). For the road, ground floor and facades planes, the deviation values are in the range of +/- 3 cm. Regarding the analysis with the SLAM scan, the mean deviation is 1.1 cm while the standard deviation is 1.26 m. In contrast to the SFM scan, the point cloud at the ledges has values that correspond to the mean deviation (+/- 1 cm). The highest deviation values (+/- 20 cm) mainly concern the ground floors (disadvantaged by heavy vehicular and pedestrian traffic). From the cloud it is visually possible to notice an absence of data beyond the first floor of the buildings and an increase in deviations with increasing elevation.

In order to evaluate the accuracy at urban scale (definition of the investigated block perimeter) horizontal slices were extracted at ground level (1.60 m from the lowest point of the cloud). These were then analysed using C2C. The main observation that emerges is that for the SFM scan the lowest offset values are found in the proximity of wider and well-lit urban canyons while the SLAM scan performs better in narrower and shaded urban canyons. It is worth highlighting that the SLAM scan has a drift that in the maximum deviation reaches 20 cm over a distance of about 200 m (fig. 24).

Fig. 24 | *C2C analyses of horizontal slices for SLAM cloud (a, c) and 360 SFM cloud (b, d). Better viewed digitally.*



Regarding the local analysis, it was focused on a portion of the building on four levels that has architectural elements typical of Italian historic centers, with an exception for planarity analysis. In this case, a plain wall (dimensions 3.50x2.50) at ground level was chosen. With regard to the analysis of planarity, the SFM and SLAM scans are then evaluated using the Cloud-to-Mesh algorithm. The table below shows the percentages of points with respect to the ranges of +/- 1 cm and +/- 3 cm (tab. 1).

Planarity analysis	+/- 1 cm	+/- 3 cm
TLS (BLK360)	94%	100%
SFM (GoPro Fusion)	35%	78%
SLAM + MVS (BLK2GO)	92%	96%

Tab. 1 | *Percentage of points matching the plane identified by the TLS scan in the given ranges.*

For the density analysis, the Number of Neighbours algorithm was used, which returns the number of points contained within a sphere of specified radius. In this work, a sphere radius of 5 cm was used. Visual analysis of the scans reveals a more homogeneous density in the SFM scan compared to the SLAM scan where there are more data gaps between overlapping parts (fig. 25). The table below (tab. 2) shows the mean deviations from the three scan types.

Density analysis	N° of Neighbours (r = 0.05m) | Mean
TLS (BLK360)	94%
SFM (GoPro Fusion)	35%
SLAM + MVS (BLK2GO)	92%

Tab. 2 | *Density analysis: mean deviations from the three scan types.*

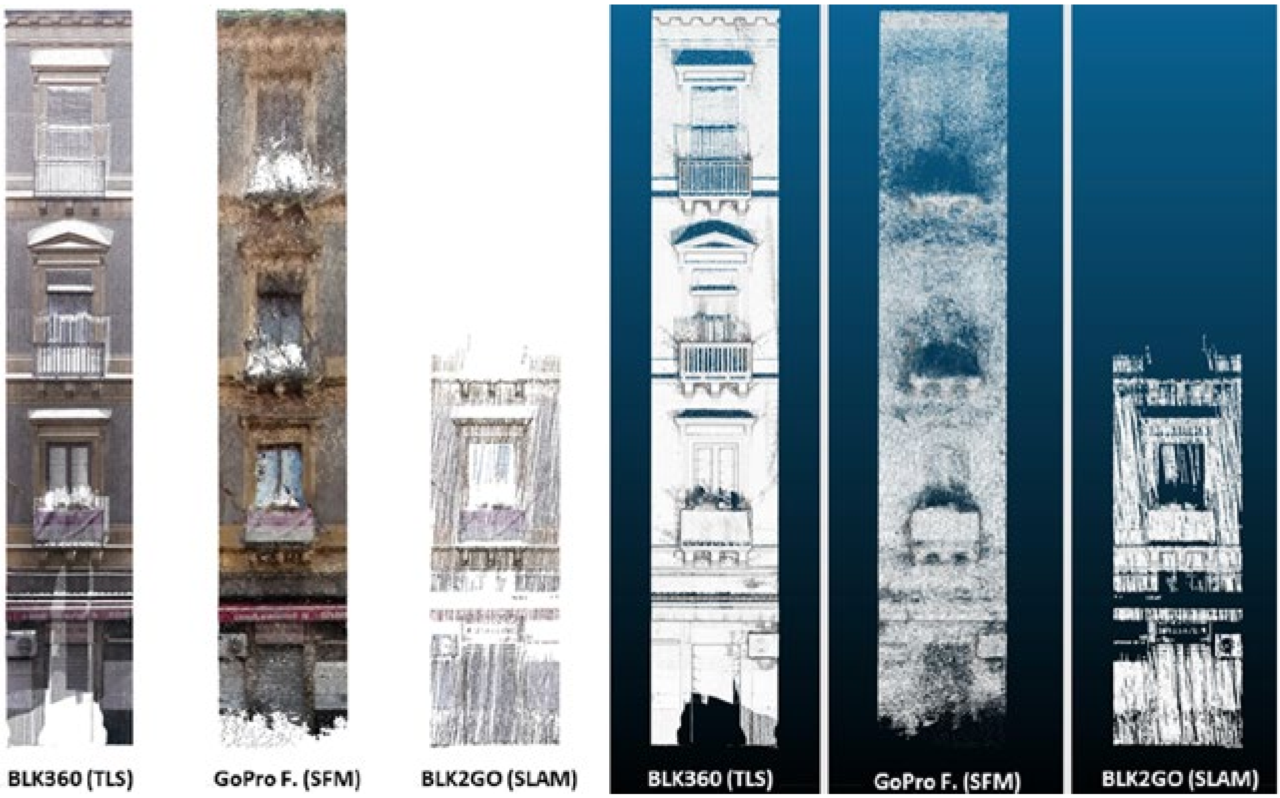


Fig. 25 | *Density comparison between TLS, SFM and SLAM.*

With reference to the roughness values of the scans, a radius of 5 cm in this case was considered as well. This comparison shows that the SLAM scan has relatively low noise values, with peaks at the overhangs. On the contrary, the SFM scan presents more noise and it is distributed over the whole cloud. Finally, the curvature was analysed in order to understand the level of detail achievable by the two clouds in relation to the recognition of openings in the facades. In the SLAM scan, edges can be clearly identified with 15 cm kernel sphere, while the radius has to be doubled in the SFM scan. However, the higher noise level makes it difficult to clearly identify edges in the SFM scan (fig. 26).

The analyses conducted so far allow qualitative and quantitative comparisons between the two tested technologies (fig. 27). First of all, it is important to keep in mind that the results have to be assessed against the finality of the work. In this case, a fast urban 3D acquisition for the creation of a CIM of the historical center is to be updated during the time. The table below (tab. 3) compares the main characteristics that emerged from the technical and qualitative analyses.

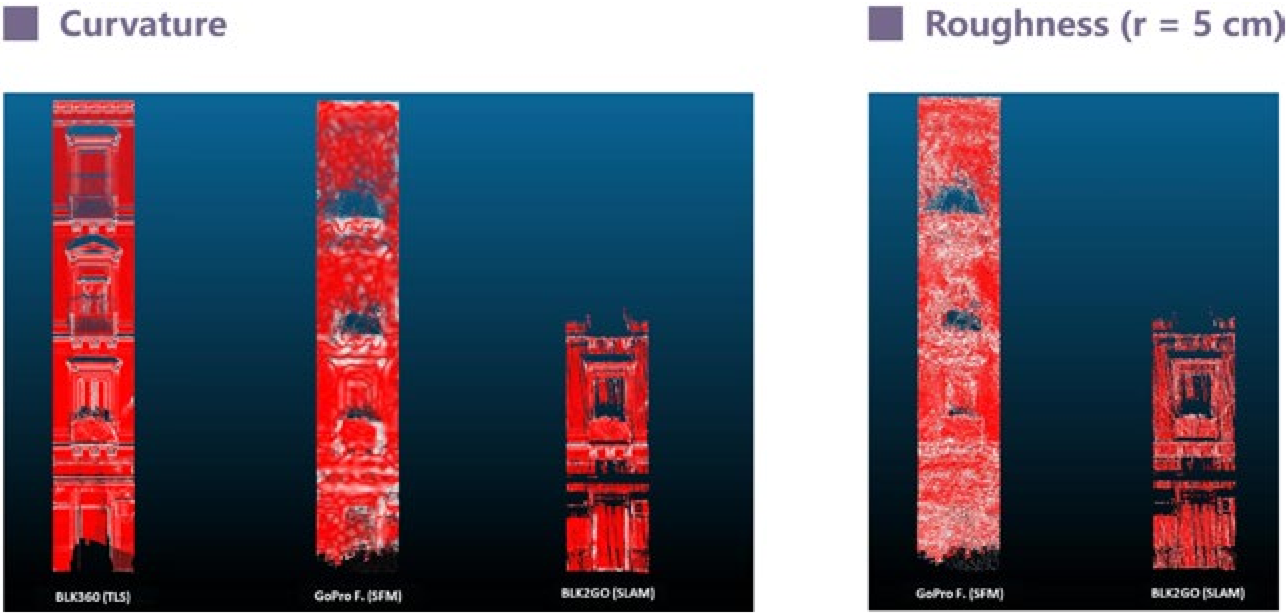


Fig. 26 | *Curvature and Roughness analyses between (from left to right) TLS, SFM, SLAM scans.*

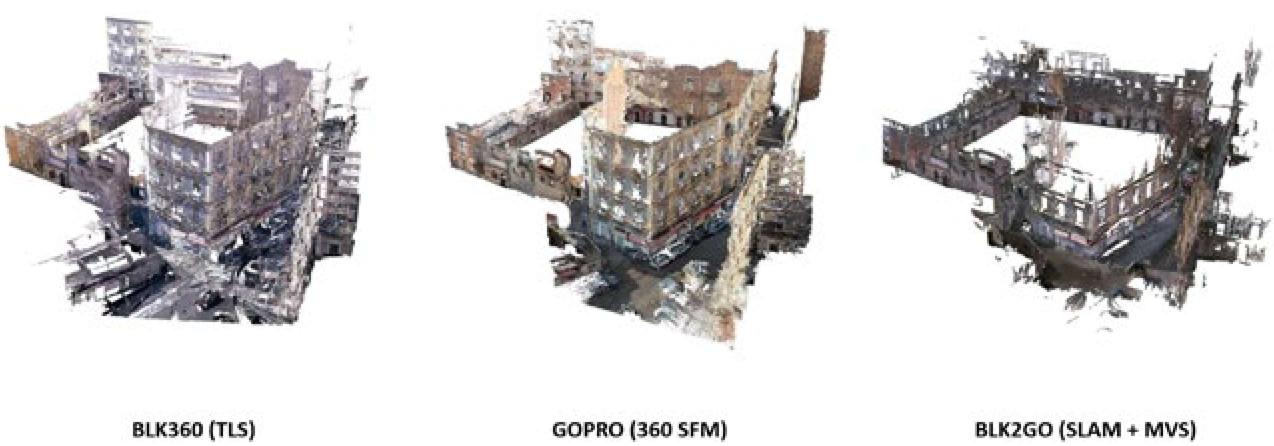


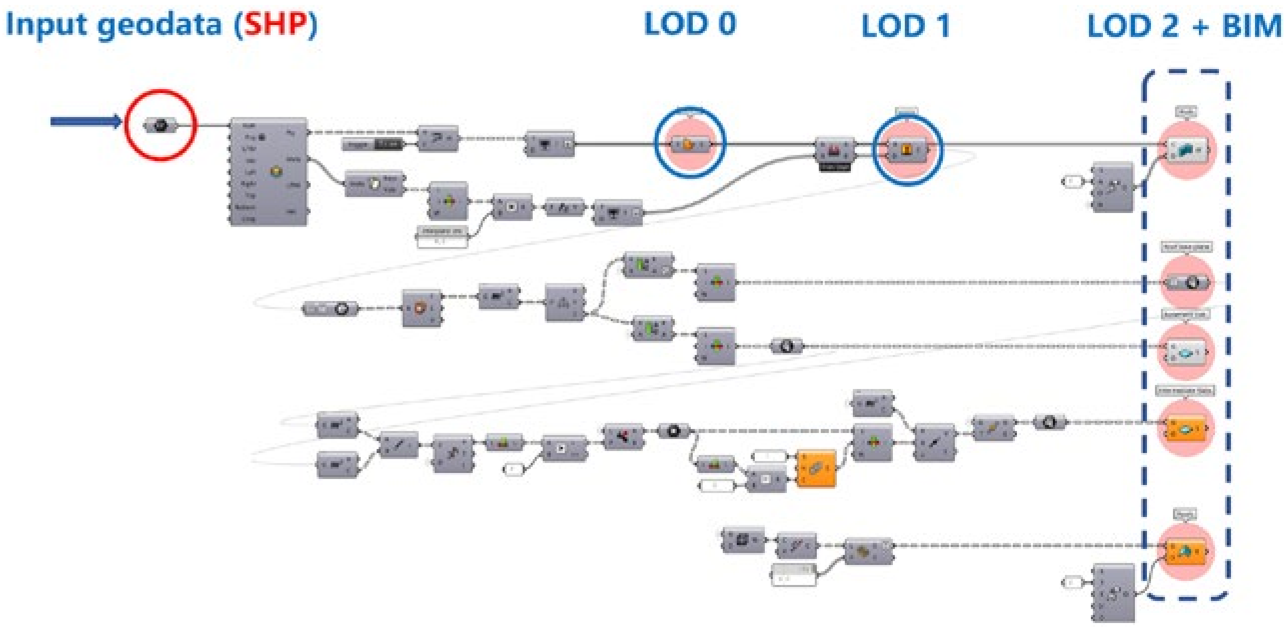
Fig. 27 | *View of the final point clouds obtained from (from left to right) TLS, SFM, SLAM scans.*

Category of comparison	SFM (360 images) – GoPro Fusion	SLAM (iMMS) – BLK2GO
Main planes reconstruction	Medium	High
Elevation data acquisition	up to 3rd floor	up to 1st floor
Readability of RGB data	High	Medium
Level of geometric accuracy	Low	Medium
Metric quality	1:200	1:100/1:200
Noise level	High	Low
Noise location	Diffuse	Edges
Density	High	Low
Max deviation (ca.)	30 cm	20 cm
Shift	/	20 cm
Data acquisition time	4' 48''	7' 34''
Data processing time	3h 25'	20'
User expertise needed	Medium/High	Low
Price of the sensor (ca.)	500 €	50 000 €

Tab. 3 | *Comparison table between SFM (GOPRO Fusion 360) and SLAM (BLK2GO) workflows.*

The comparison shows the potentialities of BLK2GO SLAM technology even though there are limitations. The main one is the acquisition range: 0.5 - 25 meters according to the technical specifications and around 10 meters in this particular case study. On the other hand, the SFM technique with spherical images is sustainable with respect to the product it returns, despite the lower quality of the cloud compared to the SLAM scan and the problems related to light conditions. The BLK2GO appears to be useful in historic urban areas consisting of buildings on 1/2 levels, for massive survey operations and with on-site personnel who may not be experienced. Possible applications could be urban post-emergency scenarios. The GOPRO is an effective, affordable tool but requires the involvement of experts. Therefore, colud be assumed a more localized use related to risk assessment and prevention activities.

Once the comparative analysis of the SLAM and SFM techniques was finished, the Survey-to-CIM method was applied as in the Fleri case study (section 4.1.1) in order to visually verify the overlapping of the SFM cloud with the CIM model up to LOD 2.6 developed within Grasshopper. LOD 3 according to CityGML standards consists of modelling the elements of the envelope, in particular the openings in the facades. In order to support the modelling operations, it is useful to include the point cloud of the block fronts obtained through SFM techniques (figg. 28, 29).



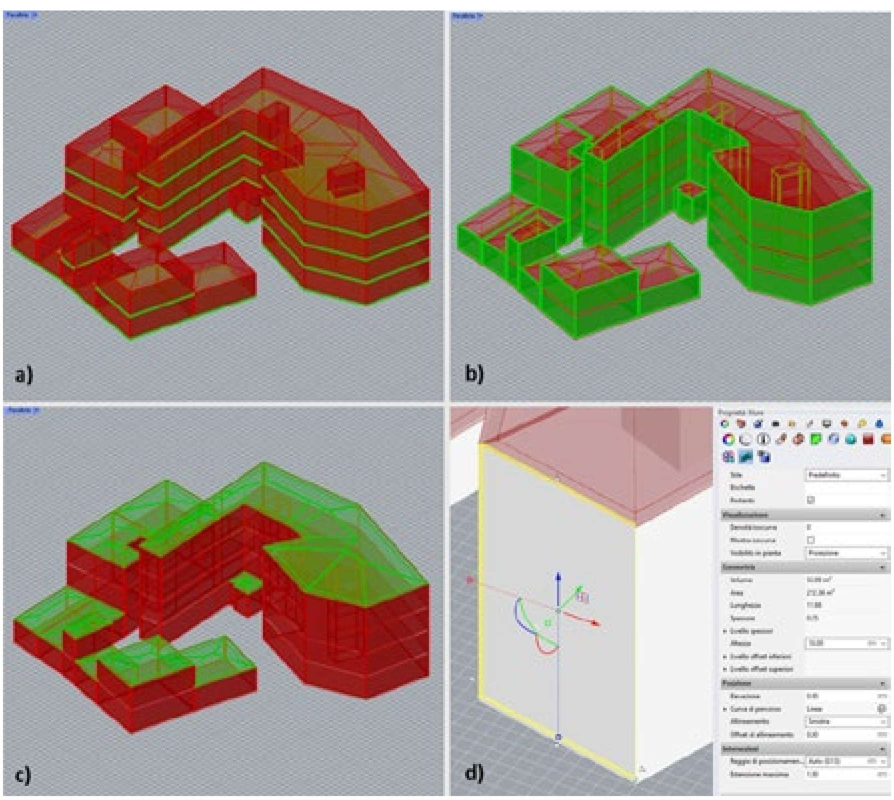


Fig. 28 | *View of the VPL code developed to obtain LOD 2.6.*

Fig. 29 | *LOD 2.6 CIM Model in Grasshopper. Focus on slabs (a), walls (b), roofs (c) and BIM attributes with VisualARQ plugin for Rhinoceros (d).*

In this way it will be possible to identify the position of the openings with a metric error tolerance compatible with the scale of urban representation (1:200). The area studied in this research work does not easily permit the use of UAVs for the photogrammetric reconstruction of roof geometry. Moreover, the high level of complexity of the geometry of the roofs hinders the definition of procedural modeling processes for their correct representation. To fill this gap, the 3D mesh of the block was downloaded from Google Earth using the software RenderDoc and the add-on MapsModelsImporter for Blender. Despite the metric inaccuracy that affects these models, the quality of the mesh roofs is still sufficient to help the user in the manual urban modeling phase (fig. 30).

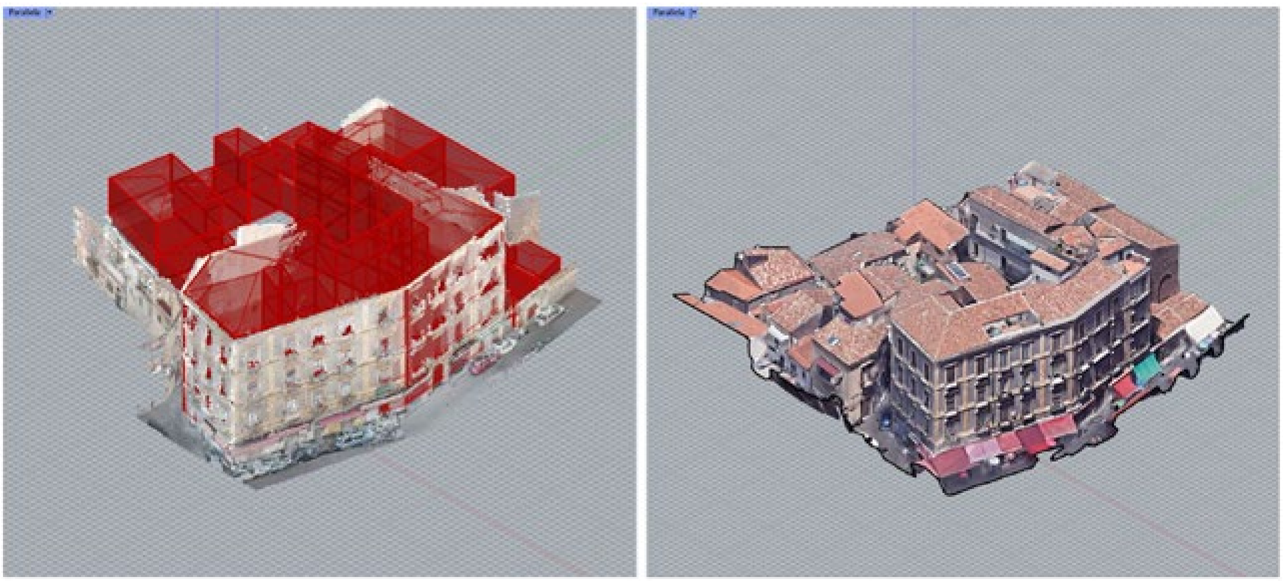


Fig. 30 | *On the left, SFM point cloud in Grasshopper. On the right: 3D Google Earth mesh of the city block under examination. Model attribution: Google Earth, @2021 Google*

4.2.2 Cityblock Survey-to-CIM application with FEM models

The application presented in the previous section allowed the acquisition of a lot of data in relation to the configuration of the facades in the urban canyons analyzed. In the Fleri case study (section 4.1.1), the transition to LOD 3 (openings in the envelope) is achieved through manual modeling with a workflow similar to the one adopted in the HBIM approach (manual modeling of building components with the reference of a point cloud). The purpose of this application is to obtain usable data for the definition of LOD 3 from the initial phase of data collection (without the need for a digital survey) and the creation of structural geometric models to be used in the FEM analysis environment. The methodology adopted in this case study is the ‘Survey-to-CIM’ already discussed in section 3.1.1 but now includes the transition to the geometric FEM models. Below is showed a conceptual scheme of the workflow (fig. 31).

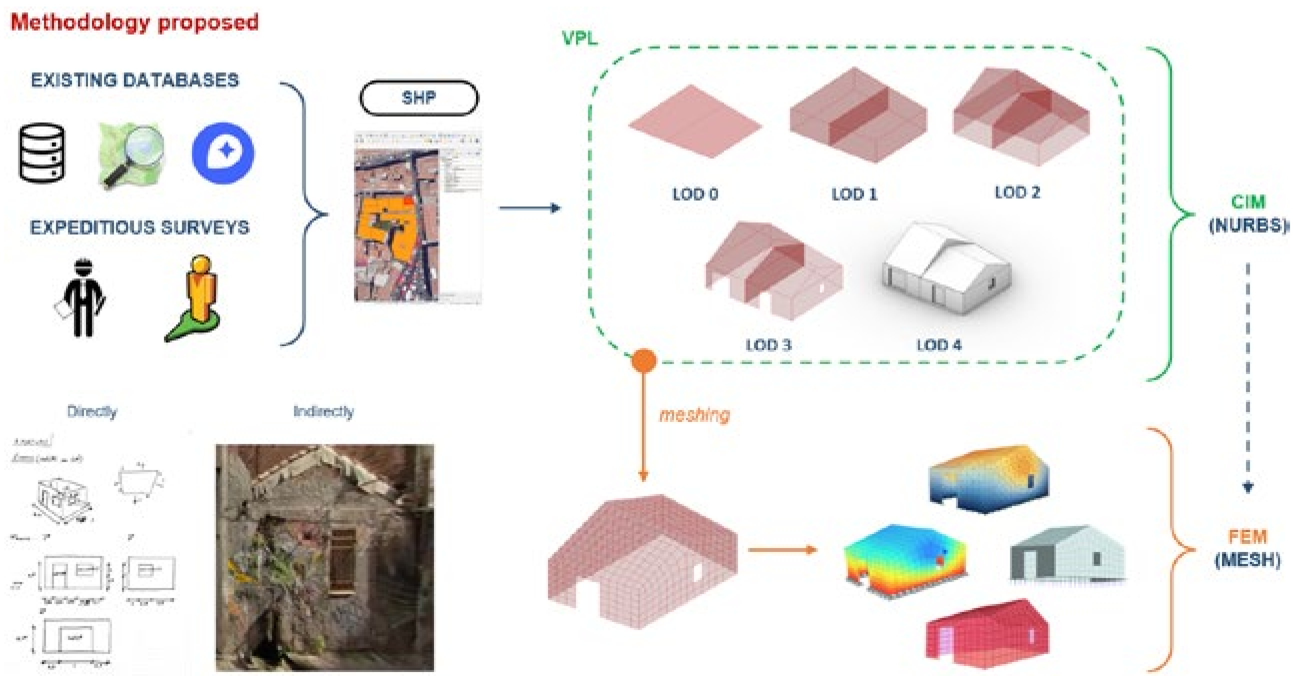
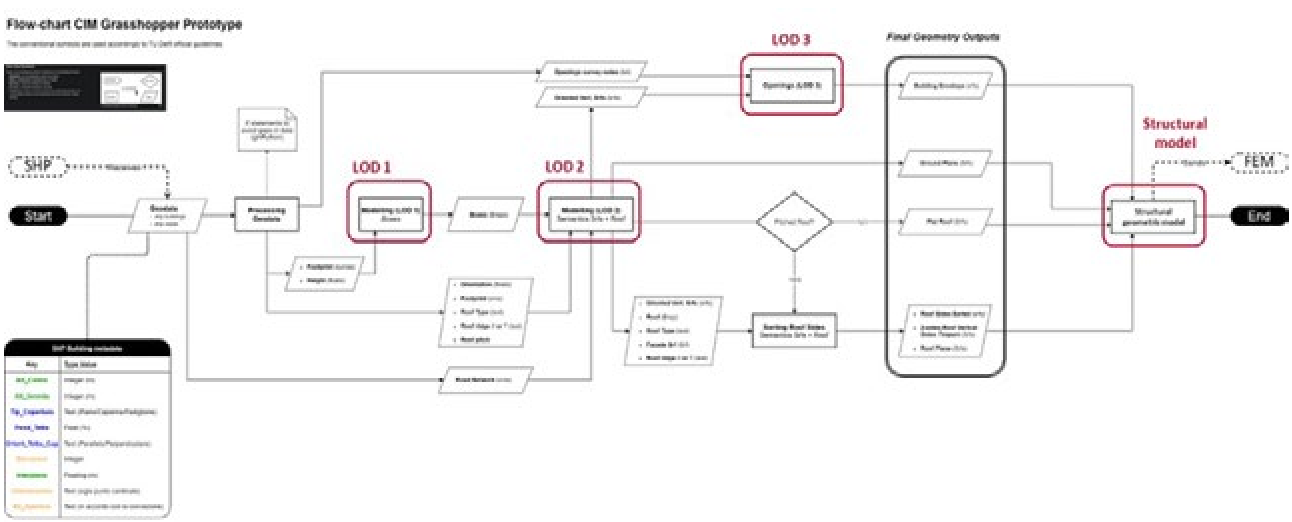


Fig. 31 | *Pipeline of work of the methodology proposed.*

In order to develop a prototype, it was identified a one-level building included in the already analyzed city block studied in section 4.2.1. The typology of this building called *casa terrana (ground floor house')*, can be fully described for CIM purposes by reaching LOD 3. For this building typology, LOD 3 and LOD 4 coincide since there are not interior walls relevant for seismic analysis. A VPL code was then designed by defining a flow-chart according to the TU Delft guidelines (fig. 32).

Fig. 32 | *Flowchart of the VPL code in Grasshopper (TU Delft guidelines) for CIM modeling of the one-storey building typology. Better view digitally.*



The building chosen as a case study was included in a mapping process that produced geodata on the historic center. These geodata consist of a shapefile that, in addition to the building footprints, contains various metadata about each building (Galizia, Santagati, 2012). Through the Urban GH plugin, it was possible to read inside GH both the geometries and the metadata contained in the shapefile. The initial modeling step was to achieve LOD 1 (box) according to the standards defined by CityGML. Afterwards, LOD 2 was reached by deconstructing the box from LOD 1 and semantically identifying the surfaces by taking the surface normals and coordinates of the barycentres as references. Finally, for LOD 3 the openings were inserted by extracting position and size from the text strings initially inserted (figg. 33, 34).

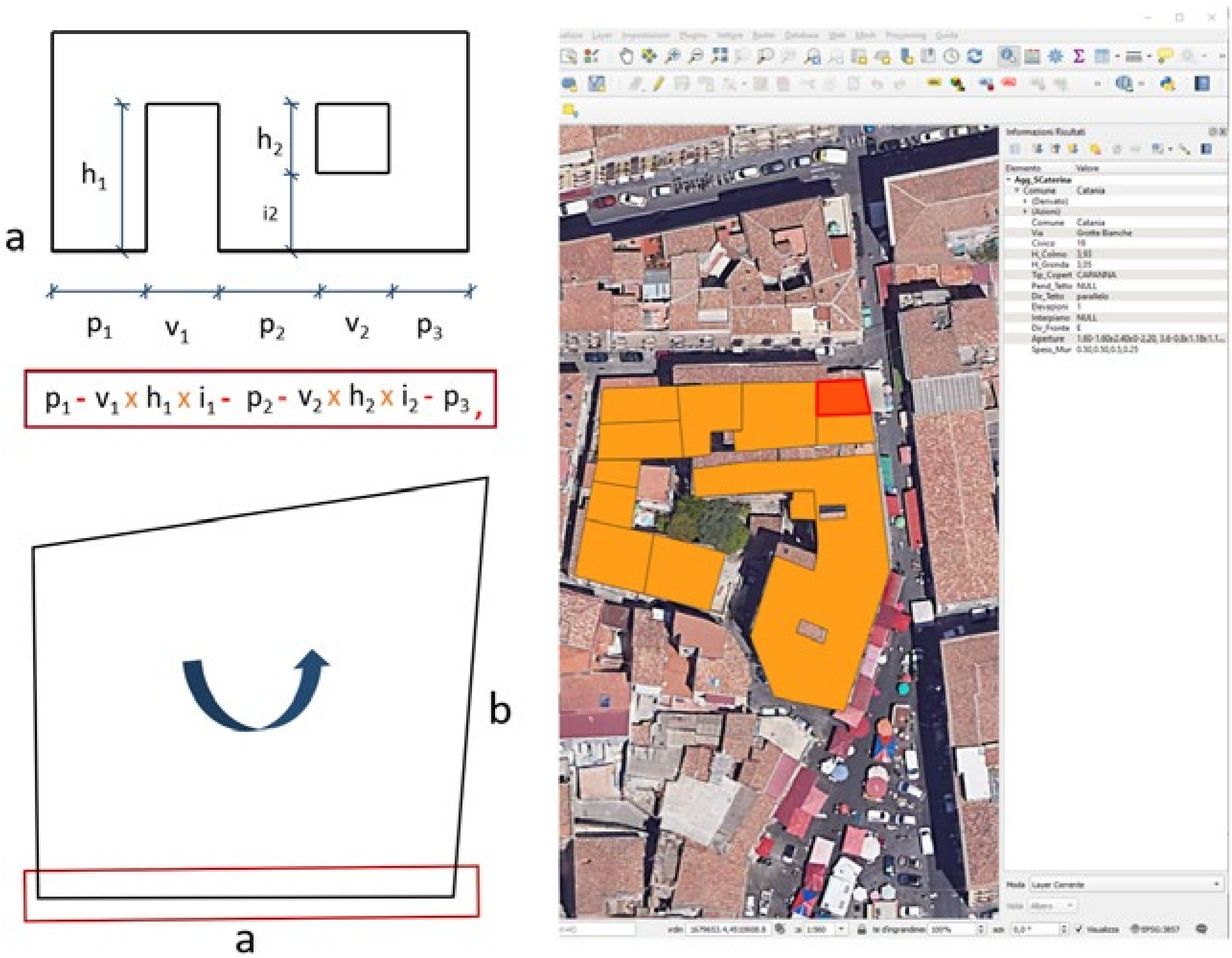


Fig. 33 | *Convention for openings (left) and shape file (right).*

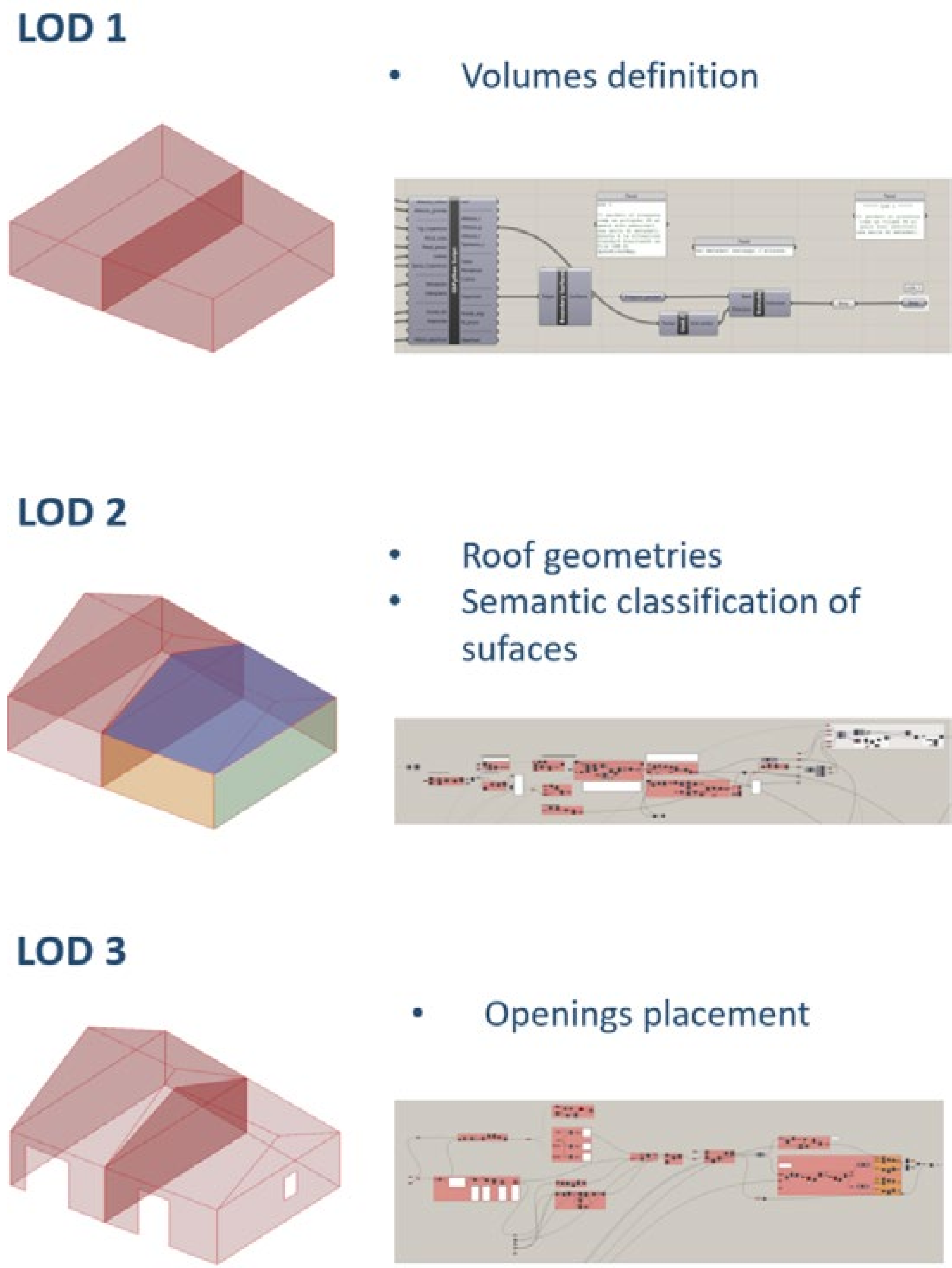


Fig. 34 | *Parametric CIM modeling phases (LOD 0 – 3).*

With the aim to make the mesh of the FEM model seamless, all NURBS surfaces were treated using GH tools for mesh-manipulation that allowed to preserve the conformity of the mesh between the surfaces of the model. Finally, the mesh model has been used for FEM analysis through several plugins for GH related to structural analysis software. Some of the plugins made it possible to perform structural analysis directly within the Grasshopper workspace. This is the case for Karamba3D and Alpaca4D (OpenSees). Other ones have worked as connectors transporting (automatically) the mesh model from Grasshopper to the working environment of the analysis software. In particular, for SAP2000 was developed a specific component that enables the user to extract the mesh model from GH and to import it into SAP2000 (fig. 35).

To verify the procedure and the results that can be extracted from the analyses performed on these models, an analysis of the vibration periods with the same system configuration (geometric and material) was carried out. In Figure 36 are reported results and deformations obtained. The results are homogeneous in respect of the tolerances due to the intrinsic differences of the calculation software used.

Moreover, from the qualitative analysis of the deformations obtained, the behavior of the geometries is consistent. In conclusion, it has been made a comparison of the modeling times taking as reference the same geometry but modeled inside a software (well-known and diffused among professionals) for structural analysis of masonry buildings (3DMacro Development Team, 2021). In Figure 37 are shown models and times of comparison.

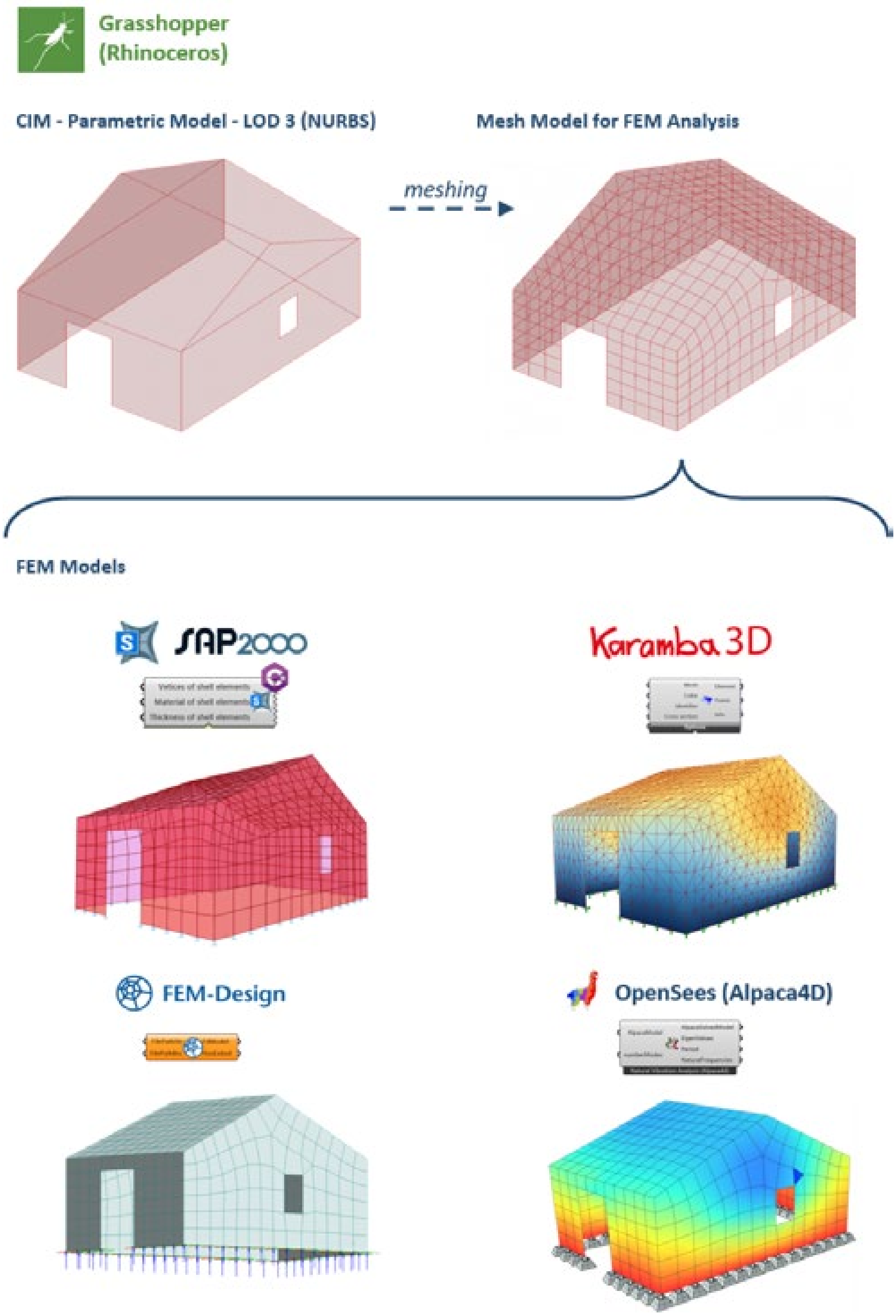


Fig. 35 | *Parametric CIM model discretized into FEM models*

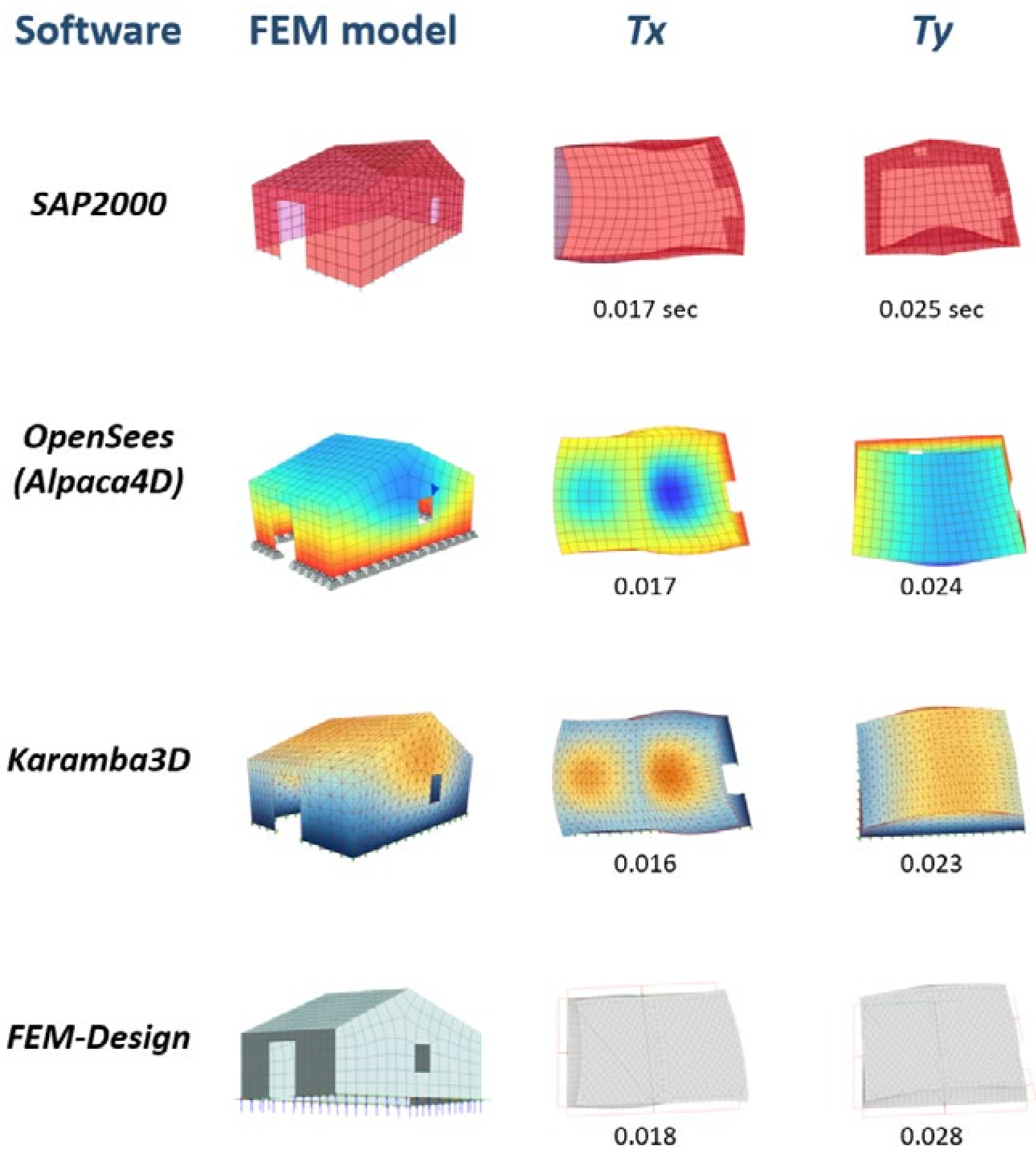
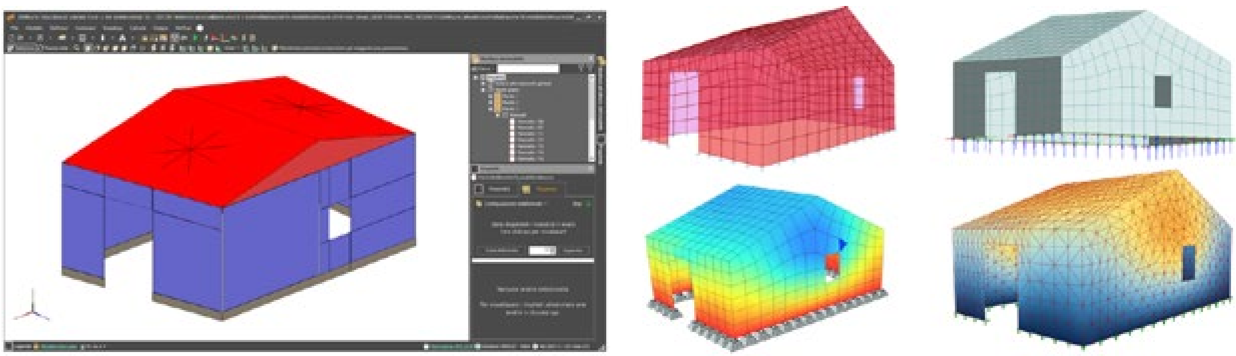


Fig. 36 | *Analysis of the vibration periods of the same model.*



Manual modeling on 3DMacro		CIM parametric modeling	
- DXF creation for reference lines	30'	- Inserting input data	10' 0''
- Wall, foundation and roof modeling	1h 40'	- CIM computational time	0' 12''
- Openings placement	20'	- FEM model generation	0' 7''
Total	**2h 30'**	**Total**	**10' 19''**
N° of models	**1**	**N° of models**	**4**

Fig. 37 | *Comparison of modeling times between a traditional FEM modeling procedure and parametric CIM modeling.*

4.2.3 Cityblock Scan-to-CIM with AI Segmentation

In the previous application, the *Survey-to-CIM* method was applied to generate CIM models taking into account low resource availability. However, although the method is also applicable in dense urban scenarios such as Catania's historical city center, it may have limitations when the quantity of the study object becomes very high and therefore take much longer to apply, thus reducing the effectiveness of the strategy. As a solution to this problem, an additional procedure called *Scan-to-CIM* was defined in this research work, which allows for expeditious modeling from the point cloud acquired in situ to the CIM and FEM model at city block scale. This semi-automatic procedure, described methodologically in section 3.1.2, combines a parametric approach at the urban scale starting with point cloud segmentation as input data. This segmentation is achieved through Machine Learning techniques, in particular by applying Random Forest to classify defined classes of objects in the point cloud. The goal of this work is to obtain a LOD 4 model and then convert it into one city-block geometrical structural model but also to have the possibility to export the single building units as geometrical structural models.

The methodology was applied in the same urban area described in sections 4.2.1 and 4.2.2 (about 200 m of distance from the previous case study). In this case, it was identified an aggregate that has been analyzed in the past (during the Catania project, see section 2.3.2) and of which some studies can still be found in the literature (Angiolilli et al., 2021; Greco et al., 2020) (fig. 38). The architectural features of this aggregate (floor bands, stone-framed

Fig. 38 | *From left to right: top and bird's eye view of the urban block under study.*

balcony doors, pilasters) and the construction technique consisting of a masonry structure designed and built only for vertical loads made of stone-lava material combined with brick elements (called *'intosta'*), make this aggregate the most exemplary for the historical center of Catania. The entire aggregate is rectangular shaped (approximately 90x40 m with an area of 3501 square meters) and it occupies one city block and has five main building units of different typologies (in-line building, open courtyard building) with 3 to 4 elevations (fig. 39). These buildings have evolved in different years since 1840. An

Fig. 39 | *Street level image of a side of the city block. In the image can be seen the different elevations, the repetitive pattern of opening and the obstacles at the ground floor.*

important statistic is the number of facade openings, which is 201 openings. This information is relevant because it suggests the potential of the proposed methodology if compared with current methodologies that involve manual use for the identification and modelling of openings on building envelopes. Another important point to highlight is the constant presence of obstacles at the ground floor level. In contrast to the narrow streets of the previous case study, in this one the streets have heavy traffic with part of the street occupied due to commercial activities and car parks.

As described in section 3.1.2, after acquiring the cartography made available on the municipality's website, it was planned the digital urban survey campaign. The results obtained from the comparison between the different sensors (described in section 4.2.1) highlighted how acquisition techniques such as SLAM and SFM360 can be useful for a digital survey that aims to provide the operator with all the information useful for the description of the external configuration of the buildings and therefore a manual modelling. Nevertheless, these techniques do not offer sufficient quality of geometric detail to be used in artificial segmentation tasks using Random Forest algorithm. For this reason, the digital survey was conducted with a terrestrial laser scanner. The sensor is Leica Geosystem's RTC360, which was well suited to the surveying task as its Visual Inertial System allows the various point clouds to be pre-registered already in situ and their alignment checked in real time. Along with the scanning, Ground Control Points with a GNSS antenna were marked in order to have the point cloud georeferenced (fig. 40).

Fig. 40 | *Images of the acquisition phase in situ with the Leica RTC360 and GNSS antenna for marking Ground Control Point..*

16 scans were made at medium detail mode (6mm at 10m distance) taking just under 2 minutes per scan and a total of more than 30 millions of points. The entire acquisition activity took approximately 40 minutes with delays due to heavy vehicular traffic. The latter can be avoided in the early hours of the morning, but there would be more obstacles due to more parked cars. Thanks to the Field 360 application, the correct alignment of the different clouds was monitored. This made it possible in laboratory to directly register the final cloud after a quick cleaning of the most disturbing elements and the quality check of the alignment through the extraction of vertical and horizontal slices. The final cloud counts 16,589,256 points (figg. 41 - 44).

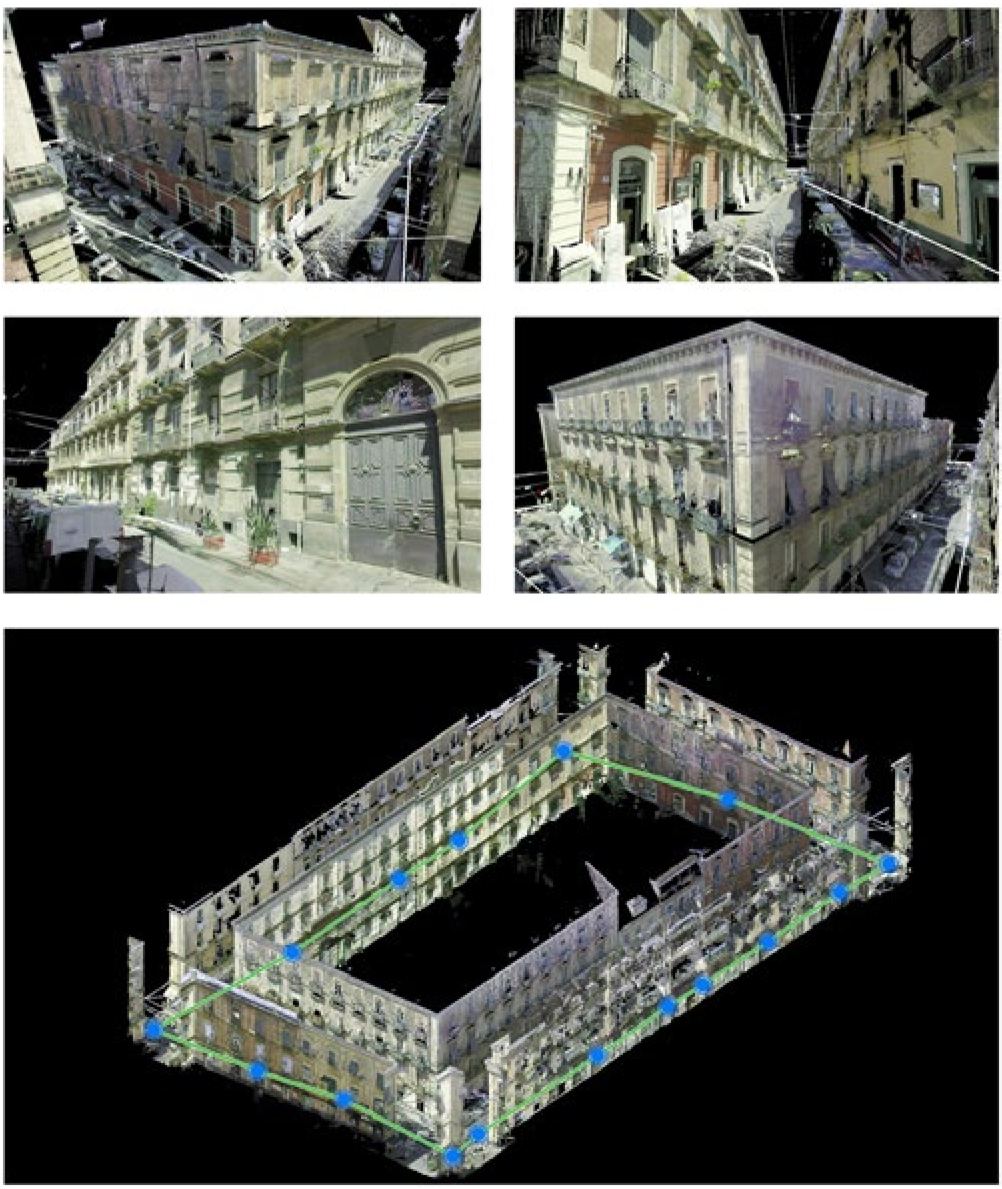
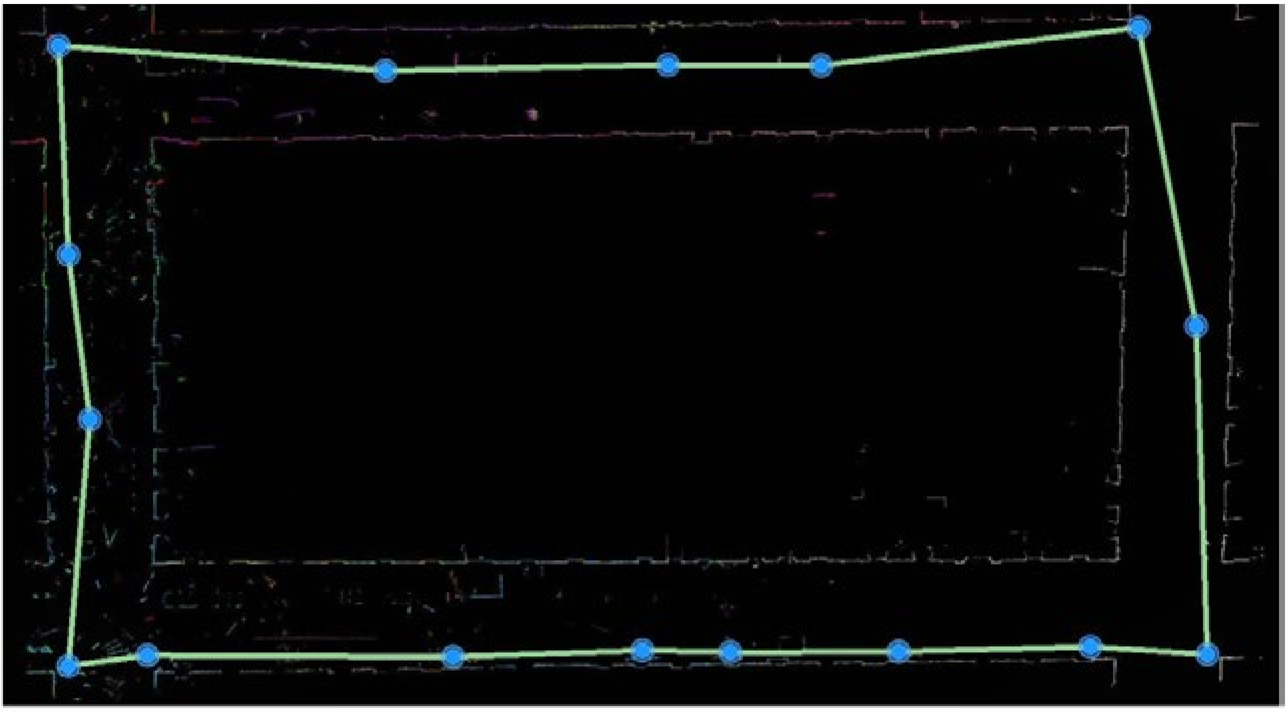


Fig. 41 | *Perspective views of the point cloud imported (top) and axonometric view with scan locations (blue dots) and links of overlapping scans (green lines) generated during the acquisition phase (bottom).*



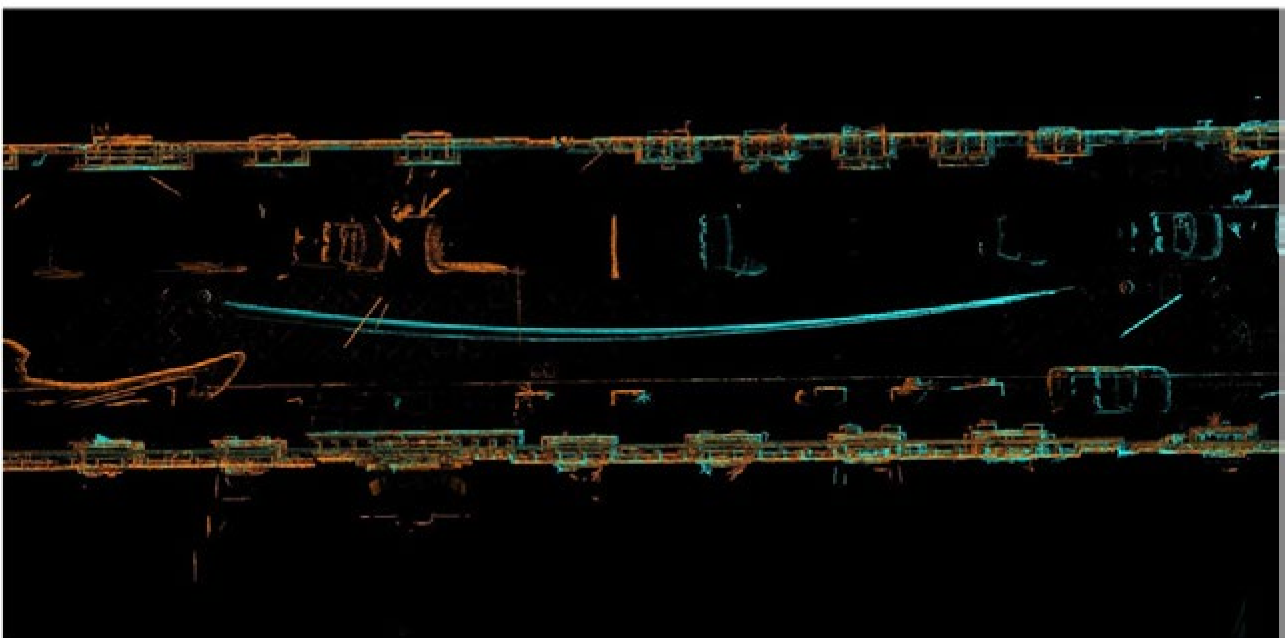
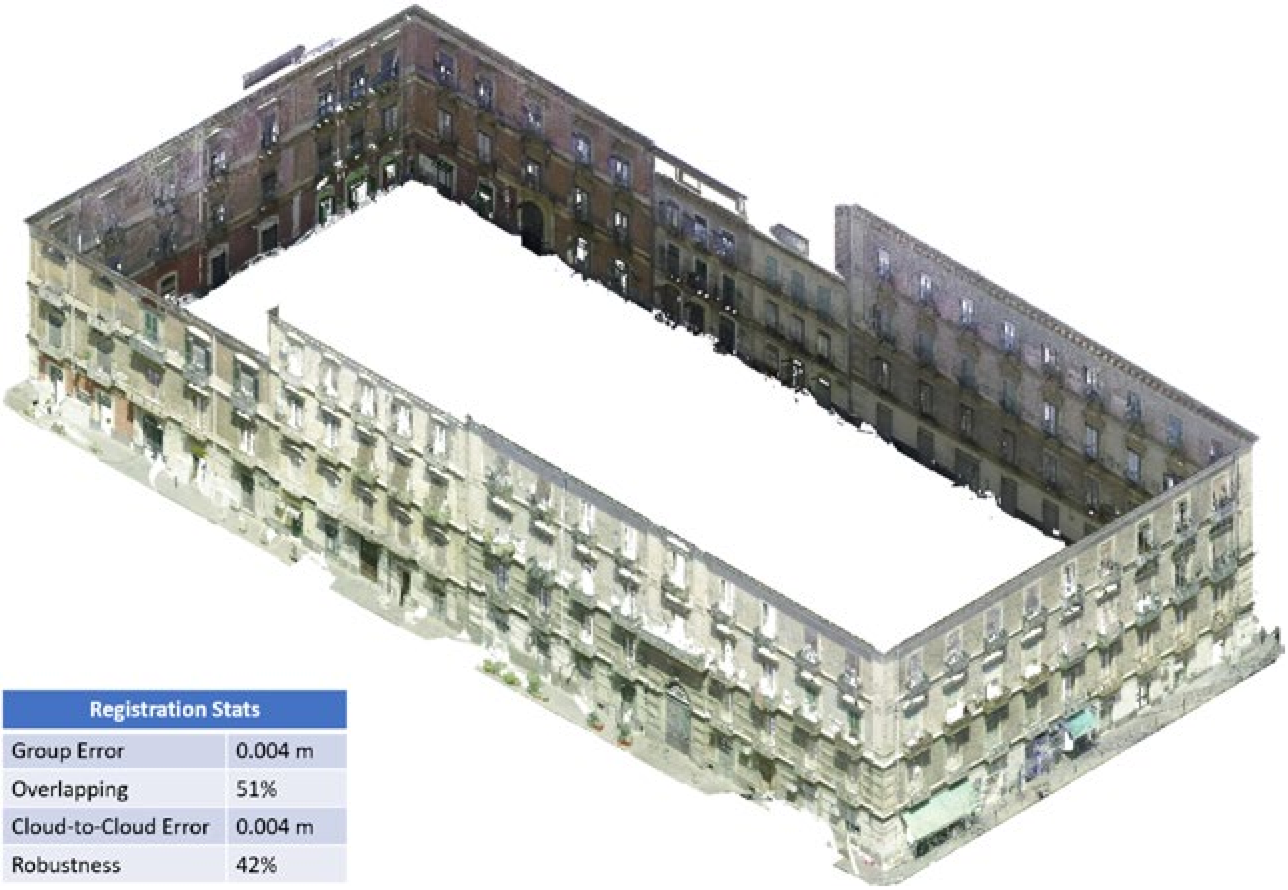


Fig. 42 | *Checking the correct overlapping of the acquired point clouds with slicing tools (top), 'Visual Alignment' with Register360 of two point cloud to improve overlapping stats.*

Fig. 43 | *From top to bottom: top view of the registered point cloud (scan spots in red) and table of scans; elevations of the point cloud.*



Registration Stats	
Group Error	0.004 m
Overlapping	51%
Cloud-to-Cloud Error	0.004 m
Robustness	42%

Fig. 44 | *Axonometric view of the registered point cloud and table with registration stats.*

Once the digital acquisition phase was completed, the next step was the automatic segmentation process using Random Forest, adopting the methodology described in section 2.1.2. First, it was necessary to identify the classes to be used to train the algorithm. Given that the modeling requirement with respect to the envelope concerns LOD 3.1 (envelope with openings without roof geometry), three main classes were defined: walls, openings, and string courses (fig. 45).

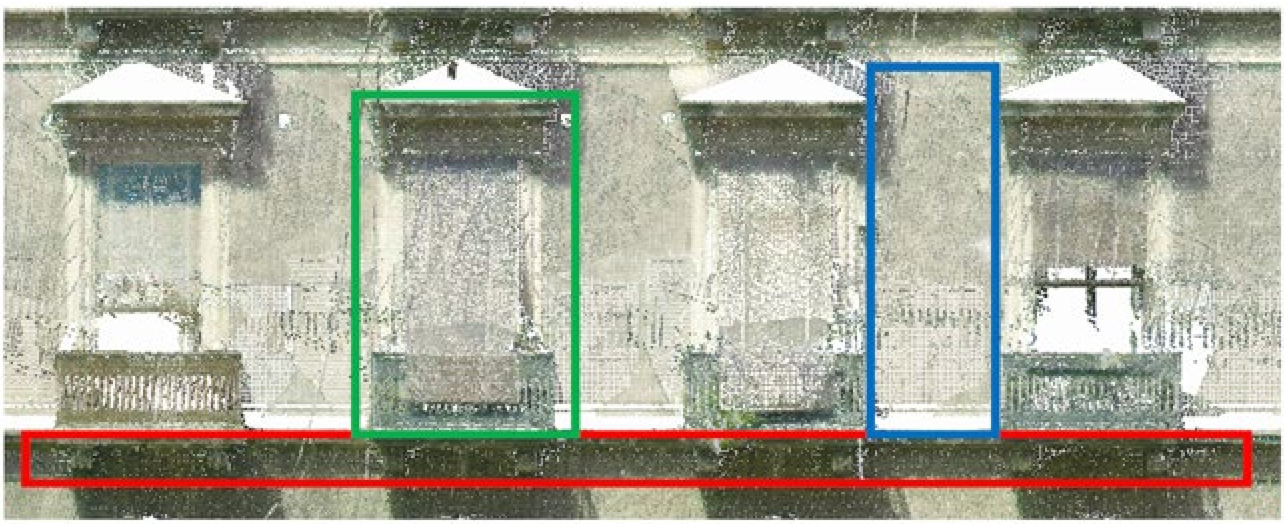


Fig. 45 | *Classes of object defined for Machine Learning training: walls (in blue), openings (in green) and string courses (in red).*

The next step was the manual annotation of some random portions of the cloud. It should be pointed out that the definition of openings appears difficult since in many cases the openings themselves are occluded by shading systems and the presence or absence of glass can lead to uncertain classification. Therefore, taking into consideration the final objective which is the structural analysis, a safer and more effective choice was made. The stone frame and balcony (absent only on the ground floor where there are several data gaps) were also considered openings (fig). Once this was established, two datasets were annotated: one for training the Machine Learning system and the other for validating the result. The open-source software CloudCompare was used to carry out the annotation and any treatment of the point cloud at this stage. The geometric features extracted for each point and used for training are the following:

- Roughness (0.2m);
- Verticality (0.1m);
- Omnivariance (0.1m);
- Coordinate Z;

- Height from the ground (since the entire city block is not perfectly planar);
- Planarity (0.2m);
- Planarity (0.5m);
- Mean Curvature (0.2m)

Below an image of the training dataset is shown (fig. 46). In this case, the training dataset counts 2.057.924 points which means around 1/10 of the entire dataset. This ratio is due to the fact that currently there are no training datasets already available of architectures that match the architectural features of the historical center of Catania. Nevertheless, this first training dataset could be reused in the future in other similar city blocks in Catania in order to speed up, even more, the procedure here described.

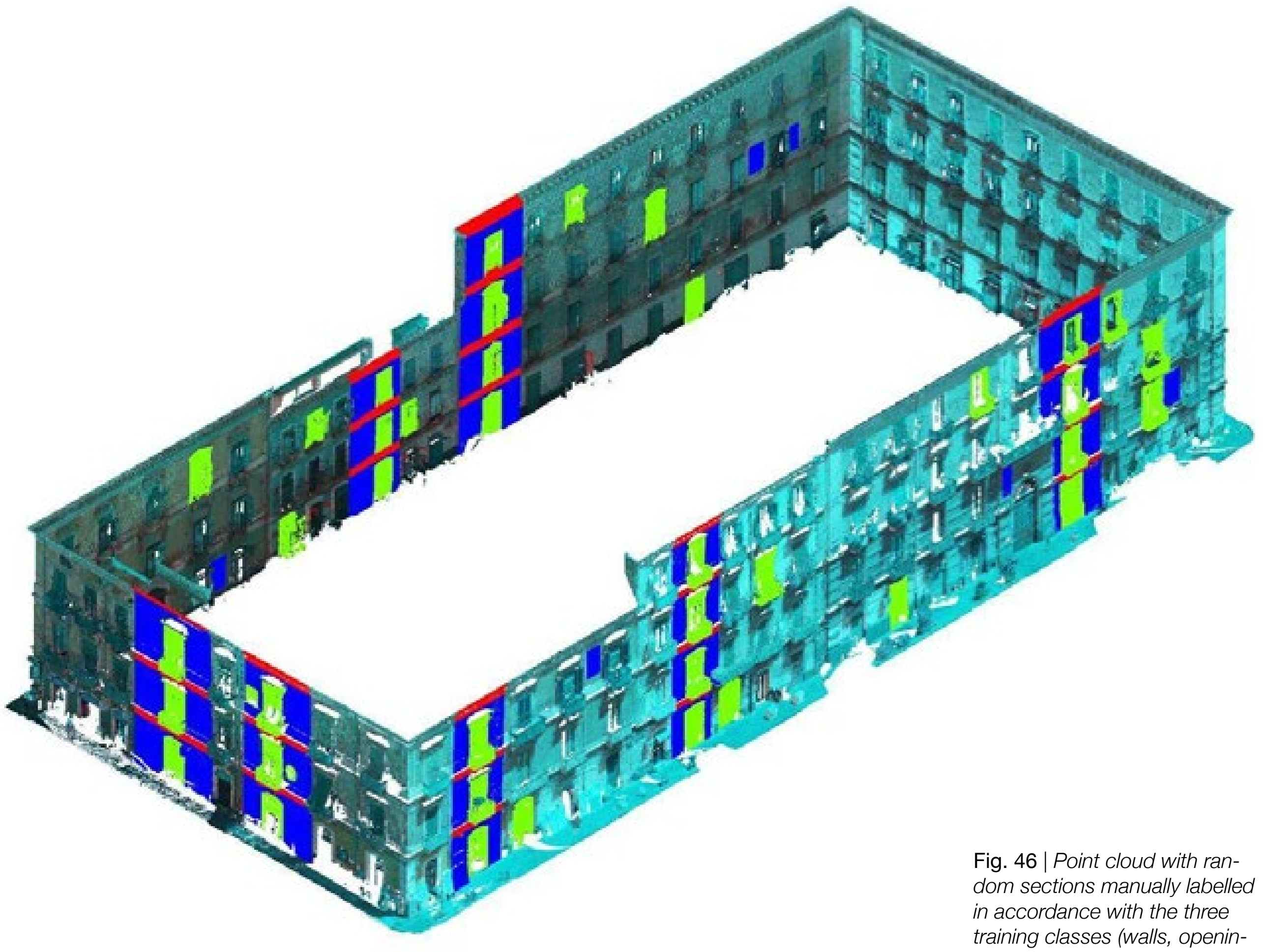
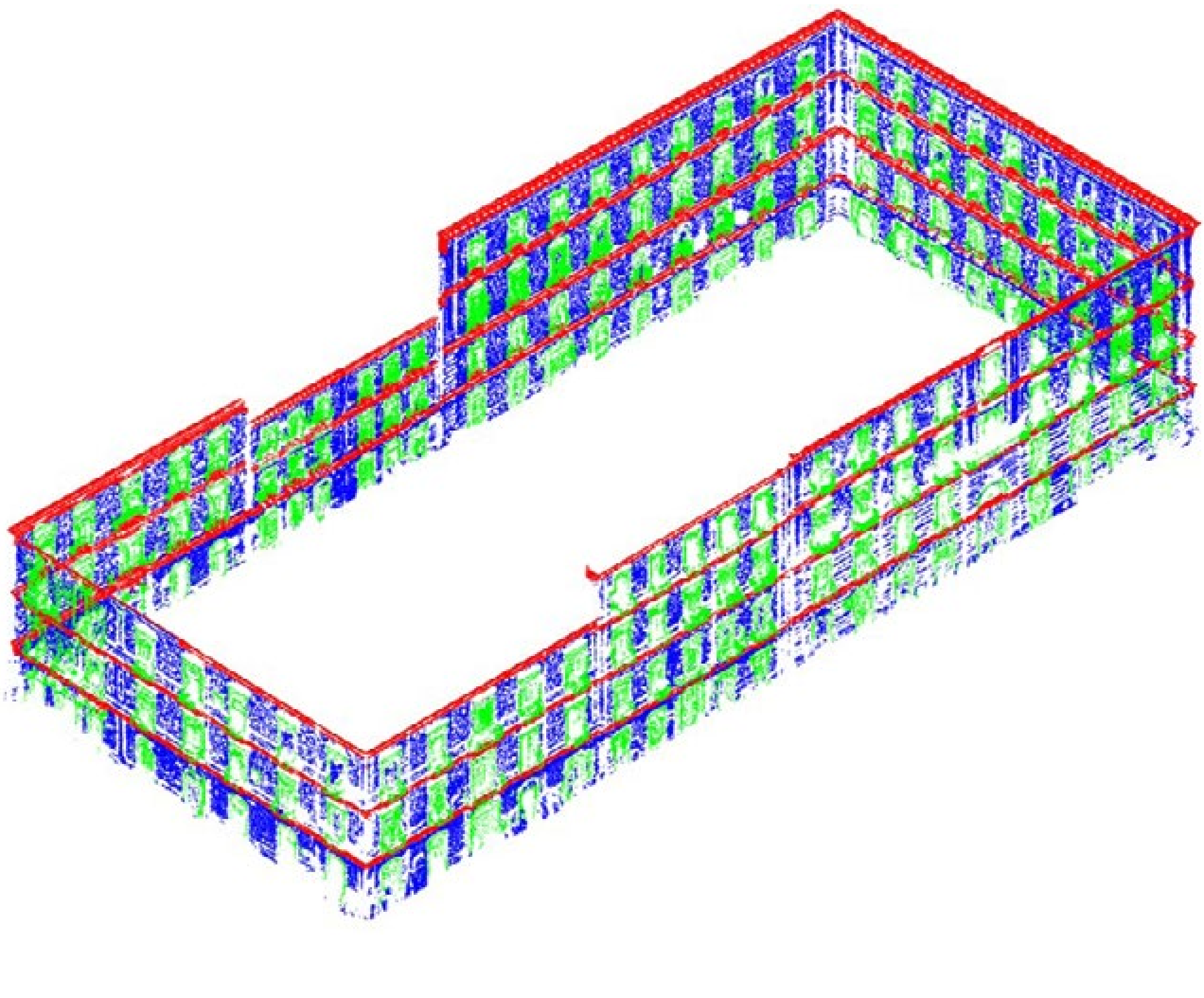


Fig. 46 | *Point cloud with random sections manually labelled in accordance with the three training classes (walls, openings, string courses).*

Finally, after 99.7 seconds required to train the algorithm, the cloud was classified with an overall accuracy of 0.84 and an average F1 score of 0.84. An image of the classified cloud and tables regarding the confusion matrix and result statistics extracted by the algorithm are shown below (fig. 47, tab. 4).

Fig. 47 | *City block point cloud classified.*



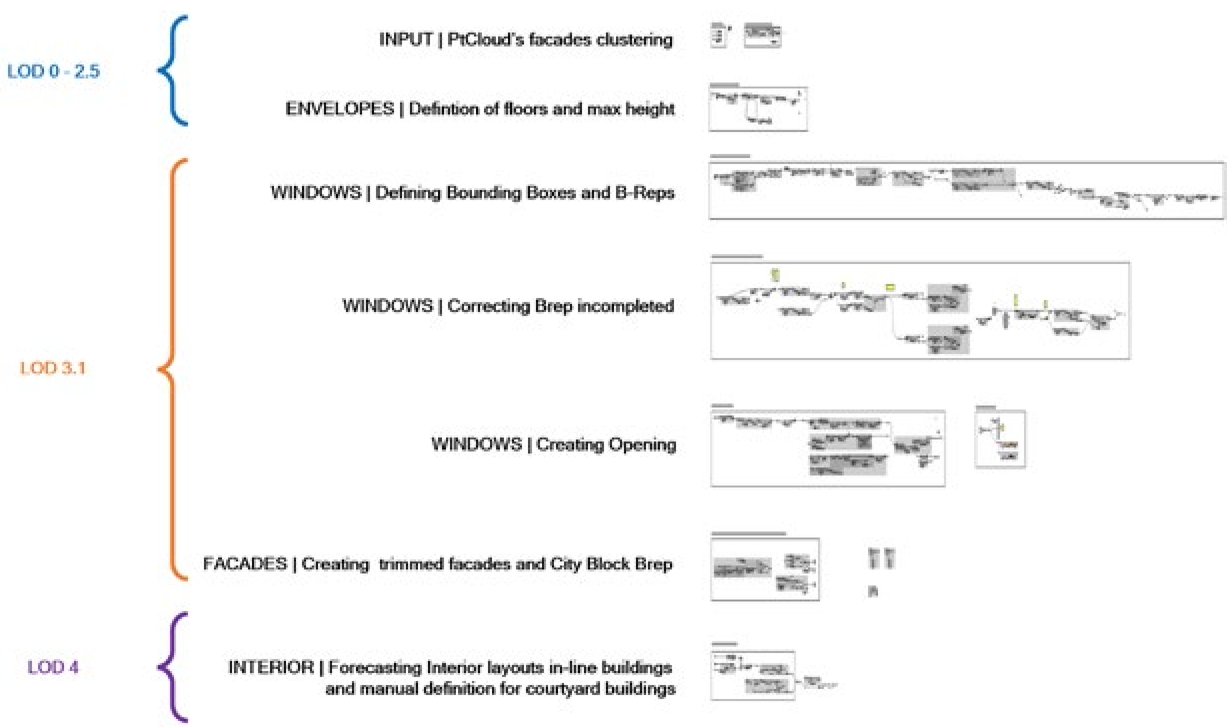
Class	Walls	Openings	String Courses	Precision	Recall	F1 Scores	IoU
Walls	270925	63866	12133	0.9162	0.7809	0.8432	0.7289
Openings	19674	172616	925	0.7186	0.8934	0.7965	0.6618
String Courses	5100	3738	112485	0.896	0.9272	0.9113	0.8371
			Average	84%	87%	85%	74%
			Weighted	85%	84%	84%	73%

Tab. 4 | *Confusion Matrix and results using eight geometric features.*

At this stage, the three classes allow the initial cloud to be subdivided into three different point clouds, each one for a different class. Generally, the point clouds for each class should be further subdivided into the individual entities they describe. This operation is known as instance segmentation. However, this operation was not carried out within CloudCompare but within Grasshopper thanks to the Cockroach plugin that allows the import and processing of point clouds within Grasshopper.

Then, the three clouds (walls, windows and string courses), together with the ground footprints of the block obtained from the cartography, become the input data of the VPL algorithm that allows the generation of the CIM model within Grasshopper (fig. 48).

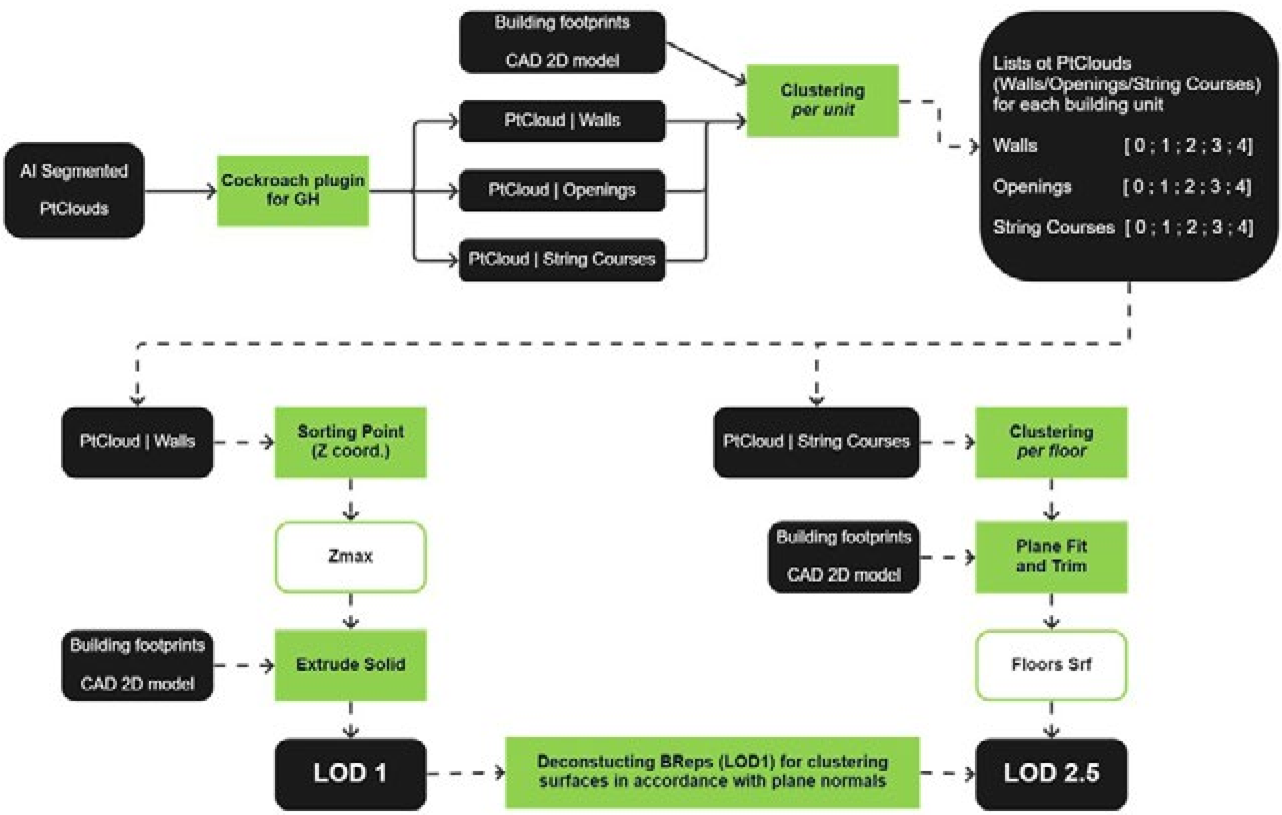
Fig. 48 | *Scheme of the VPL code and LODs developed in Grasshopper for Scan-to-CIM.*



The VPL algorithm was developed taking into account the specific modeling requirements related to the case study (no survey of summit parts: LOD 3.1) but still setting steps to allow for modifications if the workflow differs from the case study. Following the general methodology, for this code the reference was the sequence of LODs of CityGML, trying whenever possible to find references in the 16 LODs proposed with CityJSON.

The first part of the code relates to modeling from LOD 0 to 2.5 . First, the three clouds are imported. Using the Cockroach plugin and the different footprints on the ground of each unit, it was possible to subdivide each cloud with respect to the unit it belongs to (facade clustering) in order to develop the geometry with its own semantics. Through the parameterization of the point clouds, it was possible to deconstruct them in order to obtain information such as the eaves height (required for LOD 1) or the position of the intermediate planes to define the floors (LOD 2.5) (fig. 49). In these steps, the semantics have been maintained in such a way that the urban block is the 'parent' and the buildings and individual building components (facades and floors at this stage) are the 'children' and 'grandchildren' (fig. 50, 51).

Fig. 49 | *Conceptual scheme of the VPL code for LOD1 and LOD2.5.*



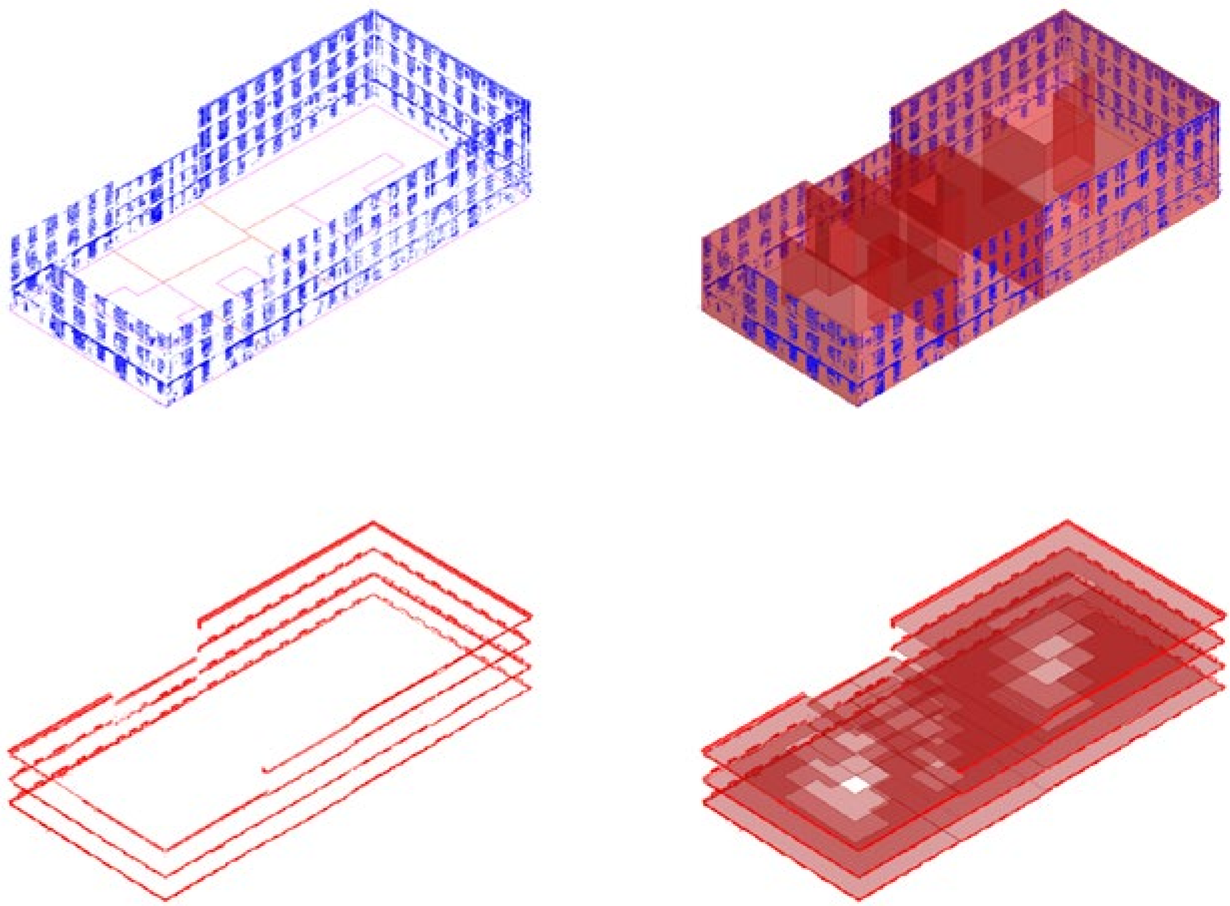


Fig. 50 | *Generation of LOD1 and LOD2.5 using Walls and Strin Courses classified point clouds.*

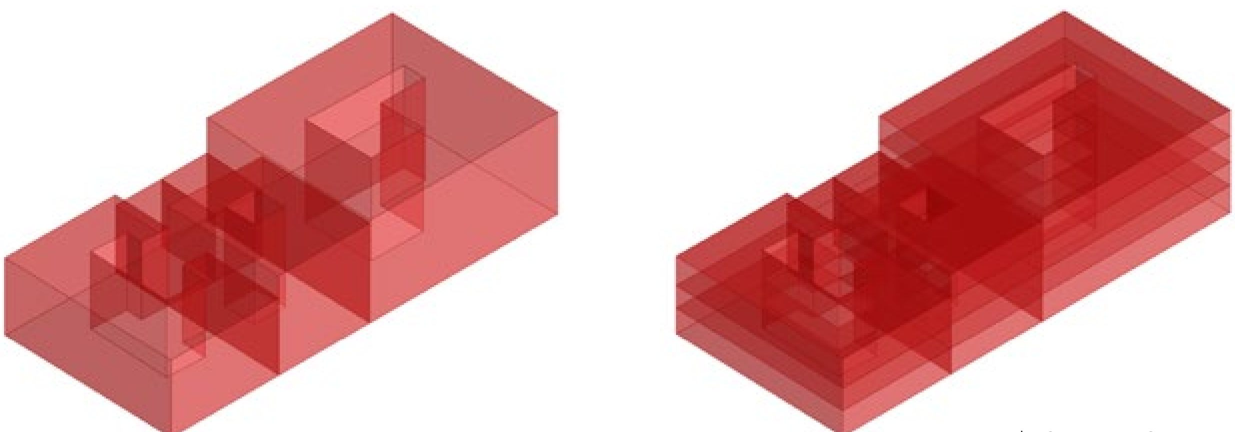


Fig. 51 | *LOD1 and LOD2.5 of the parametric CIM model.*

LOD 3 is then defined. The starting point is the openings cloud, which is subdivided into various units by facade clustering. At this point, each sub-cloud is further subdivided with respect to the reference floor (the creation of the slabs was essential for this operation). After this, the windows are grouped by horizontal bands of openings. Thanks to a clustering algorithm from Cockroach, these sub-clouds can be clustered until the individual windows are obtained. In this way, each window is a separate cloud which is, however, semantically linked to the succession floor - facade - building - city block (fig. 52).

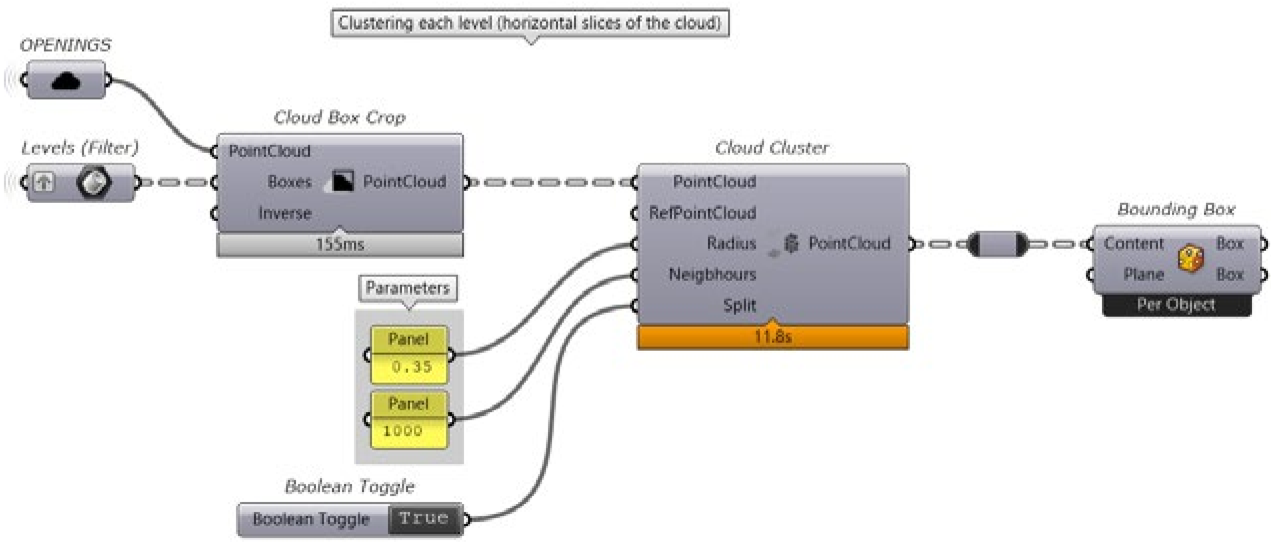


Fig. 52 | *Cockroach clustering components for instance segmentation of the openings cloud. The result is a collection of bounding boxes which define height and width of the openings. Each bounding box is semantically linked with the facade that includes it.*

The objective to be achieved with this clustering is to create a bounding box parallel to the facade in order to obtain a surface with which to trim the facade and thus recreate the opening. However, this process is not without its imperfections. Indeed, the noise present between one opening and the next results in the creation of false bounding boxes that do not correspond to an opening. Another problem with noise is that it can result in a change to the actual size of an opening by creating bounding boxes that are much larger than those required. For this reason, it is essential to clean the clouds of isolated groups of points. For this operation, the SOR (Statistical Outlier Removal) algorithm available as a component of Cockroach was used. Another weak point is the openings on the ground floor, which due to the obstacles present (cars, commercial activities, heavy vehicular traffic) did not allow many openings to be correctly identified during the survey campaign. However, given the extremely regular pattern of openings in the building types under study, it is possible to recreate such openings with an acceptable tolerance considering the urban scale under consideration. Once the openings have been defined, they receive the same semantic structure as the clouds, thus becoming linked to the floor and the facade to which they belong (as well as to the building and the entire city block) (figg. 53, 54).

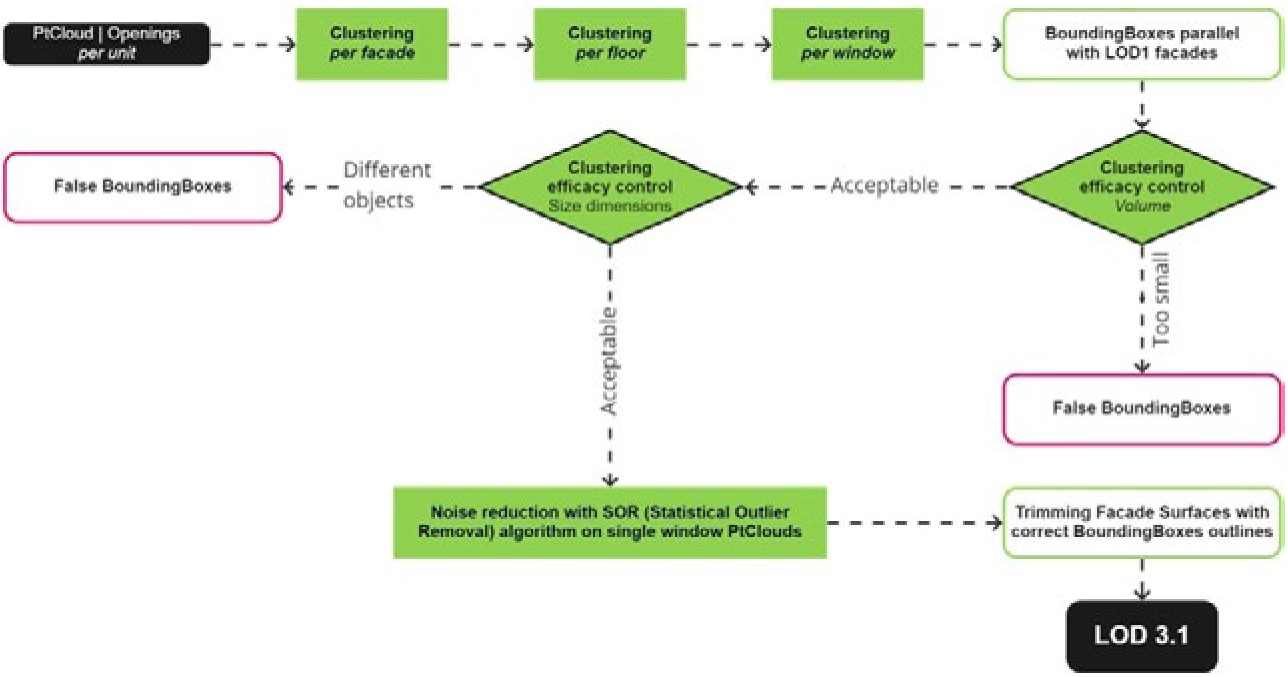


Fig. 53 | *Conceptual scheme of the VPL code for LOD3.1.*

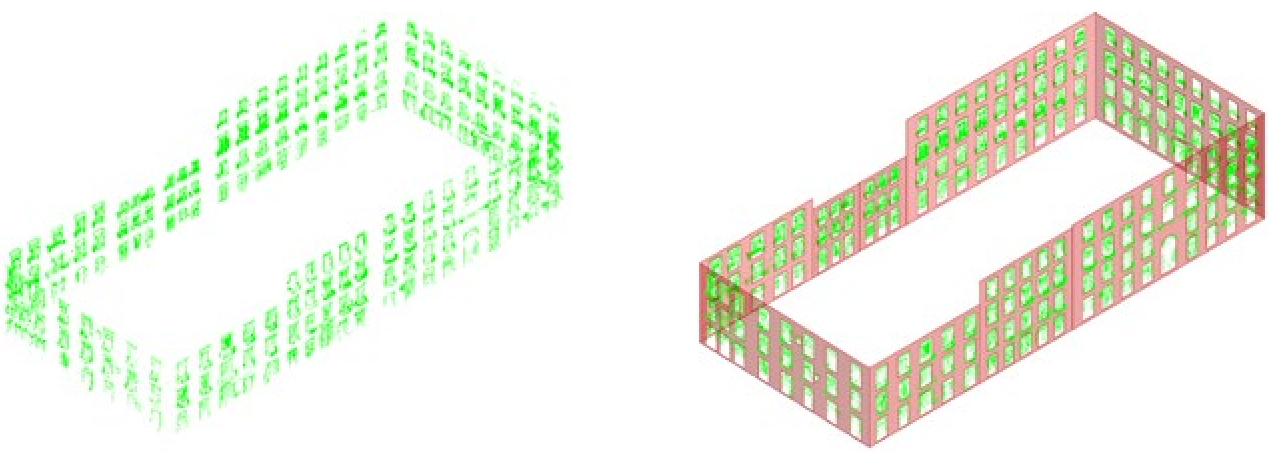


Fig. 54 | *Generation of openings for LOD3.1 after the instance segmentation of the openings classified cloud.*

Each opening, as well as every other component of the CIM model, has an index assigned to it, which also defines its semantic hierarchy. In the case of openings, there are four numbers. The first indicates the building to which it belongs, the second the building facade, the third the floor level, and the last is the specific identifier of the specific opening (figg. 55, 56).

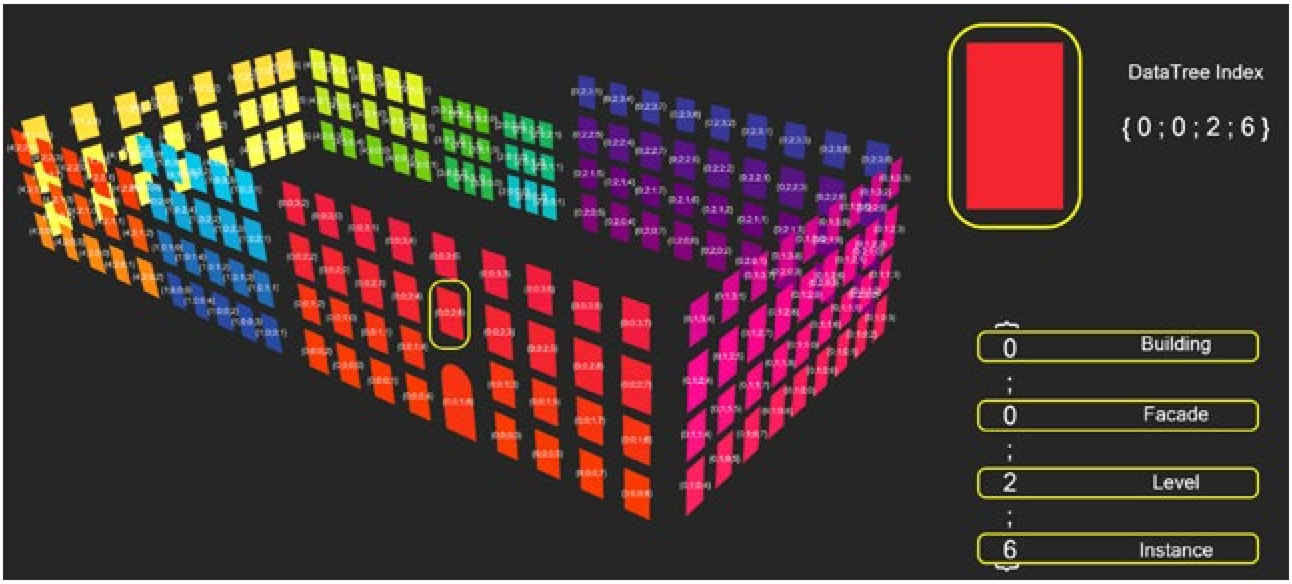


Fig. 55 | *Visualisation of coloured openings in relation to the facade they belong to. Each opening has an individual index describing its semantics thanks to DataTree structure manipolation in Grasshopper.*

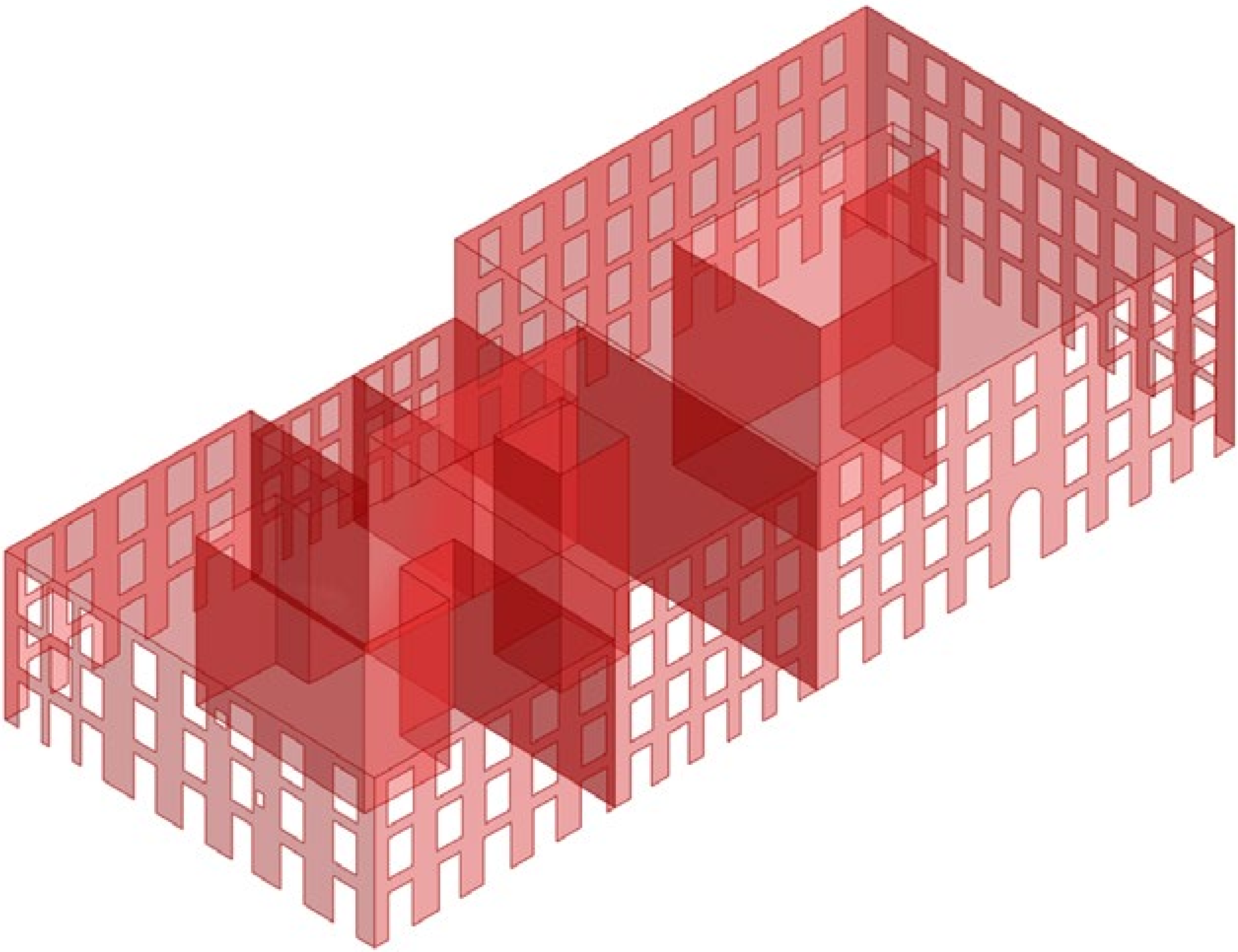


Fig. 56 | *LOD3.1 of the parametric CIM model.*

At this point, an analysis of the accuracy of the reverse modelling operations conducted so far was carried out. This analysis is fundamental since the building footprints obtained from 2D CAD models (made available by the technical office of the municipality of Catania) were considered reliable for generating the CIM model. In addition, this analysis also makes it possible to highlight the presence of surfaces out of the average vertical plane. This information can contribute significantly for understanding the behaviour of the city block in the presence of seismic actions. The analysis conducted computed the distances from the walls point cloud to the CIM model. The choice of the walls point cloud is based upon the fact that it is the one that best represents the envelope of the city block. In particular, a 20 cm range was considered from the facades generated for LOD3.1 in order to ensure the most reliable analysis in accordance with the point cloud selected. To evaluate the results, the point cloud was coloured with a colour gradient representing the distances. In addition, the percentages of points included and their average deviation in the intervals considered were calculated.

A visual analysis of the results shows that the largest deviations occur in the areas where there are the majority of moldings. In addition, the non-linearity of the facades is also evident, especially near the north-east corner of the city block. However, the facade areas without moldings show acceptable levels of deviation (under 10 cm) (fig. 57). The analysis made it possible to calculate the percentage of points included and the average deviation in two ranges (+/- 10 and 20 cm). In the +/- 20 cm range, 92% of the total points are contained with an average deviation of 2.2 cm, while in the +/- 10 cm range, 80% of the total points are contained with an average deviation of 2.1 cm (tab. 5). Given the urban scale of the model, these values are acceptable with respect to the CIM purpose of this thesis work.

Tab. 5 | *Point include and average deviation values of the Cloud-to-Mesh analysis.*

Range Cloud-to-Mesh	+/- 20 cm	+/- 10 cm
Points included	92%	80%
Average Deviation	2.2 cm	2.1 cm

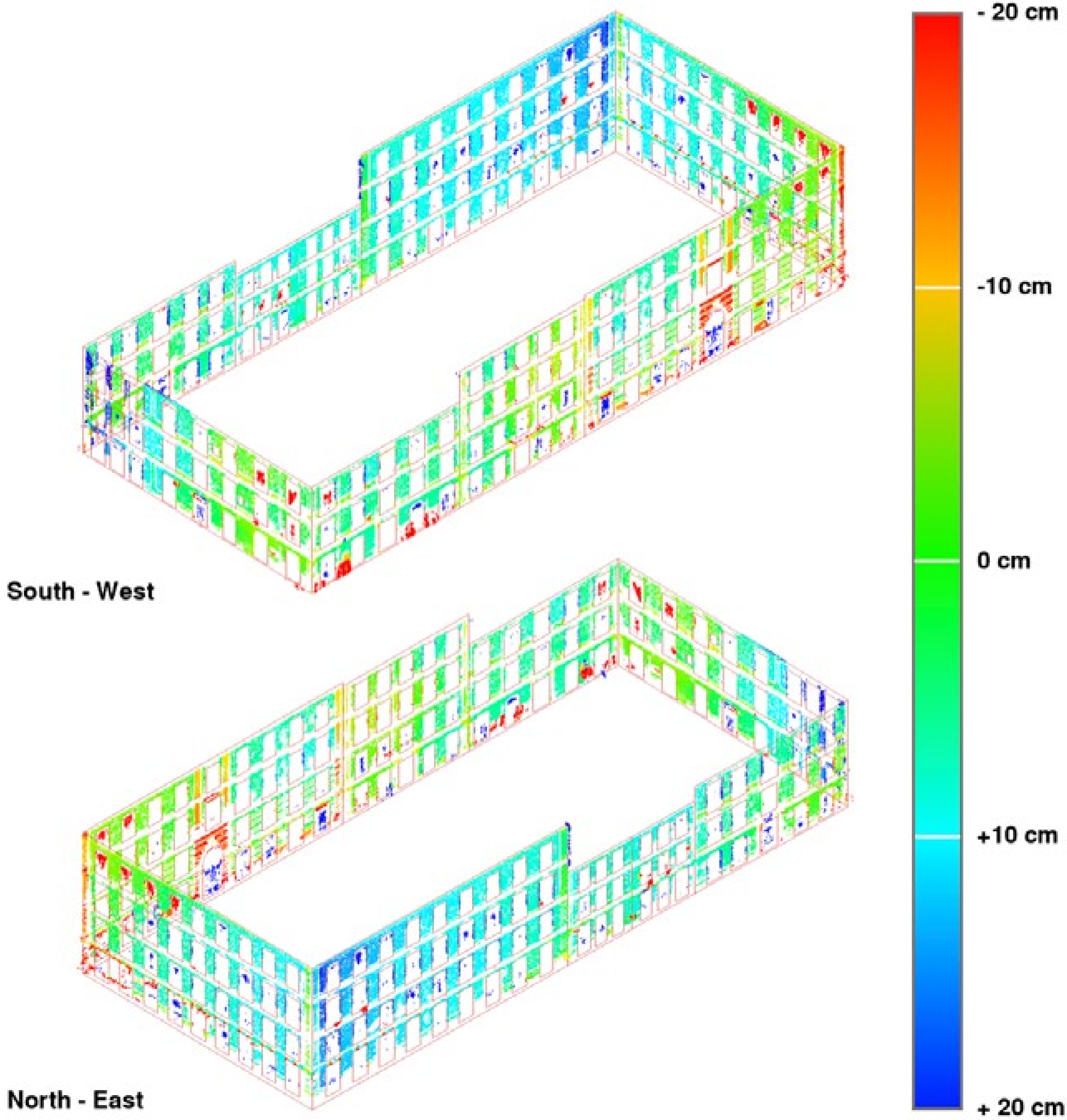
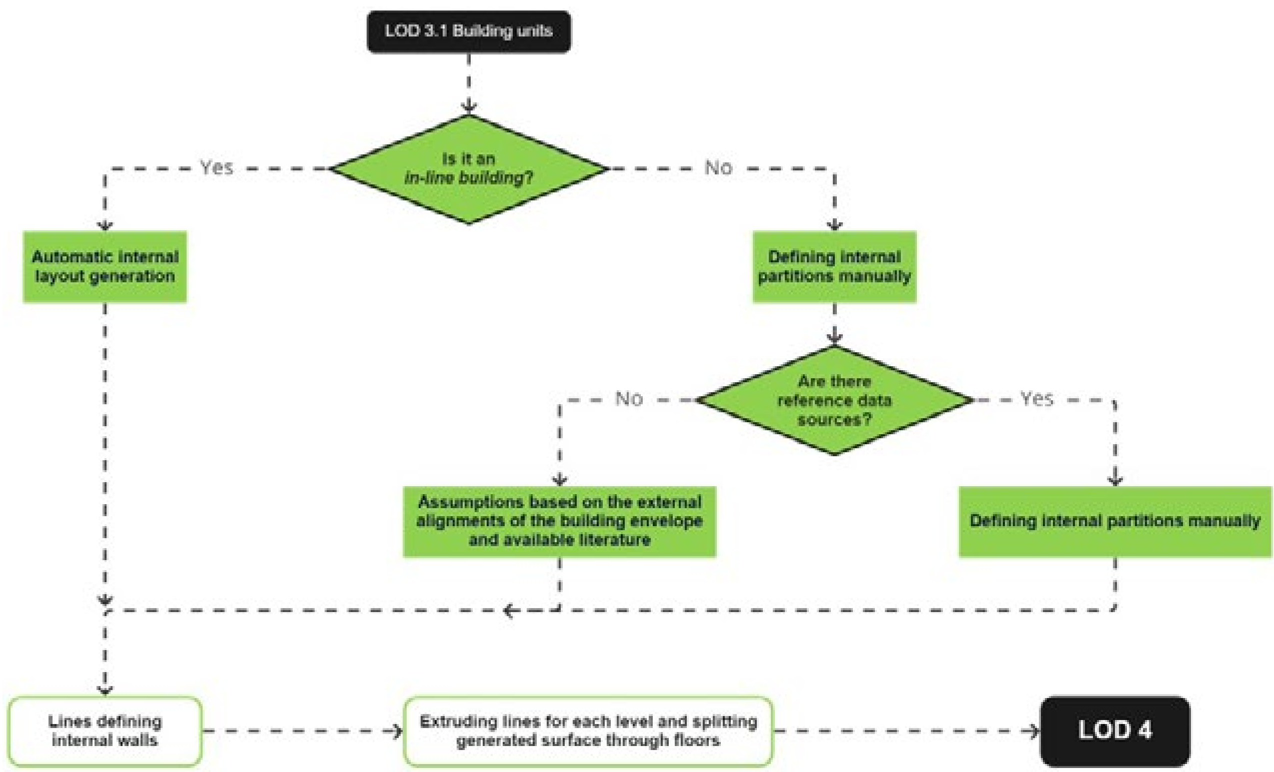


Fig. 57 | *Cloud-to-Mesh accuracy analysis of the 'walls point cloud' with the LOD3.1 surfaces (range of +/- 20 cm).*

Finally, the subject of LOD 4 (interior) was approached. Two approaches were taken here. For in-line buildings, the distribution of interior spaces is widely discussed in the literature and due to the simplicity of the configuration of these buildings, it is possible to automate the creation of interior partitions relevant for the structure. On the other hand, concerning buildings with open and closed courtyards, their internal configuration is very complex to predict using rule-based algorithms. In addition, the example configurations found in the literature appear to oversimplify in comparison to real conditions where urban morphologies always determine different configurations. For these reasons, it was decided to identify the internal partitions manually on the model. The modelling of these partitions is based on collected material where possible, while where there is no source it was assumed on the basis of external observation of the building configuration. As in Fleri's application (section 4.1.1), the different degrees of reliability of the data were noted for the subsequent information enrichment phase of the geometries (figg. 58 - 60).

Fig. 58 | *Conceptual scheme of the VPL code for LOD4.*



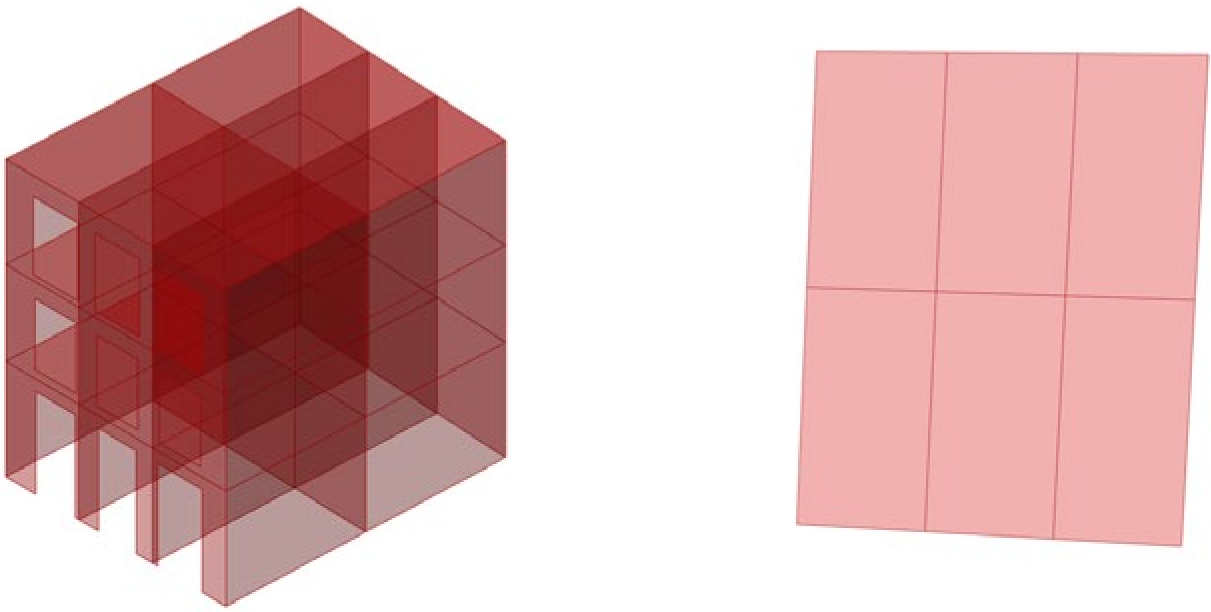


Fig. 59 | *LOD3.1 of the parametric CIM model.*

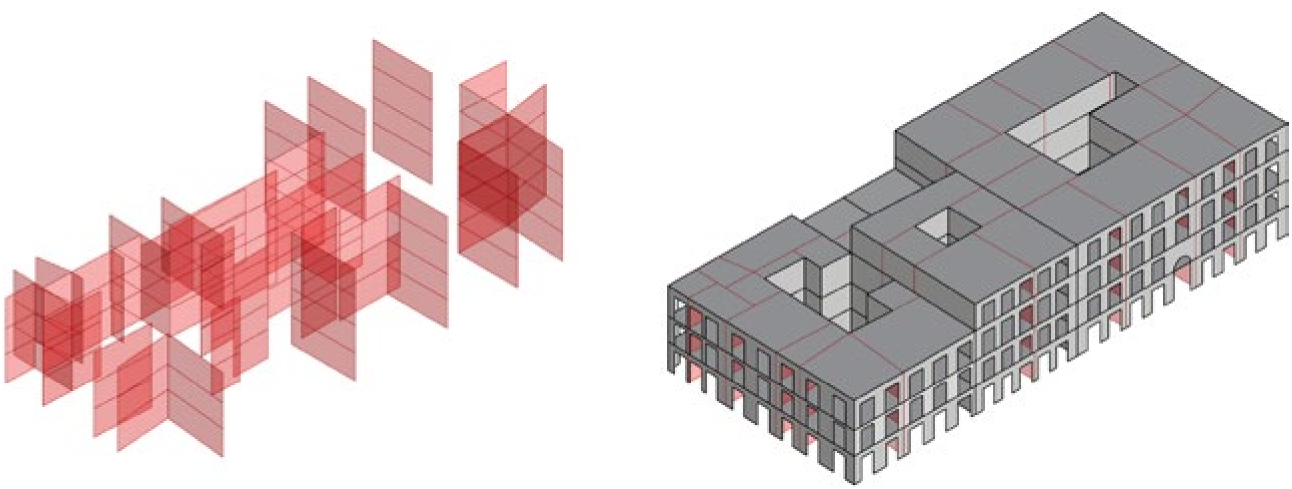


Fig. 60 | *Internal partitions (left) and LOD4 model with internal partitions highlighted.*

At this point, the CIM model is geometrically and semantically complete. The entire code produces the presented model in 21.5 seconds. The total size of the Grasshopper file is approximately 7 Mb. The total size of the clouds, after filtering and cleaning operations, is approximately 15 Mb. It should be noted that in addition to the model at LOD 4, the code also produces the same model at smaller details (LOD 3, 2, 1, 0), so it is possible to choose which model to handle according to project needs (figg. 61, 62).

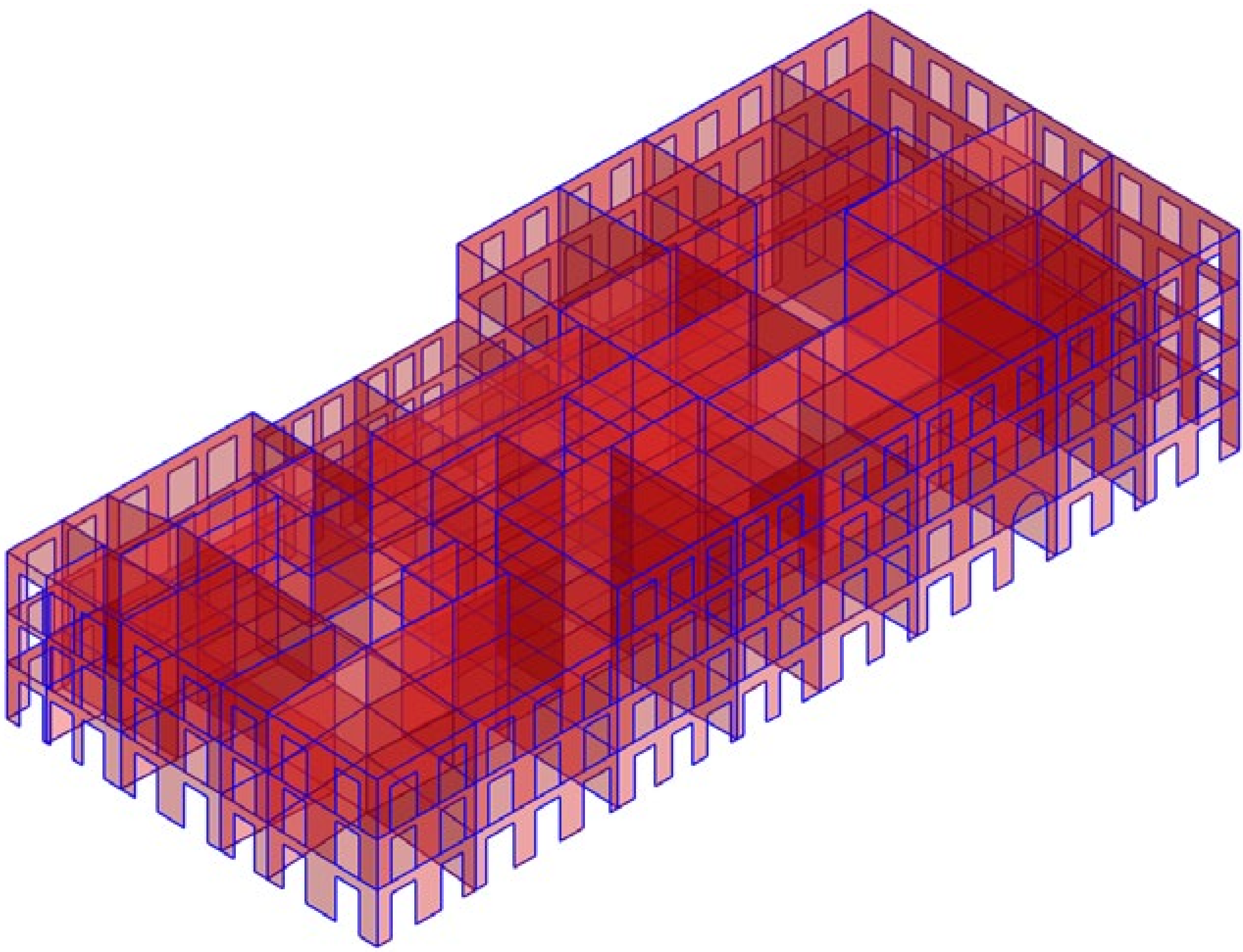


Fig. 61 | *Parametric CIM model at LOD4 (edges in blue to improve visual readability).*

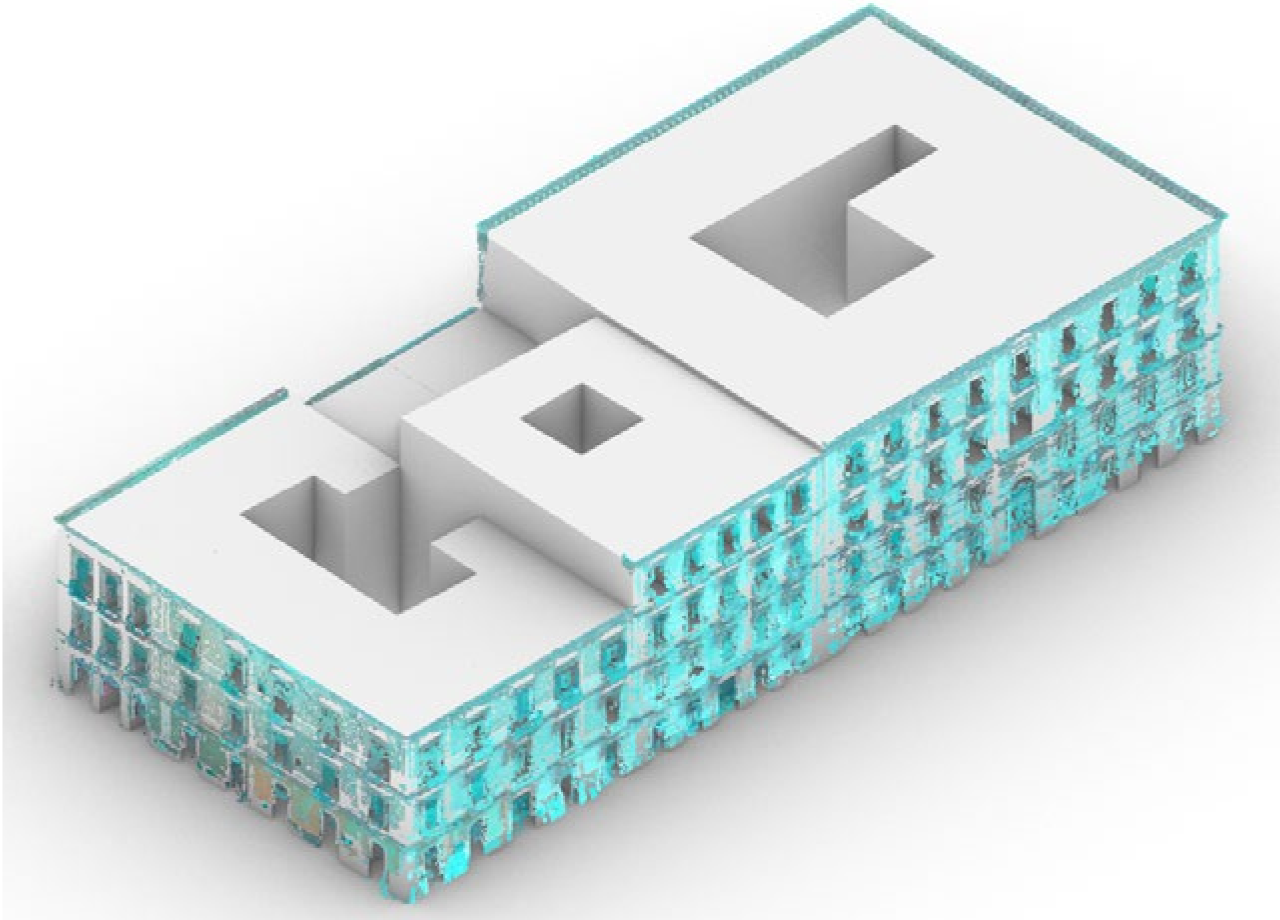


Fig. 62 | *Parametric CIM model with the original point cloud overlapped.*

The CIM model obtained, even if accurate in relation to the point clouds acquired in situ, contains several small misalignments of planes and levels (fig. 63, edges and corners highlighted in red) that invalidate the discretization process aimed at FEM analysis. For this reason, a section of the developed VPL code is dedicated to resolving these shortcomings by returning a model as linear as possible within a user-defined tolerance. In this case study, the tolerance was defined at 50 cm, so all adjacent elements with distances shorter than 50 cm were automatically aligned (fig. 63, aligned elements highlighted in blue).

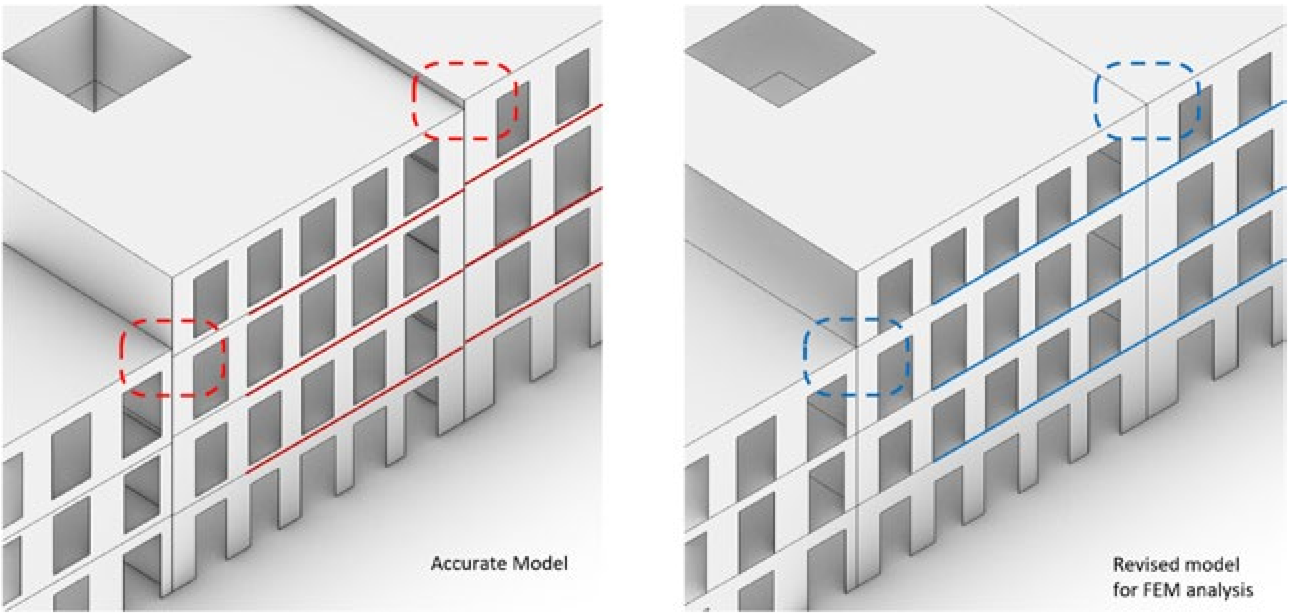


Fig. 63 | *Comparison of the CIM model obtained from point clouds with several inaccuracies unsuitable for FEM analysis software (left), and revised model for FEM analysis (right).*

Finally, a second algorithm was developed to handle the transition of the CIM model to structural geometric models for FEM analysis. The method applied is the same as that presented in the previous application (section 4.2.2) and consists of the possibility of exporting the geometric model either as a quandrangular/triangular mesh (fig. 64) or directly as a NURBS model. Since the analysis will deal with an urban scale, the absence of the roof geometries is not relevan with reference to the mechanisms analysed. However, as future development, for further analysis more in detail the roof geometries should be included.

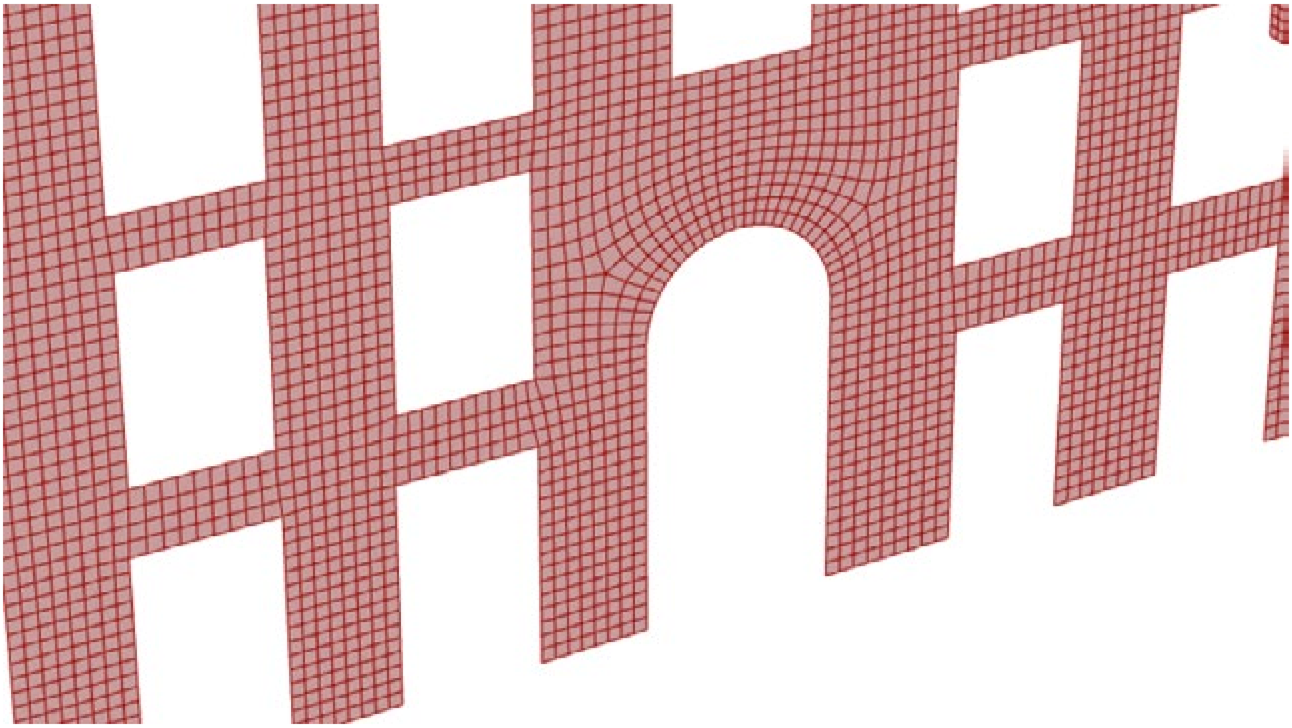


Fig. 64 | *Example of a portion of the CIM model after the discretization in quad-mesh. In this example, it can be seen how even curved openings are effectively handled by the mesh algorithm.*

Again, the same test analysis environments were used as in the previous application. In particular, an initial attempt was made on only one of the buildings on the line due to the simplicity of their configuration. A principal mode analysis was performed on this model to check whether, with the exception of the direction, the cinematics of the model were the same in the different analysis software considered (fig. 65). Afterwards, the entire model of the urban block under analysis was exported in the same environments (fig. 66) and verified by performing a modal analysis as well (figg. 67, 68).

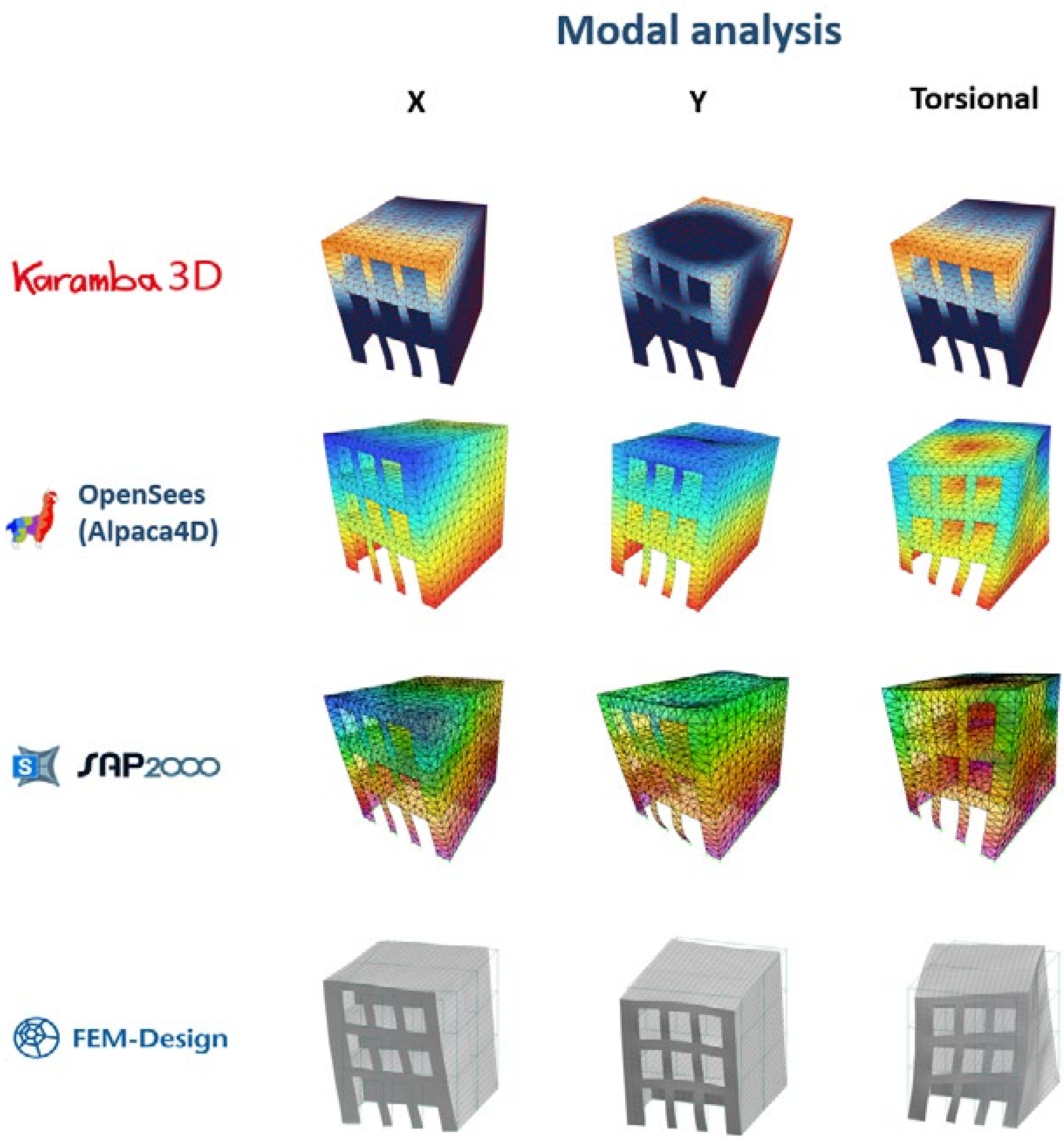


Fig. 65 | *Modal analysis of a building unit coming from the parametric CIM model.*

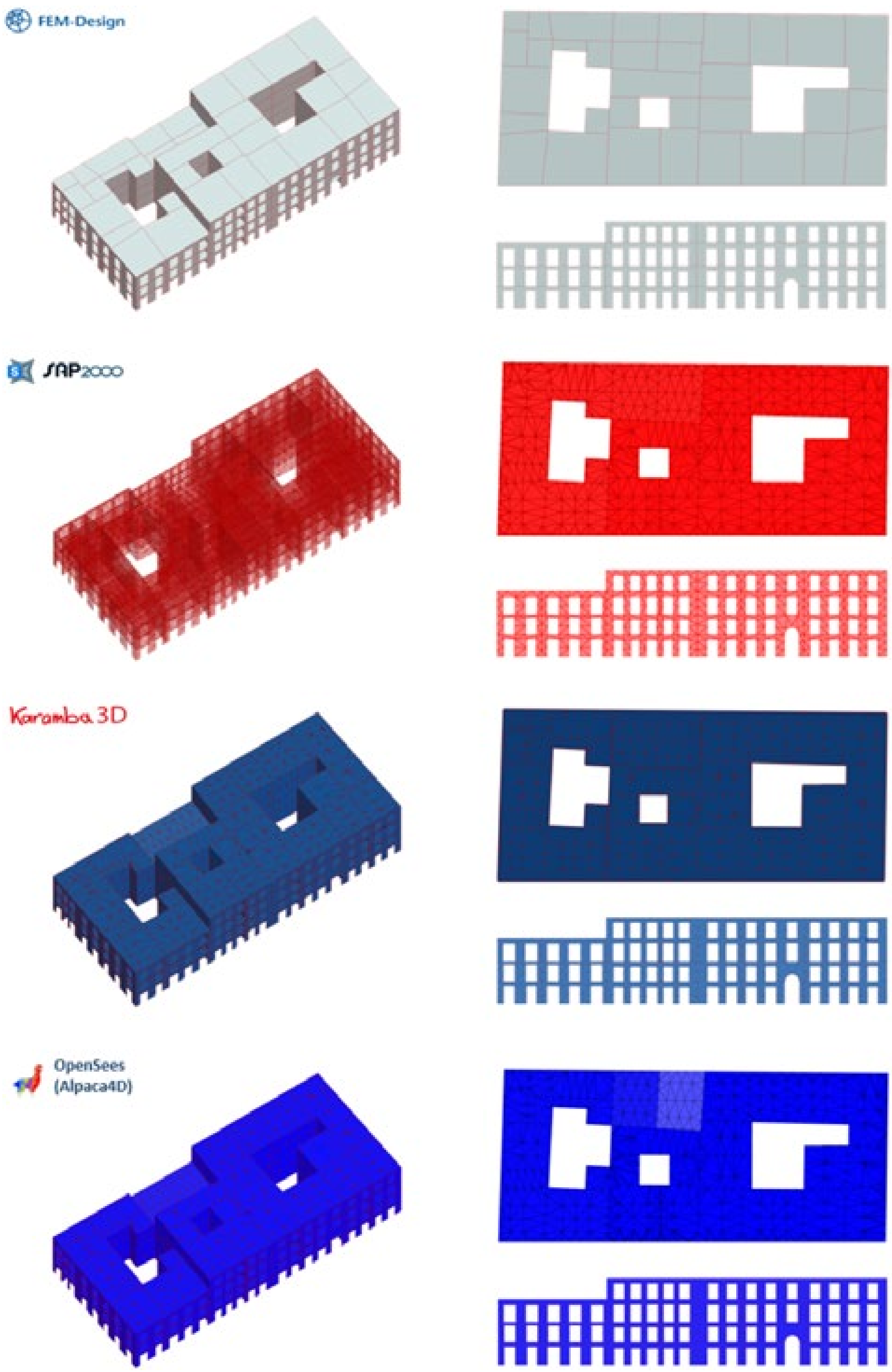


Fig. 66 | *Isometric, top and front view of the geometrical structural model for FEM analysis in (from top to bottom): FEM-Design, SAP2000, Karamba3D and Alapaca4D (OpenSees).*

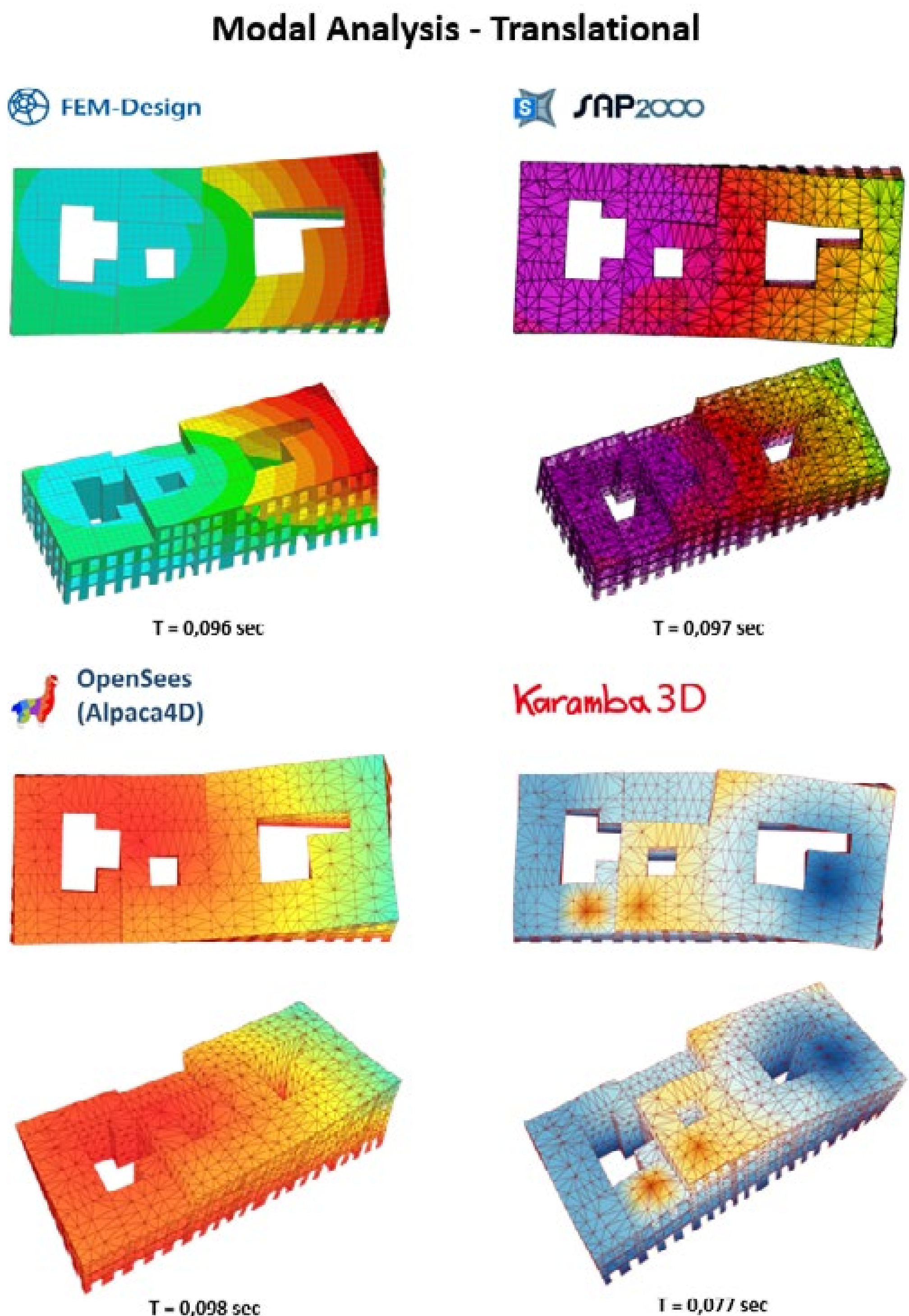


Fig. 67 | *Modal analysis (translational) of the whole city blokc coming from the parametric CIM model.*

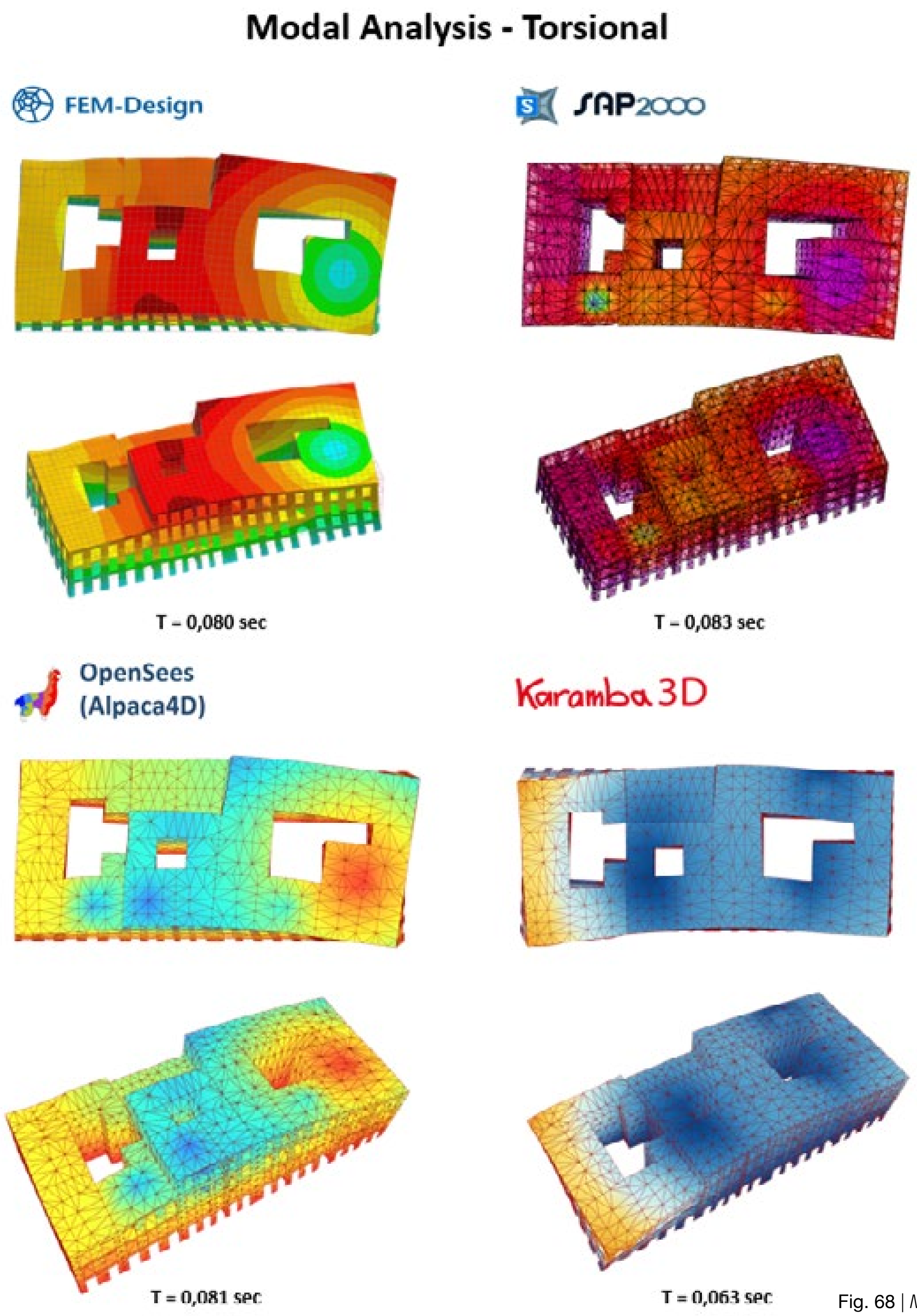


Fig. 68 | *Modal analysis (torsional) of the whole city blokc coming from the parametric CIM model.*

4.3 A proposal for a parametric 3D city models format: CityGH

The applications presented in the scenarios of smaller and larger urban centres (sections 4.1 and 4.2) have often focused on the problems of surveying and modelling. However, of equal importance is the question of the semantics of the 3D city model represented in these parametric City Information Models. Indeed, although the parametric VPL environment allows for maximum flexibility, the exchange of the data produced and the management of information within all geometries is central to the diffusion of a common work pipeline in both the academic and industrial fields, which through the use of standards and conventions enables the development of plug-ins for reading and writing 3D city models.

As already discussed in the Background chapter (see section 2.4.1), currently in the field of formats for the dissemination of 3D city models, CityJSON format is gaining popularity due to its simple structure and ease of development within various programming environments. Unfortunately, in the parametric domain, although there is a large use of Grasshopper and other VPLs for spatial and urban modelling, there is still no format to unify all the experiences conducted and to facilitate interoperability. Therefore, 3D city models in the parametric context are developed through different methods depending on the modeller's skills, but their utilisation stops at these individual applications. The alternative is to fall back on a format linked to the BIM or GIS sphere, thus vanishing the efforts to adopt a holistic approach offered by City Information Modelling.

The aim of the work presented in this section is to create a comprehensive modelling workflow that at the same time enables the information enrichment of the different geometric components within the CIM model and also normalises the semantic structure of the entire CIM model by creating a structure similar to that of CityJSON but applying the Grasshopper data structure. This operation is essential to manage and quickly access all the information from the material collected during the survey phases in order to convey all the useful information for structural analysis such as construction period, material, construction technique, thicknesses, etc.

The data structure of CityJSON provides for two types of objects, first- and second-level CityObjects. Second-level CityObjects belong to the first-level ones. In addition, a first-level CityObject called CityObjectGroup can be used as 'containers' of first-level CityObjects (useful when clustering to indicate a specific aggregate) (fig. 69).

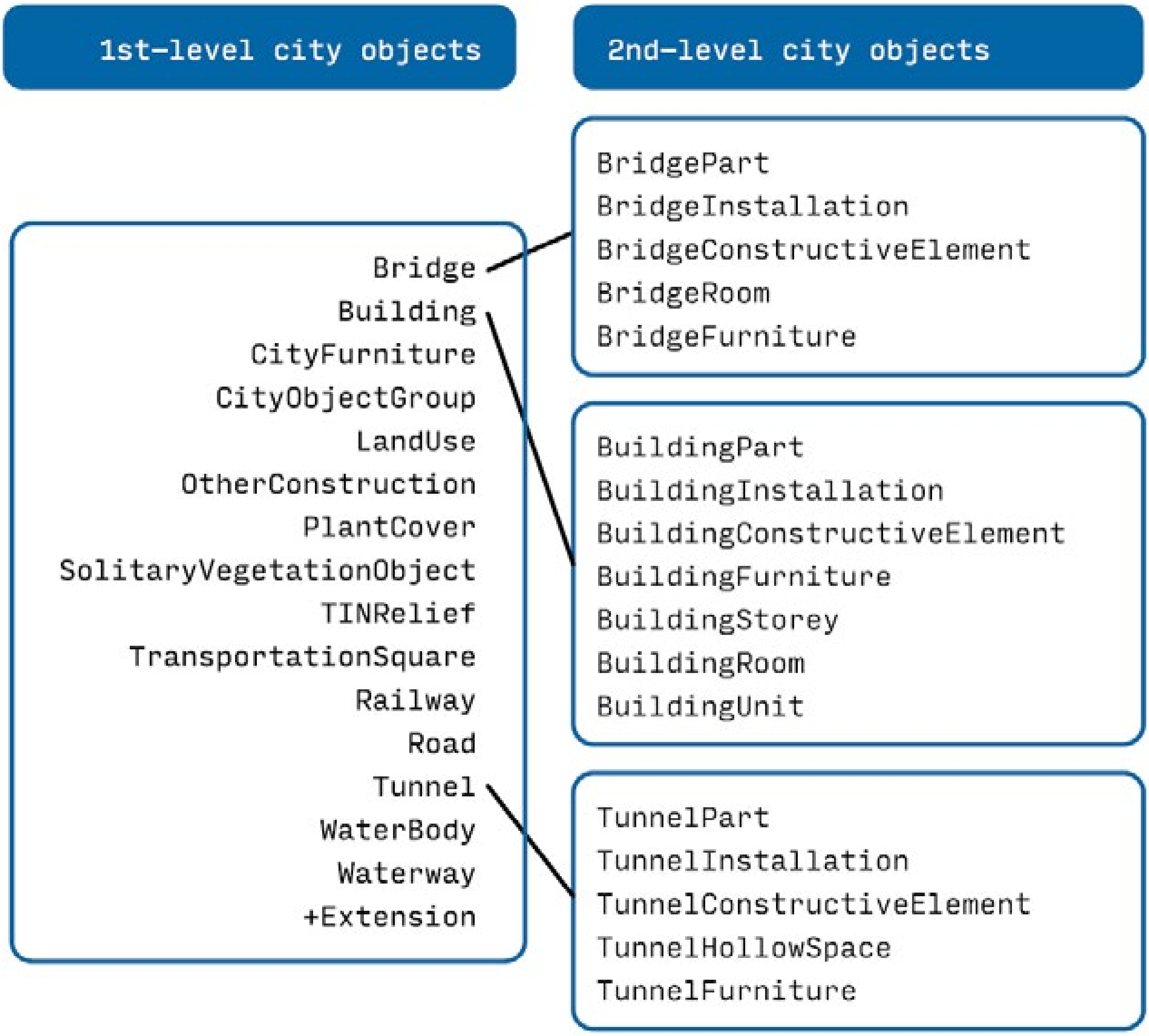


Fig. 69 | *Hierarchical structure of CityObjects in CityJSON. Source: Arroyo Ohori et al., 2022.*

In this work, a prototype plugin for Grasshopper was realised, which allows the creation of first- and second-level objects and from their combination to obtain a file which, by analogy with CityJSON (specifically, version 1.12), was named *CityGH*.

In CityJSON, first-level CityObjects are data dictionaries that contain within them all the second-level CityObjects that belong to them. It is therefore a nesting of dictionaries on several levels. Below is an example of a first-level CityObject (Building) containing related second-level CityObjects (fig. 70).

```
"CityObjects": {
  "id-1": {
    "type": "Building",
    "attributes": {...},
    "children": ["id-2", "id-3"],
    "geometry": [{...}]
  },
  "id-2": {
    "type": "BuildingPart",
    "parents": ["id-1"],
    "geometry": [{...}]
    ...
  },
  "id-3": {
    "type": "BuildingPart",
    "parents": ["id-1"],
    "geometry": [{...}]
    ...
  }
}
```

Fig. 70 | *Example of a first-level CityObject (Building) containing related second-level CityObjects. Source: Arroyo Ohori et al., 2022.*

Multiple first-level CityObjects are all contained in the main top-level dictionary which is constituted by the CityJSON file. Below an example of complete but empty CityJSON object (fig. 71). The value of “CityObject” is a list of dictionaries each one of them represents a specific CityObject of 1st level.

```
{
  "type": "CityJSON",
  "version": "1.1",
  "extensions": {},
  "transform": {
    "scale": [1.0, 1.0, 1.0],
    "translate": [0.0, 0.0, 0.0]
  },
  "metadata": {},
  "CityObjects": {},
  "vertices": [],
  "appearance": {},
  "geometry-templates": {}
}
```

Fig. 71 | *Example of a complete but empty CityJSON file. Source: Arroyo Ohori et al., 2022.*

As can be seen from the examples shown, CityObjects present in their structure initially values that refer to attributes or metadata such as: "type" (indicating the type of CityObject), "attributes" (consisting of a user-customised dictionary that allows all the desired attributes to be collected), "parents" and "children" (indicating the semantic relationships between objects), “lod” (which shows the LOD or LODS used as reference for the geometries stored), etc. The last element is always the geometry, which is represented by means of a list of vertex ids collected in the CityJSON object, thus allowing geometries to be transformed into text according to the OBJ format. It is noteworthy that the name of the individual object that is stored by the key 'id' is up to the user.

The prototype currently provides two component types that allow the creation of any type of first- and second-level CityObject. Depending on the specification of the object, these components can be changed by means of a series of input lists and sliders that allow the CityObject type to be changed quickly. The function of the components for level 1 and level 2 is the same. They collect the input data reflecting the order of the key-value pairs described in the CityJSON specification and organise them in the data lists in Grasshopper. For the purpose of the application, the CIM urban block model described in section 4.2.3 was used. Below is an image of the developed VPL code (fig. 72).

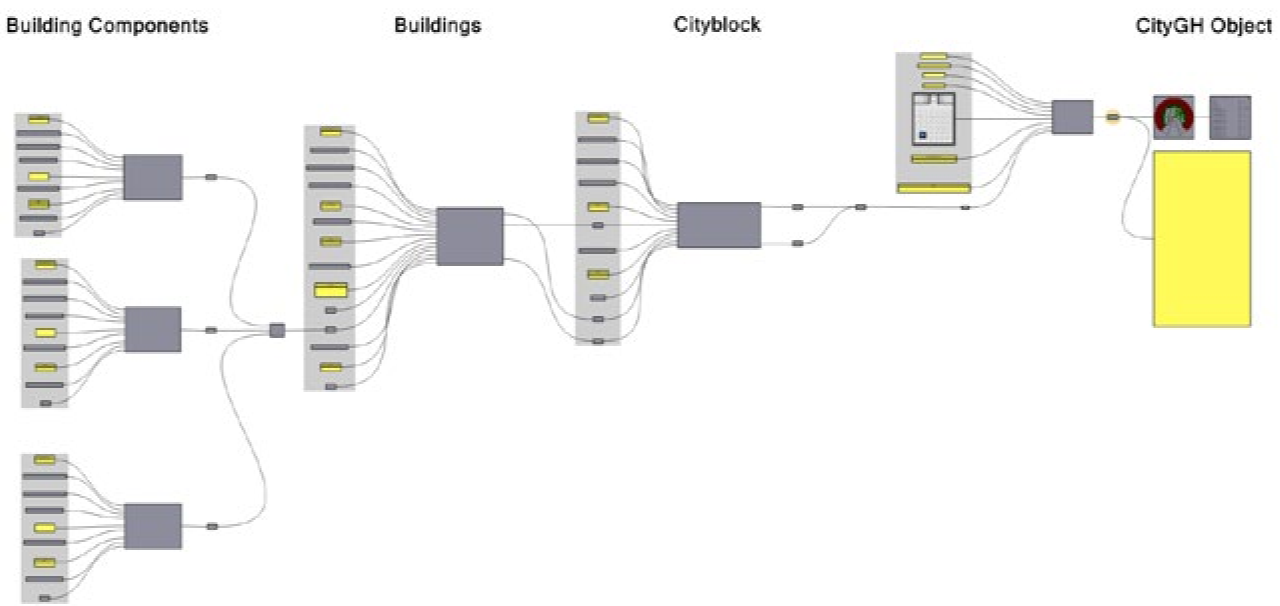


Fig. 72 | *VPL code developed in Grasshopper for the application of CityGH to the CIM model of the urban block in the case study (section 4.2.2).*

Compared to the structure of CityJSON, there are two main differences in the CityGH proposal. The first one relates to the geometries, as this format is currently designed for passing 3D city models within Grasshopper, therefore a system for deconstructing geometries has not been developed. The geometries in each list created (corresponding to a CityObject) are stored as the last item in the list and correspond to the types of geometries allowed by Grassopper (curves, surfaces, buondary representations, etc.). The second difference concerns the naming of the individual CityObject. In CityJSON it is chosen freely by the user, whereas in CityGH the id is taken from the index path generated by Grasshopper and is appropriately manipulated to have an identification code which, through the semantics of Grasshopper, allows an exhaustive description of the semantics and type of the CityObject created.

The application starts with the construction of second-level CityObjects concerning three types of building components: interior walls, floors and windows. The inputs were defined in accordance with the specifications according to CityJSON 1.1.2. In addition, it is required to enter the code of the block intended to take a part in the nomenclature. The geometries are inserted taking into account the semantic subdivision highlighted in section 4.2.3 (fig. 73).

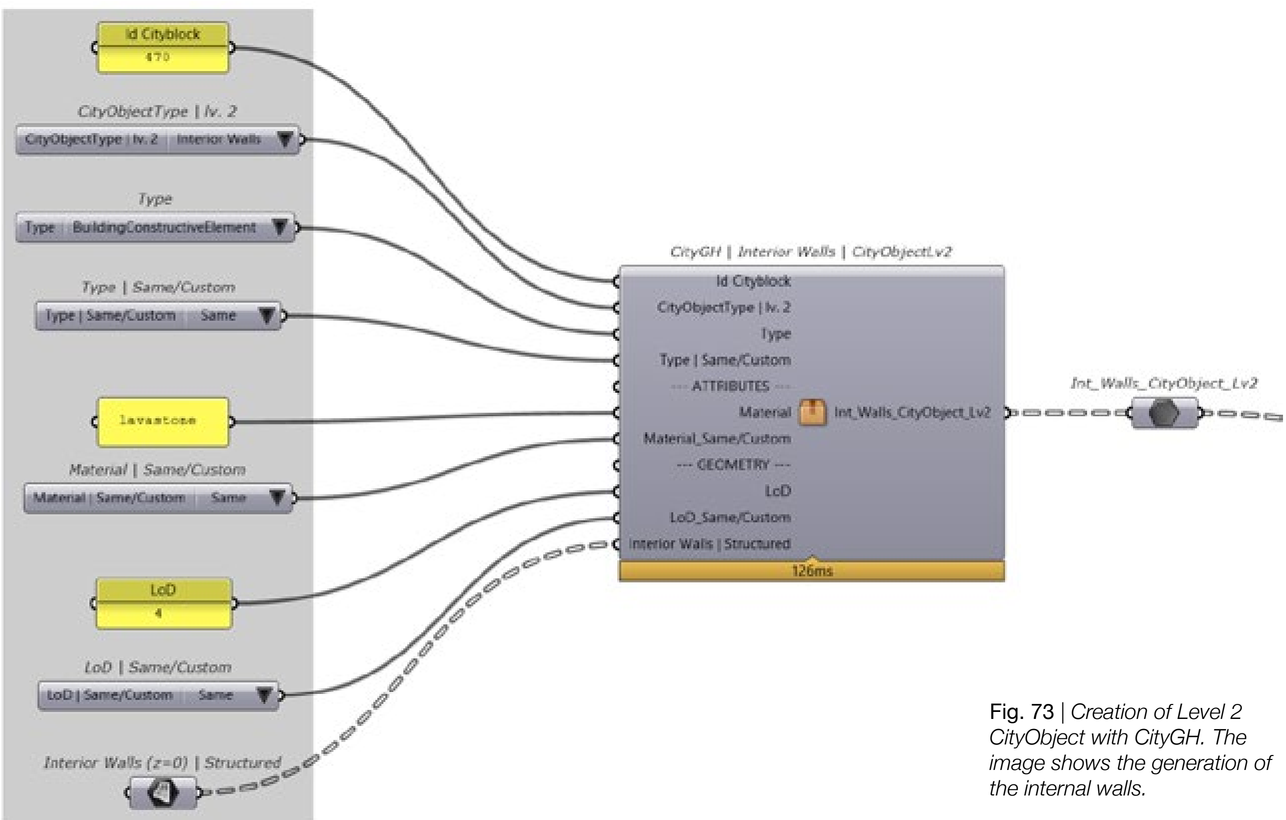


Fig. 73 | *Creation of Level 2 CityObject with CityGH. The image shows the generation of the internal walls.*

Once the building components were created, they were used to build the first-level CityObjects (fig. 74).

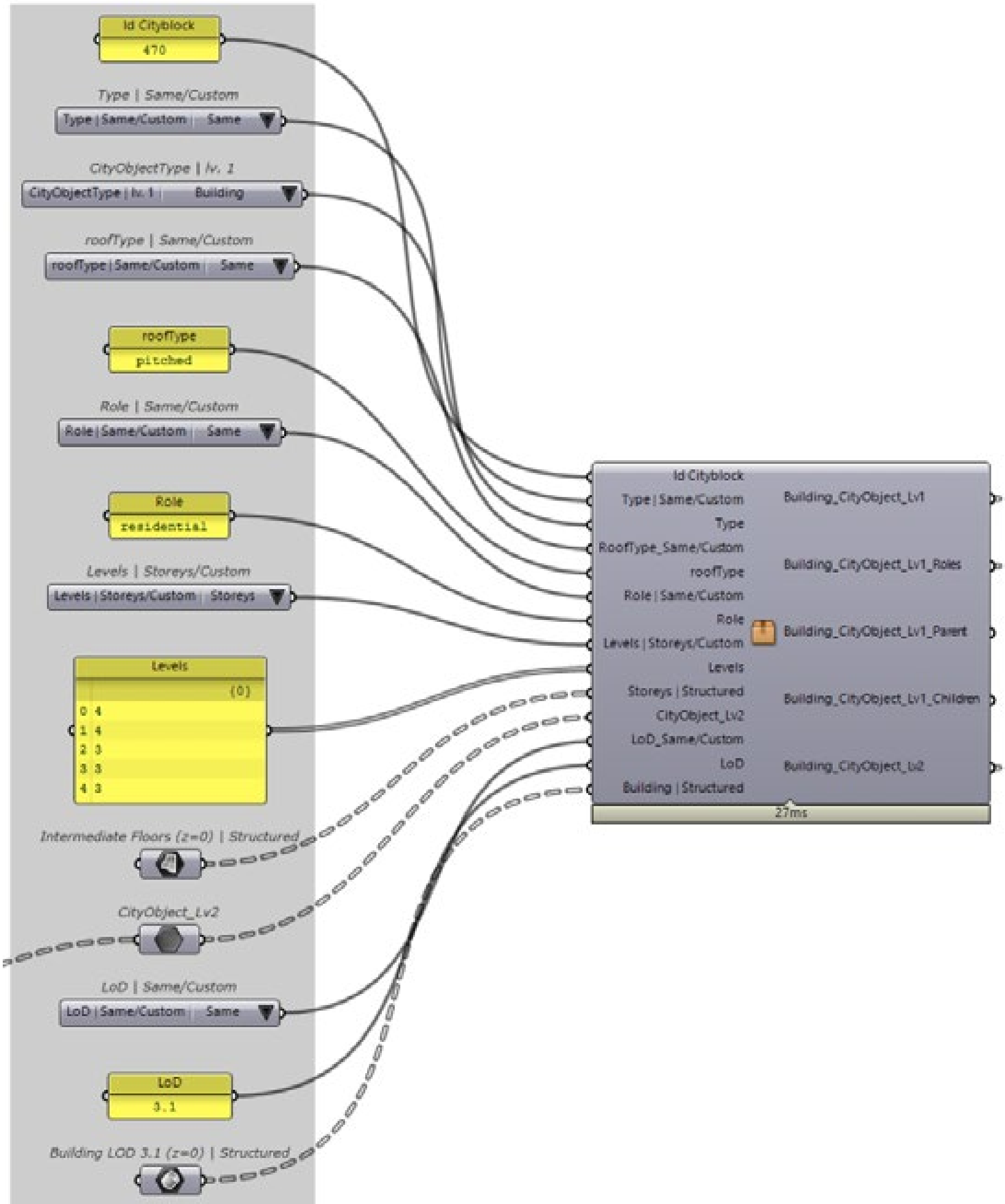


Fig. 74 | *Creation of Level 1 CityObject with CityGH. The image shows the generation of 'Building' CityObjects.*

Once the first-level CityObjects have been defined, they are grouped under a CityObjectGroup that contains attributes related to the entire city block (fig. 75).

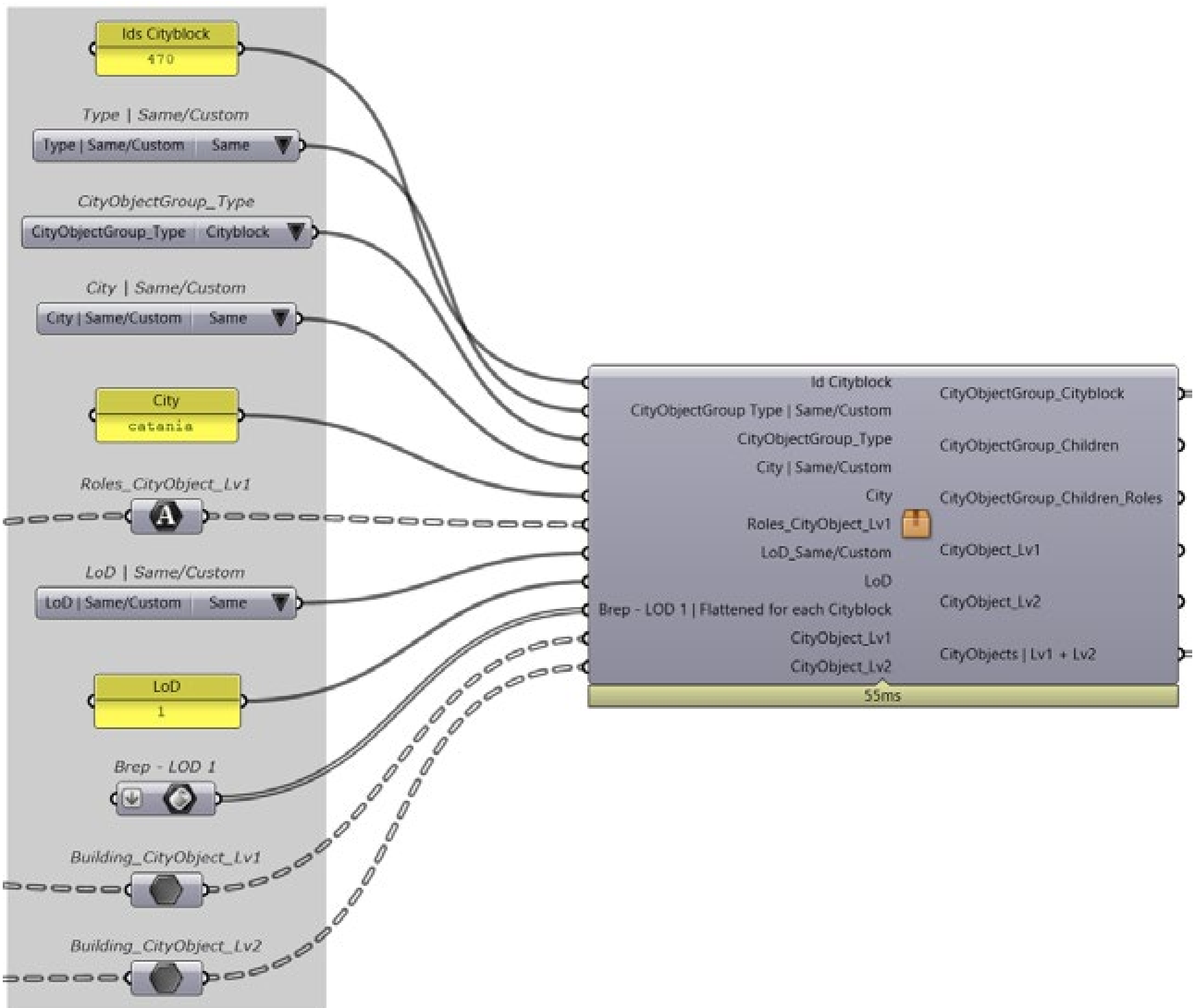


Fig. 75 | *Creation of CityObject-Group with CityGH. With this Object it is possibile to gather attributes that are useful at the territorial scale and/or for urban planning purposes.*

Since the scale of the city block has been reached, all that remains is to complete the data tree with the final construction of the *CityGH Object*. This last object is used to create metadata relating to the model such as author, entity, etc. In accordance with the CityJSON specification (fig. 76).

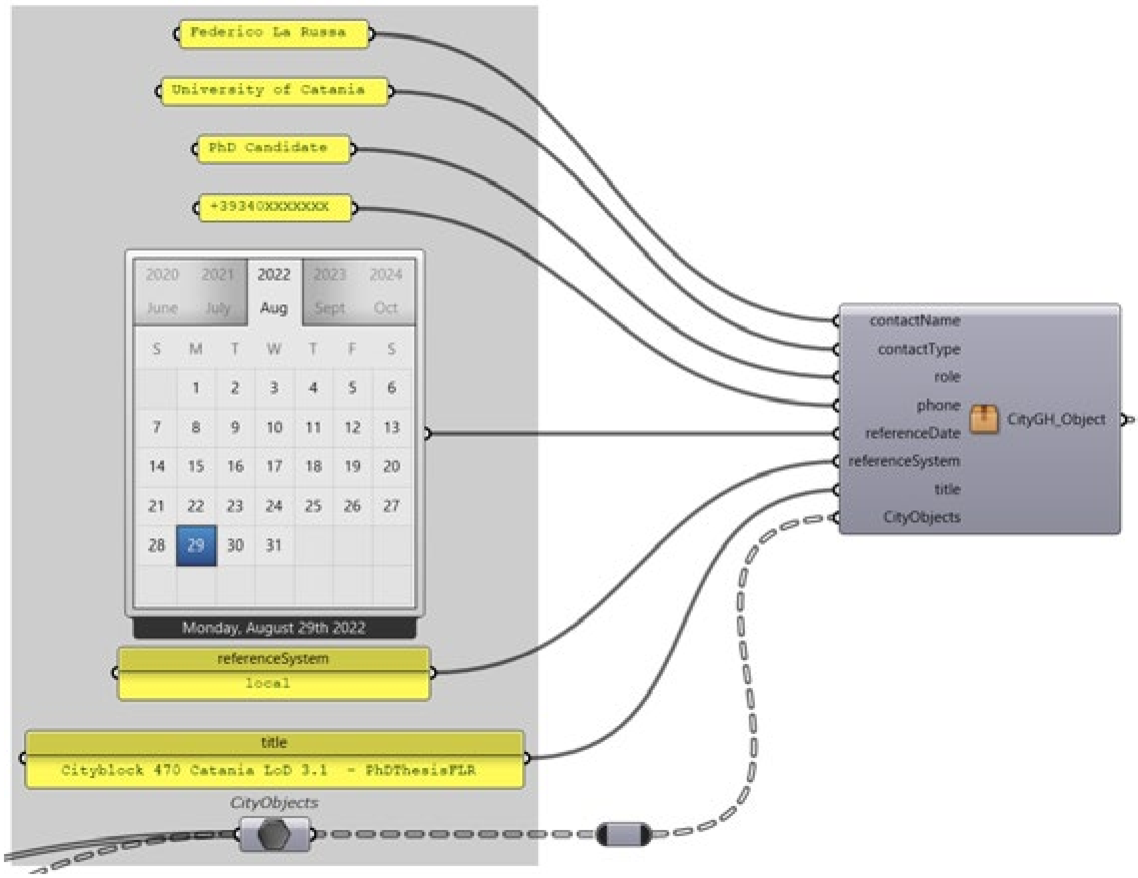


Fig. 76 | *Creation of the CityGHObject of the whole CIM parametric model. As in CityJSON, at this level all the metadata necessary for the reliability of the 3D city model are inserted.*

The CityGHObject consists of a single tree representing the entire city represented and has branches at different levels. At each level of depth of semantics, a digit is added to the index path of the object in Grasshopper. In analogy to the tree structure, the CityGH components allow this information to be layered in descending order so that each individual object has a unique identifier. An image of the data structure of the CityGH Object is shown below (fig. 77). In Figures 77 and 78, each circle corresponds to a different semantic depth level. Starting from the centre, there is therefore only one number used for the index. Grasshopper uses {0} as standard, but it appeared significant for the purposes of this work to use the code that the municipality of Catania has attributed to the city block under study (id 470) as the index of the urban block level. Next there are the first-level CityObjects so a digit, the second, is added to represent the building in relation to the block. Therefore you will have {470;0}, {470;1} and so on.

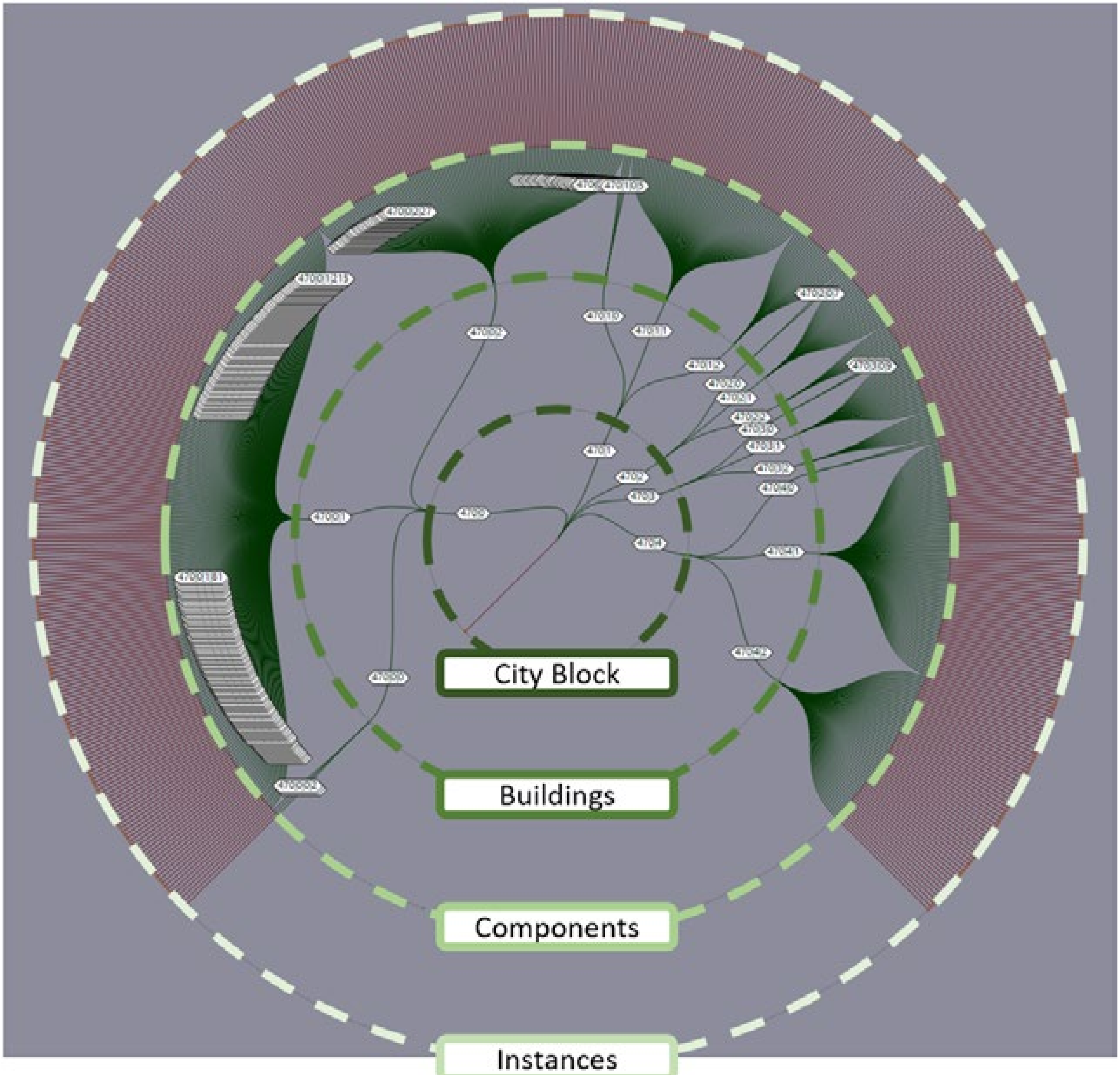


Fig. 77 | *CityGH data tree structure of the parametric CIM model.*

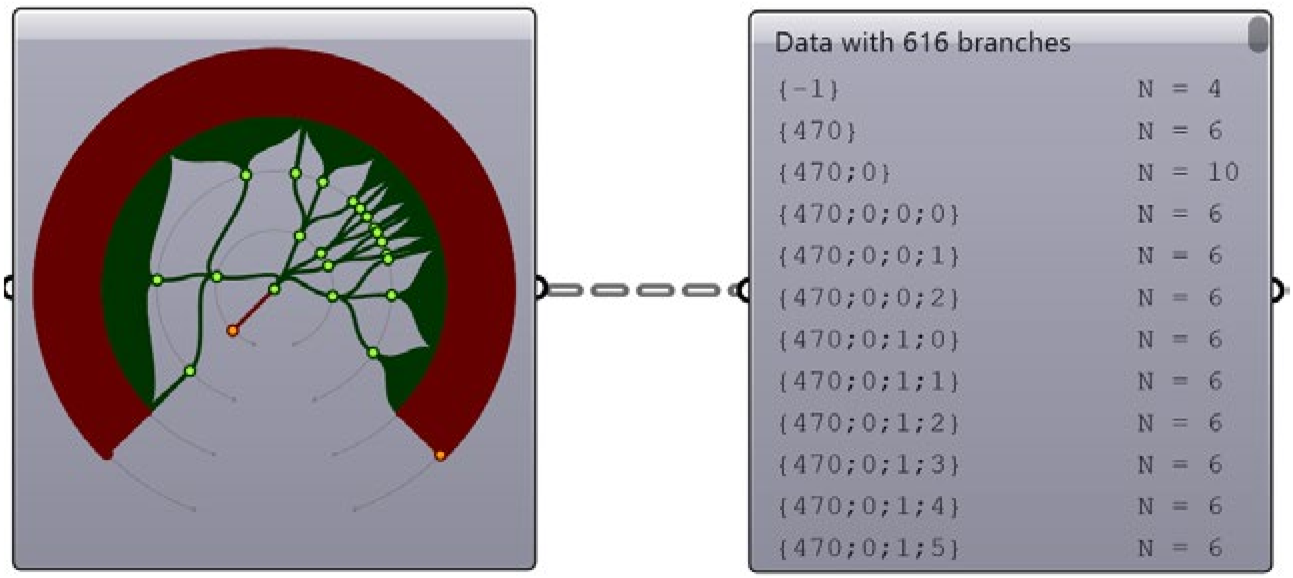


Fig. 78 | *CityGH data tree structure conpetual scheme (left) and list of all branches included (right). Each CityObject has a unique, semantically correct identifier.*

The third digit is added with the creation of the second-level CityObjects (the building components). In this case, it is not a progressive number but each of the types used is associated with a meaning. 0 stands for floors, 1 stands for internal walls and 2 stands for windows. The fourth digit is instead the identifier proper to that element and defines its uniqueness in the entire model. By way of example, an object having index {470;2;0;1} means that it is an object belonging to building 2 in block 470, and it is a slab at the first level. In Figure 68 can be seen indexes with less than 4 digits. These objects are at higher levels (1st level or CityGH object). By way of example, an object having index {470;2;0;1} means that it is an object belonging to building 2 in block 470, and is an attic on the first level. The image below shows the content of the final CityGH Object by reading from the panel component (fig. 79).

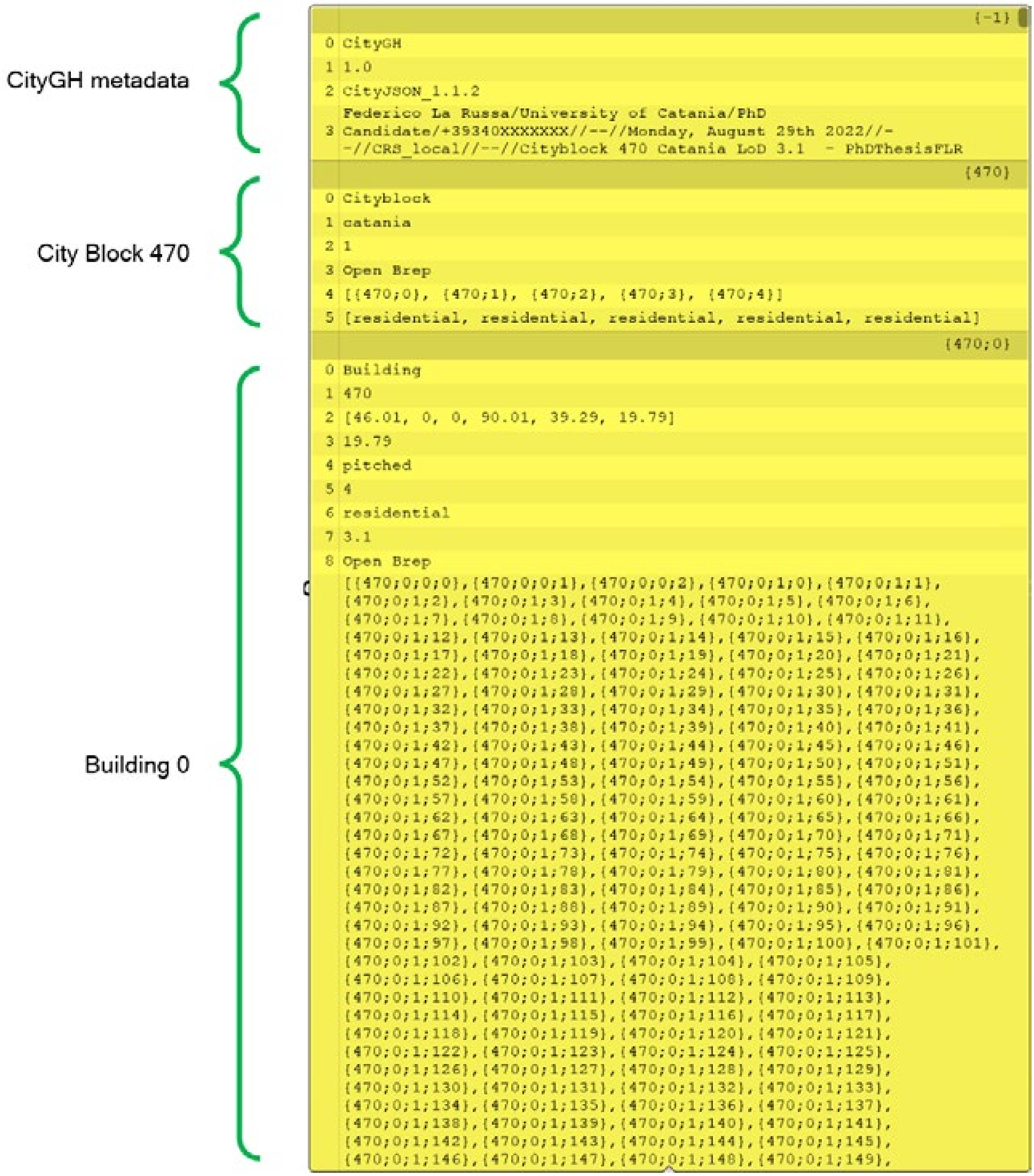


Fig. 79 | *Content of the final CityGH Object.*

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05.

DISCUSSION OF RESULTS

This chapter reviews the results obtained in the various applications described in Chapter 4, highlighting the steps forward in relation to state of the art. In particular, the results from the application on Fleri, concerning smaller urban centers (section 5.1) will be discussed. Subsequently, the result of the comparison between digital acquisition techniques in the urban context of historic centers is discussed (section 5.2). This is followed by a commentary on the two methods for the development of parametric City Information Models (sections 5.3 and 5.4). The chapter concludes with an analysis of the potential of using the CityGH format and common semantics in parametric City Information Models (section 5.5).

5.1 Minor urban center scenario: Fleri

The adoption of a workflow through Grasshopper/Rhinoceros/VisualArq allowed to work in the same environment and ensured a high degree of flexibility throughout the process. The responsiveness of the model and the parametric elements created allow updating the model over time and introducing the concept of "level of reliability" of the information through a parameter that allows the accuracy of the information displayed to be visually verified. This enables to locate interventions and survey campaigns in the points where the accuracy is lowest, reducing the planning time for these operations. Despite the initial objective (achievement of LOD 3) some elements defining the interior spaces (such as pillars and floors) have been included. With reference to current standards, both in the field of GIS (CityGML levels of detail) and BIM (UNI 11337 standard), it is a difficult task to describe the actual level of detail achieved by the CIM model. The inadequacy of the adoption of these standards is due, in both cases, to the fact that they do not consider an organic scale shift from the territorial to the architectural scale. Indeed, the description of the model passes through only one of the two. Until new standards are codified to effectively describe the level of detail of CIM models, an alternative solution can be found in the adoption of the Level of Information Need as described in ISO 19650. In this way, the level of geometry, information and documentation in relation to the purposes of the CIM model can be indicated.

5.2 Digital Urban Survey Techniques

The research work aimed to explore the potentialities of expeditious surveying techniques for the creation of informed and responsive 3D city models of historical centers. The workflow carried out contributed to evaluate the performances of cutting-edge technologies (iMMS based on SLAM and spherical photogrammetry) in comparison with well established TLS technologies. In particular, SLAM technology is currently in a phase of evolution and requires further studies in the urban field to fully understand its potential. Indeed, the expeditious urban survey is fundamental in relation to methodologies such as CIM in order to overcome the threshold of LOD 2 and allow accurate analysis and simulations for the urban scale.

The comparison showed how the iMMS SLAM (BLK2GO) technology can be used effectively outdoors for 1/2 level buildings. This condition means that the technology performs better in smaller urban centers than in high-density urban centers where buildings can be up to 4/5 levels. On the other hand, SFM360 technology is much more affordable but requires much more expertise than SLAM technology as there are more processing operations to carry out. The advantage is that it still provides a method for detecting high buildings even up to 4 levels. Although the quality of the cloud decreases with increasing height, the final product is still useful for establishing heights and hole positions with tolerances typical of the urban scale (1:200). Regarding the possibility of using Artificial Intelligence for point cloud segmentation, considering a moving acquisition process, SLAM technology is the most promising as it provides more geometric detail and less noise. However, although less expeditious, optimal results could be achieved with traditional SFM methods at the expense of acquisition time (but with less resources necessary for instrumentation).

The complexity of the investigated case study helped to point out the criticalities and advantages of setting up expeditious protocols for the urban survey. Finally, the critical-analytical reading of archive sources, the interpretation of historical cartography and iconography, the reading of the geometric-dimensional data obtained from the instrumental survey of the fronts and the road sections of the block, and the creation of the CIM ensured to understand of the historical-morphological values of the building-environmental context.

5.3 Survey-to-CIM-to-FEM: the casa terrana application

The developed framework allows to state that it is possible to develop a CIM model in an expeditious way aimed at seismic vulnerability analysis. The VPL code can be reused for modeling and the user has only the task of data collection. Therefore, this methodology may be feasible in the case of crowdmapping campaigns. An important result is the responsiveness of the parametric approach, in fact unlike bottom-up methods (see Section 2.1) the automation of most of the modeling processes allows to define and update the model in a short time also by not high specialized operators. In this direction, it is important to highlight the possibility of implementing the framework by automating the acquisition of some input data (such as the survey of openings and the type of roof) through the adoption of advanced remote sensing techniques. Another remarkable outcome is that the geometric structural model obtained is univocally defined, regardless of the operator who generates it. Therefore, any possible mistake due to a distraction, a different way of conceiving the structure, and/or modeling phases it is reduced. Of course, the operator can after modify and integrate the model according to his needs.

5.4 Scan-to-CIM: AI parametric workflow for city blocks

In the case study applied in section 4.2.2, the method adopted on the ground floor house was implemented, speeding up survey and modeling operations significantly. From a rough estimation considering also technical times and assuming already developed codes for the segmentation with Random Forest (AI) and VPL code, it is possible to state that the modeling of an entire urban block can take between 3 and 4 hours at most.

The VPL algorithm allows different models to be obtained depending on the LOD of the project. The critical points of the workflow lie in the clustering steps of the point cloud, especially those relating to apertures, which are often affected by noise and classification errors due to acquisition conditions (open or closed windows, obstacles, etc.). However, this is easily solved by manual cleaning of the cloud (a step that is still expected in the digital acquisition work pipeline), and certainly, in the future the digital reconstruction algorithms concerning laser scanning and SFM technologies will be even more refined, allowing increasingly effective filtering of point clouds.

Regarding the segmentation with Random Forest, the application demonstrated that the approach is also valid for case studies that differ in architectural style from those already known in the literature. Furthermore, this application is among the first to include a parametric VPL approach to this type of segmentation, leaving several paths open for future experimentation. The advantage of using VPL also lies in the real-time display of the code developed, allowing the programmer to design the code more easily via a faster trial-errors process than that of classic textual programming, typical of applications in the field of geomatics.

Although the technologies used in the workflow are sophisticated, they make the procedure semi-automatic, thus ensuring that even non-experts in the field can carry out the required manual operations without the need for high levels of expertise. In contrast to other experiences reported in the state of the art, this procedure removes a lot of manual work with little use of resources (the entire acquisition work can be done with a single laser scanner or in SFM with a reflex camera). The use of a VPL modeling environment compared to BIM modeling environments allows for greater flexibility, especially in export possibilities. Indeed, as demonstrated in Fleri's application, it is possible to quickly switch from the VPL environment to the BIM environment, and the same applies to the GIS environment or any other analysis environment involving the use of three-dimensional models.

The transition to the FEM model presented in the case study of the ground-floor house and in the case study of the city block, demonstrate that for expeditious seismic analyses at the urban level, it is not necessary to overload the models produced with geometries and that it is easier to initially develop parametric models that allow, like more complicated BIM models, the same information enrichment. Furthermore, the verification in the four structural analysis software presented validates the process and demonstrates interoperability that a BIM, and especially GIS, environments can hardly achieve. Therefore, with respect to the subject of expeditious urban seismic risk analysis, the proposed procedure effectively enables the development of a process that is rapid, and sustainable, and allows, at various scales, to carry out mapping campaigns for land monitoring and management against the seismic risk.

5.5 A parametric format for a parametric 3D City Model: CityGH

The proposal of a parametric format for the dissemination of 3D city models is not only a response to the increasing use of 3D city models in parametric environments such as Grasshopper. In fact, compliance with a standard provides clarity and scientific rigor that become fundamental in the definition of informative digital models.

This is all the more true if the application relates to relevant topics such as expeditious seismic analysis at the urban scale. The knowledge path described in the Italian guidelines (LLGG2011) requires a description of the entire architectural system in order to define the main characteristics against which to conduct seismic analyses. Therefore, a semantic approach that allows information to be located directly on the geometries concerned, passing from the urban to the architectural scale without discontinuity, becomes fundamental.

CityGH makes it possible to normalize 3D city models, thus laying the foundations for further development concerning the interoperability between CityJSON and CityGH by making these models more and more widely deployable. The data structure created makes it possible to define with methodological rigor the correct stratification of the different levels of the city, giving a common vision without limiting the modeling approaches, which by the nature of the work itself always remain differentiated and dependent on the resources employed.

In the context of seismic analysis, this data structure allows geometries and attributes to be transported directly into the analysis software. This allows structure engineering specialists the opportunity to have a codified framework from which they can automatically draw all the necessary attributes to perform the requested analyses.

However, the applications are numerous since what has been realized is a high-performance container whose content can be any discipline that relates to the urban environment (transport, heat island analysis, hydrogeological risk, urban planning, urban landscape, drones, economics, etc.). The development of this format also aims to provide practicality to the definitions of City Information Modelling, hoping for greater adoption of this approach both in seismic analysis at the urban scale and in the other disciplines that apply to the territory, thus making research and applications increasingly readable to a wider public.

06.

CONCLUSION AND FUTURE WORKS

This thesis work presents an innovative methodology that, through the City Information Modeling (CIM) approach, attempts to fulfil the modelling needs required by a seismic vulnerability analysis performed at the urban scale but based on an innovative original approach that should provide more accurate results compared to the simplified strategies already proposed in the literature. In particular, the thesis dealt with the question of how to sustainably allow the execution of linear and nonlinear FEM analyses on reference realistic models of the structures, within the urban area under investigation, which should provide more accurate prediction compared to the statistical and qualitative analyses generally performed.

The new proposed approach is based on the expeditious creation of models for conducting the FEM analyses based on Integrated Survey and Artificial Intelligence based Digital Survey. The applications presented seek to automate and speed up the process of knowing the built heritage in two scenarios: the territorial one closest to smaller urban centres and the denser one in larger urban centres. The applications served to develop parametric CIM models that would allow the development of expeditious methods of acquiring, modelling and exporting models ready for advanced FEM structural analysis. The applications presented seek to automate and speed up the process of knowing the built heritage in two scenarios: the territorial one closest to smaller urban centres and the denser one in larger urban centres. The applications served to develop parametric CIM models that would allow the development of expeditious methods of acquiring, modelling and exporting models ready for FEM structural analysis.

The first applications include the territorial dimension, according to LOD 0, 1, and 2 of the international standard on 3D city models CityGML, and have been conducted in the village of Fleri, in the Etnean territory in Catania (Sicily) which suffered a moderate earthquake in 2018. Namely, a parametric CIM prototype within the Visual Programming Language Grasshopper which could be useful in the knowledge management of this minor urban centre has been developed. The model was scaled up to LOD 3 and 4 (architectural scale of exteriors and interiors) demonstrating the flexibility of the proposed VPL tool also for using approaches typical of digital survey-based BIM methodologies.

The subsequent applications refer to denser urban areas, such as those in the historical centre of Catania. This urban context allowed the evaluation of different digital acquisition techniques at a larger urban scale (including iMMS, 360SFM and TLS) and their comparison, in order to identify which digital acquisition approach is nowadays more sustainable and effective with respect to the identified urban canyons. Furthermore, in this urban context, an original method, *Survey-to-CIM*, has been validated which via a VPL code developed in this research work allows an operator to create a parametric CIM model in a sustainable manner and even in the absence of digital acquisition.

Next, historical urban areas with a higher density were also approached, where the city blocks are constituted by buildings of different types with elevations up to 4 levels and characterized by the presence of several openings. In this scenario, the *Scan-to-CIM* method was developed, which through an Artificial Intelligence segmentation of the acquired point cloud and the VPL code, developed in this thesis work, allows the realisation of a CIM model up to LOD 4 in a short time compared to the methodologies currently adopted. This method was applied in a representative city block of the historic city centre of Catania and allowed the realisation of the FEM model of the single units of the city block and the overall city block itself.

Both methodologies, *Survey-to-CIM* and *Scan-to-CIM*, provide structural geometric FEM models, thus eliminating any modelling time on the part of the structural specialist who can then concentrate only on the analyses and material calibration of the material, if a further refinement of the model is needed. In addition, VPL solutions were developed that allow these FEM models to be exported to different analysis environments, thus facilitating the choice of the right software for the type of analysis that has to be performed. The efficiency of the proposed *geometrical-survey-to-FEM-model* strategy was also verified by conducting modal analyses on the final model and comparing the obtained values with realistic values obtained on more accurate models. It is worth pointing out that the method was applied to the urban scale but also is well suited for work at the architectural scale, thus becoming a general-purpose modelling solution for expeditious vulnerability assessment survey of structures.

Another application involved the proposal of a parametric format realised within Grasshopper, called CityGH, which allows the same semantic configuration required by the CityJSON format to be reproduced and thus allows a reference standard in the field of 3D City Models realised in the parametric VPL environment. This application also made it possible to organise all the necessary data attributes useful for structural analyses (e.g. material, construction technique, thicknesses).

The research paths that remain to be travelled are many. One important one certainly concerns the artificial intelligence segmentation of point clouds aimed at producing 3D city models at LOD3. In fact, the training dataset created in this thesis can enrich national and international datasets by adding data on the typical architecture of urban centres in southern Italy, thus facilitating the applicability of these technologies in the Mediterranean area as well. This could improve opening recognition by reducing classification errors and thus improve the performance of the *Scan-to-CIM* method. Within the urban surveying topic, future development could concern the automation of the extraction of useful information for LOD 3 from online street-level imagery platforms such as Google Street View or Mappillary. Furthermore, a protocol proposal that includes new keys for OpenStreetMap could make urban modelling operations even easier, especially for smaller towns that often do not have large resources for land surveying and mapping operations. This could guide the efforts of VGIs already active in the territory.

The *CityGH* proposal made in this thesis represents a further significant step for relating the urban structural vulnerability assessment procedure to the CIM, however further verifications are needed to mitigate the critical aspects of the proposed system for facilitating the interoperability of the format and making possible an increasingly widespread of the proposed innovative approach.

APPENDIX

Appendix 1 | Sinossi in lingua italiana

Generalità

L'Italia risulta essere uno dei Paesi a maggior rischio sismico del Mediterraneo a causa della frequenza dei terremoti che storicamente hanno interessato il suo territorio e dell'intensità che alcuni di essi hanno raggiunto causando un grave impatto sociale ed economico nel corso dei secoli. Attualmente, le uniche azioni efficaci per ridurre tale rischio riguardano la vulnerabilità; in particolare, la conoscenza della vulnerabilità del patrimonio edilizio permette di progettare adeguate misure di mitigazione del rischio. Data la vastità del patrimonio edilizio italiano, per calcolare i valori di vulnerabilità sismica di grandi aree spesso vengono adottati metodi statistici, i quali però spesso differiscono dalla realtà. Ad oggi tra le analisi più affidabili sono quelle condotte con il metodo degli elementi finiti (FEM) su modelli digitali discretizzati (mesh) degli edifici.

Oggetto della tesi è l’efficientamento dei processi di rilievo, modellazione e analisi in relazione alle attività di analisi della sicurezza sismica su scala urbana. In particolare, lo scopo della tesi consiste nello sviluppo di una metodologia di modellazione parametrica che faciliti la generazione di modelli geometrici FEM per l’esecuzione di analisi strutturali su aggregati ed unità strutturali alla scala urbana. La metodologia proposta e le applicazioni condotte si inseriscono nel dibattito internazionale relativo alle discipline inerenti Disegno e Rilievo, in particolare vengono affrontati temi relativi a Modellazione Parametrica, Rilievo Digitale, 3D City Models e City Information Modeling.

È stata quindi definita la Domanda di Ricerca Principale (MRQ):

MRQ: attraverso quale strategia è possibile accelerare il processo di conoscenza stabilito nella LLGG 20111 in modo sostenibile che porti ad una valutazione che sia il più possibile accurata e aderente alla realtà in relazione alla scala urbana e ai requisiti dell'analisi strutturale?

Data la complessità dell'argomento e la conseguente necessità di un approccio interdisciplinare, ci è sembrato efficace perseguire questa direzione di ricerca affrontando tre tematiche è sembrato efficace proseguire in questa direzione di ricerca affrontando tre domande di ricerca aggiuntive (RQ) che sono funzionali alla definizione degli obiettivi della ricerca obiettivi:

- RQ 1: È possibile semi-automatizzare il processo di conoscenza geometrica a scala urbana e architettonica del patrimonio edilizio dei centri storici?
- RQ 2: È possibile condurre campagne di indagine urbana digitale rapide e sostenibili? Campagne di indagine urbana digitale?
- RQ 3: È possibile ottenere modelli geometrici strutturali da un Modello Informativo della Città per accelerare l'esecuzione di analisi strutturali?

Obiettivi

In relazione alle RQs sopra citate, sono stati definiti Scopo (A) e Obiettivi (O) della ricerca:

- A: Sviluppare una procedura accessibile, semi-automatica e rapida per sismica dei centri storici e dei tessuti urbani secondo metodi meccanici.
    - 1: Sviluppare una procedura per l'indagine, il rilievo e la modellazione parametrica modellazione urbana parametrica del patrimonio esistente (in particolare degli edifici residenziali in isolati urbani storici).
    - 2: Analisi e confronto di tecniche di acquisizione digitale rapida di tecniche di acquisizione digitale rapida di canyon urbani.
    - 3: Discretizzazione di modelli CIM con informazioni parametriche in modelli geometrici strutturali utili per motori di analisi FEM generici.

Stato dell'arte

Lo stato dell'arte descritto nella tesi è sviluppato in quattro sezioni, ognuna delle quali fornisce il background di riferimento per la definizione dei research gaps.

Nella prima viene approfondito il tema del rilievo urbano, con particolare attenzione alla sua evoluzione storica e transizione tecnologica da metodo analogici a digitali. In questa sezione viene evidenziato il concetto di rilievo urbano come processo continuo, flessibile ed implementabile nel tempo (Coppo e Boido, 2010)2.

La seconda sezione si occupa di introdurre il paradigma della modellazione parametrica informativa, nella sua duplice declinazione implicita ed esplicita (Calvano et al., 2022). In particolare, viene approfondito il tema della modellazione esplicita e dell'adozione sempre più frequente dei Visual Programming Languages nel settore dell'Architettura e delle Costruzioni, in particolare per temi quali BIM, Geomatica, Modellazione Urbana e Analisi Strutturali.

La terza sezione riguarda le metodologie di valutazione di rischio sismico alla scala urbana. Vengono introdotte le principali scuole di pensiero a livello nazionale (metodi statistici, meccanicisti e olistici) (Caddemi et al., 2018)3 e dei casi studio riguardanti la città di Catania ("Progetto Catania" e "Risk-UE"). Successivamente viene introdotta la metodologia Cloud-to-FEM e discussa la sua applicazione attraverso ambienti di modellazione BIM, NURBS e MESH. Particolare attenzione viene dedicata all'attuale utilizzo della modellazione parametrica esplicita tramite Visual Programming Languages nelle analisi strutturali.

La quarta ed ultima sezione tratta il tema dei 3D City Models analizzandone definizione, standard internazionali correnti e loro applicazione (Arroyo et al., 2022)4. Viene quindi introdotta la metodologia del City Information Modeling, la quale si pone come sintesi e sviluppo dell'unione procedure GIS e BIM. Segue un'analisi delle attuali applicazioni di City Information Models in ambito internazionale e nazionale rilevanti rispetto al tema della ricerca.

Principali risultati raggiunti

Le applicazioni condotte durante il progetto di tesi hanno permesso di ottenere diversi risultati innovativi, i quali determinano un avanzamento rispetto lo stato dell'arte relativo ai modelli 3D di città e la loro applicazione nell'area mediterranea.

L'applicazione sul caso studio di Fleri, preso come riferimento per i centri urbani minori, ha messo in evidenza le potenzialità dei modelli di città sviluppati all'interno di un ambiente di modellazione parametrica VPL. In particolare, tale ambiente consente una responsività elevata dei dati e delle geometrie a loro connesse permettendo una transizione senza soluzione di continuità da modelli di città a modelli BIM con relativa gestione di livelli di dettaglio delle geometrie e livelli di accuratezza dei dati inseriti.

Il lavoro di tesi ha esaminato le potenzialità delle tecniche di rilievo digitale speditivo per la creazione di modelli CIM di centri storici, assumendo come caso studio un isolato del centro storico di Catania. La complessità del caso studio individuato ha permesso di valutare le prestazioni di tecnologie all'avanguardia (iMMS basato su SLAM e fotogrammetria sferica) rispetto a tecnologie TLS maggiormente consolidate. I risultati della comparazione mostrano come la tecnologia SFM 360 sia più sostenibile e permette di avere dei riferimenti sufficientemente accurati per operazioni di modellazione manuali. D'altra parte, la tecnologia SLAM consente l'elaborazione di nuvole di punti più definite e meno affette da rumore (utilizzabili per operazioni di segmentazione automatica tramite AI), tuttavia risulta efficace per cortine urbane non più alte di 2/3 livelli (affinità ai centri urbani minori).

La metodologia proposta, attraverso i due flussi di lavoro (Survey-to-CIM e Scan-to-CIM), ha permesso di sviluppare un metodo scalabile e sostenibile per lo sviluppo speditivo di modelli CIM tramite modellazione parametrica esplicita e la generazione di modelli geometrici strutturali per analisi FEM. Il modello geometrico strutturale ottenuto è univocamente definito, indipendentemente dall'operatore che lo genera. Pertanto, ogni possibile errore dovuto a una distrazione, a un diverso modo di concepire la struttura, e/o a fasi di modellazione è ridotto. Lo specialista addetto alle analisi può modificare e integrare il modello in base alle esigenze di progetto. Inoltre, il codice VPL può essere riutilizzato e l'operatore ha solo il compito di raccogliere i dati consentendo agli specialisti di analisi strutturali di focalizzarsi solo sull'analisi e non problemi di modellazione. Proprio per la sua natura algoritmica, questa metodologia è altamente replicabile e adottabile anche in campagne di crowdmapping che possono amplificare qualità e quantità dei dati (e quindi dei risultati conseguibili) rispetto processi di mappatura della vulnerabilità sismica.

Il flusso di lavoro Scan-to-CIM basato su Intelligenza Artificiale propone un approccio innovativo di modellazione automatizzato tramite VPL a partire da nuvole di punti segmentate. Da una stima approssimativa, considerando anche i tempi tecnici e ipotizzando codici già sviluppati per la segmentazione con codici per la segmentazione con Random Forest (AI) e il codice VPL, è possibile affermare che la modellazione di un intero isolato urbano può richiedere dalle 3 alle 4 ore al massimo dall'acquisizione alla generazione del modello CIM. Inoltre, il caso studio individuato ha permesso di testare le tecniche di segmentazione su elementi architettonici non ancora discussi in letteratura consentendo quindi l'applicazione di queste tecniche avanzate all'interno dei tessuti urbani complessi tipici dell'area mediterranea.

Infine, la proposta di un formato parametrico per la diffusione dei modelli di città 3D non è solo una risposta al crescente utilizzo di modelli di città 3D in ambienti parametrici come Grasshopper. Infatti, il rispetto di uno standard garantisce chiarezza e rigore scientifico che diventano fondamentali nella definizione di modelli digitali informativi. CityGH consente di normalizzare i modelli di città 3D parametrici, ponendo così le basi per un ulteriore sviluppo dell'interoperabilità tra CityJSON e CityGH e rendendo questi modelli ampiamente utilizzabili. La struttura dati permette di definire con rigore metodologico la corretta stratificazione dei diversi livelli della città, fornendo una visione comune senza limitare gli approcci di modellazione, che per la natura stessa del lavoro rimangono sempre differenziati e dipendenti dalle risorse impiegate.

Possibili sviluppi futuri

Il progetto di ricerca di questa tesi definisce numerosi percorsi sviluppabili. Uno importante è sicuramente la segmentazione attraverso tecniche di intelligenza artificiale di nuvole di punti finalizzata alla produzione di modelli 3D di città con LOD3. Infatti, il dataset di addestramento creato in questa tesi può arricchire dataset nazionali e internazionali, aggiungendo dati sull'architettura tipica dei centri urbani del Sud Italia, facilitando così l'applicabilità di queste tecnologie anche nell'area mediterranea. Questo potrebbe consentire un miglioramento del riconoscimento delle aperture riducendo errori di classificazione con un ulteriore miglioramento delle prestazioni del metodo Scan-to-CIM.

Nell'ambito del tema del rilievo urbano, gli sviluppi futuri riguardano l'automazione dell'estrazione di informazioni utili per il LOD 3 da immagini a livello stradale online come Google Street View o Mappillary. Inoltre, appare perseguibile la definizione di un protocollo che includa nuove chiavi per OpenStreetMap, facilitando ulteriormente le operazioni di modellazione urbana, soprattutto per le città più piccole che spesso non dispongono di grandi risorse per le operazioni di rilevamento e mappatura del territorio. Questo potrebbe orientare gli sforzi dei VGI già attivi sul territorio.

La proposta di CityGH avanzata in questa tesi rappresenta un ulteriore passo significativo per relazionare la procedura di valutazione della vulnerabilità strutturale urbana al CIM; tuttavia, sono necessarie ulteriori verifiche per mitigare le criticità del sistema proposto per facilitare l'interoperabilità del formato e rendere possibile una sempre maggiore diffusione dell'approccio innovativo proposto.

Appendix 2 | List of publications and awards

Articles and chapters

Galizia Mariateresa, D'Agostino Graziana, Garozzo Raissa, La Russa Federico Mario, Seminara Gaetano, Santagati Cettina (2019). Novel cultural experiences for the communication of museum collections: the Francesco Fichera projects fund at Museo della Rappresentazione in Catania. DISEGNARECON, 12 (23), pp. 8.1 – 8.11, ISSN 1828-5961

La Russa Federico Mario (2019). HS – BIM: Historical Sentient – Building Information Model.In: (a cura di): Cettina Santagati e Sandro Parrinello, Dienne - Building Information Modeling, Data & Semantics, 5, pp. 17 – 27, ISSN 26108755

Santagati Cettina, D'Agostino Graziana, Garozzo Raissa, La Russa Federico Mario, Galizia Mariateresa (2020). Participatory approach for the enhancement of architectural archives funds: the experience at Museo della Rappresentazione in Catania. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Volume XLIII-B5-2020, pp. 99 – 106, doi: 10.5194/isprs-archives-XLIII-B5-2020-99-2020

Santagati Cettina, La Russa Federico Mario (2020). Historical Sentient – Building Information Model: a Digital Twin for the management of museum collections in historical architectures. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Volume XLIII-B5-2020, pp. 755 – 762, doi: 10.5194/isprs-archives-XLIII-B4-2020-755-2020

Galizia Mariateresa, D'Agostino Graziana, Garozzo Raissa, La Russa Federico Mario (2020). Connessioni tra museo/archivi e città: strategie digitali per la valorizzazione e comunicazione del fondo Fichera del Museo della Rappresentazione. In Arena A., Arena M., Brandolino R.G., Colistra D., Ginex G., Mediati D., Nucifora S., Raffa P. (a cura di). Connettere. Un disegno per annodare e tessere. Atti del 42° Convegno Internazionale dei Docenti delle Discipline della Rappresentazione. Milano: FrancoAngeli, pp. 2224-2241, doi: doi.org/10.3280/oa-548.120

La Russa Federico Mario, Santagati Cettina (2020), From Cognitive to the Sentient Building. Machine Learning for the preservation of museum collections in historical architecture. In: (a cura di) Liss C. Werner and Dietmar Köring, Proceedings of the 38th eCAADe Conference on Education and Research in Computer Aided Architectural Design in Europe, 2, pp. 507 – 516

La Russa Federico Mario, Santagati Cettina (2020), From Open Data to city models: an Antifragile approach for City Information Modeling. In: (a cura di) Sandro Parrinello e Massimiliano Lo Turco, Dienne – Building Information Modeling, Data & Semantics, 7, pp. 83 – 95, ISSN 2610-8755

Galizia Mariateresa, D'Agostino Graziana, Garozzo Raissa, La Russa Federico Mario, Santagati Cettina (2020), Raccordo urbano e spazio architettonico: la scalinata della chiesa di an Nicola di Bari a Trecastagni. Eikonocity, 2020, anno V, n. 2, pp. 69-87, DOI: 110.6092/2499-1422/7218 (BEST PAPER)

La Russa Federico Mario, Santagati Cettina (2021). An AI-based DSS for preventive conservation of museum collections in historic buildings. Journal of Archaeological Science: Reports, Volume 35, 102735, ISSN 2352-409X, DOI: https://doi.org/10.1016/j.jasrep.2020.102735.

La Russa Federico Mario, Genovese Giulia, (2021). City Information Modeling and seismic risk: integrated HBIM-GIS approaches for the management of post-earthquake scenarios. In: (a cura di) Cecilia Bolognesi e Cettina Santagati, Dienne – Building Information Modeling, Data & Semantics, 8, pp. 71 – 82, ISSN 2610-8755

La Russa Federico Mario, Galizia Mariateresa, Santagati Cettina (2021). Remote Sensing and City Information Modeling for revealing the complexity of historical centers in Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLVI-M-1-2021, 367–374, https://doi.org/10.5194/isprs-archives-XLVI-M-1-2021-367-2021

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Awards

Winner 'UID Youth Prize Vito Cardone 2021', member of the research team of the winning project 'metodus.eu - the database of treatises on representation methods'

Winner BEST PAPER AWARD 2021 - 3D MODELING & BIM | Digital Twin. 3D Modeling & BIM - Digital Twin 2021 held online and organised by Sapienza University of Rome with the contribution entitled: City Information Modeling between knowledge and prevention of the territory: an application in post-emergency scenarios (F. M. La Russa, G. Genovese, C. Santagati).

Winner BEST PAPER AWARDS – PROCIDA ITALIAN CAPITAL OF CULTURE. XIX International Forum ‘Le Vie dei Mercanti’ World Heritage and Design for Health con il contributo dal titolo: The Language of Urban landscape between architecture perception and surveying: the staircase of the church of San Nicola di Bari in Trecastagni (M. Galizia, G. D’Agostino, R. Garozzo, F. M. La Russa, C. Santagati).

Winner BEST PAPER AWARD – 3D-ARCH 2022. 9th International Workshop 3D-ARCH | 3D Virtual Reconstruction and Visualization of Complex Architectures con il contributo dal titolo: An Expeditious Parametric Approach for City Information Modeling and Finite Element Analysis (F. M. La Russa, M. Intelisano, M. Galizia, I. Caliò, C. Santagati).

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