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Methodological Approach for the Management of the Urban Context: Towards the Challenges of Transition through the City Information Modeling (CIM) Process

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LIST OF ACRONYMS AND ABBREVIATIONS

Acronym	**Extended term / definition**
AEC	Architecture, Engineering and Construction Industry
AI	Artificial Intelligence
API	Application Programming Interface
BIM	Building Information Modeling
CAD	Computer-Aided Design
CIM	City Information Modeling
CityGML	City Geography Markup Language
CityJSON	Jason-based City Model Format
Coordinated Model	Model created through the union (federation) of several disciplinary models.
Data	A tangible and elementary cognitive element, interpretable within a communication process through rules and syntactic structures that have been previously shared.
DB	Database
Discipline	Specialisation towards a form of knowledge of a humanistic, scientific, or practical nature.
DT	Digital Twin
EU	European Union
GPS	Global Positioning System
IFC	Industry Foundation Classes
ICT	Information and Communication Technologies
Information	A set of data organized for a specific purpose, aimed at communicating knowledge within a given process.
Informative Model	Virtualisation of the work and its components. Informational vehicle for the virtualisation of products and processes in the construction sector. The graphical virtualisation of the information model is also referred to as the graphical model.
ISO	International Standards Organisation
IoT	Internet of Things
JSON	Java Script Object Notation
LiDAR	Light Detection and Ranging
LOD	Level of Development
LOIN	Level of Information Need
Object	Virtualisation of the geometry and the non-geometric characteristics of finite, physical or spatial entities pertaining to a work, or to a set of works, and to their processes.
OGC	Open Geospatial Consortium
Open format	File format organised on specific public syntaxes whose use is open to all operators.
OSM	OpenStreetMap
Proprietary format	File format based on a proprietary encoding from a specific manufacturer. Its use is restricted to specific terms of use.
Pset	Property Set

PSC	Piano Strutturale Comunale (Municipal Strategic Plan)
SLAM	Simultaneous Localization Mapping
XML	eXtensible Markup Language
.bin	CloudCompare file format
.e57	e57 is a compact, open file format for storing point clouds, images and metadata produced by 3D imaging systems, such as terrestrial laser scanners, developed by ASTM.
.dwg	AutoCAD (Autodesk) file format used for storing 2D and 3D design data and metadata
.dxf	Drawing eXchange Format
.las/.laz	las (LASer) is an open binary vector file format designed for the exchange and storage of LiDAR point cloud data
.obj	open, geometric definition file format
.rcp	ReCap (Autodesk) point cloud file format
.rft	Revit families (Autodesk) file format
.rvt	Revit (Autodesk) file format
.shp	GIS file format

ABSTRACT

Urban areas, including both metropolitan cities and smaller municipalities, are facing multifaceted challenges in a context of transitions toward sustainability. Conventional urban governance approaches prove inadequate, constrained by fragmented data silos and the lack of a unified data-driven governance framework. The transition from traditional forms of urban and territorial governance to new sustainability-oriented systems represents a critical issue. Within this framework, three major transitions: ecological, demographic, and digital, emerge as fundamental and interconnected dimensions of the transformation processes that cities and territories are required to undertake. Within this scenario, the research develops a methodological approach based on City Information Modeling (CIM), conceived as an information-management process capable of supporting knowledge, representation, and strategic decision-making for the urban environment. The research is developed within the disciplinary framework of *Area 08 - CEAR-10/A: Drawing*, addressing methods for visualizing CIM models according to their associated information and indicators. In this regard, the study focuses on the semantic and parametric dimensions of CIM, defining how geometric and informational attributes can be structured to create a coherent descriptive and operational model of the urban scene. The research defines three spatial dimensions of the urban scene (enclosed, unenclosed, and threshold spaces) and proposes twelve synthetic indicators. A system-based framework is developed to guide the parametric representation of urban contexts, supported by typological object families, dedicated data sheets, and a consistency analysis that verifies the coherence between parameters and indicators. The methodological approach is validated through the development of CIM models for three case studies selected for their differing morphological and governance conditions: Higienópolis in São Paulo, the historic town of Verucchio and the Darsena area in Ferrara. For each case, heterogeneous datasets, ranging from open data and institutional archives to surveying and remote-sensing outputs, are integrated into an integrated model through top-down and bottom-up modelling procedures. The simulation of the indicator set demonstrates the potential of CIM to support data integration, scenario visualization, and multi-scalar interpretation, translating analytical layers into graphical insights directly connected to the semantic model. The research highlights CIM as a scalable system, fostering future developments such as IoT-based monitoring, big data analytics, and AI-enhanced digital twins.

Chapter 1
INTRODUCTION

1.1 Individuation of the research field

Urban areas, including both metropolitan cities and smaller municipalities, are facing multifaceted challenges in a context of transitions toward sustainability. Conventional urban governance approaches prove inadequate in addressing these complex issues, constrained by fragmented data silos and the lack of a unified data-driven governance framework (Gil et al., 2011; Soltanifard et al., 2024). The transition from traditional forms of urban and territorial governance to new systems centered on sustainability represents a critical issue. Widely acknowledged in the literature is the definition of sustainable development set out in the Brundtland Report, Our Common Future, published in 1987 by the World Commission on Environment and Development. Sustainable development is defined therein as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”.[1]

Within this framework, three major transitions: ecological, demographic, and digital, emerge as fundamental and interconnected dimensions of the cross-cutting transformation process that cities and territories are required to undertake. These transitions aim to address current challenges with a forward-looking perspective on the coming decade, when the most significant effects of the anticipated changes are expected to be underway. In this context, a prospective vision aligned with the principles of sustainability becomes essential. The themes of ecological, demographic, and digital transition are currently at the center of both European and national strategic planning. Among the key instruments at the European level are the European Green Deal (2019), the Digital Compass 2030, and the Next Generation EU programme (2020), which outline long-term objectives in terms of climate neutrality, digital transformation, and socio-economic resilience. At the national level, these strategic directions are implemented through the National Recovery and Resilience Plan (PNRR), the National Strategy for Digital Transition, and the National

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[1] World Commission on Environment and Development. (1987). *Our common future* (The Brundtland Report). Oxford: Oxford University Pres

Strategy for Sustainable Development (SNSvS), together outlining an integrated framework of interventions aimed at fostering innovation, inclusion, and territorial sustainability.

To bridge this gap, *City Information Modeling (CIM)* is emerging as a digital solution, providing a multidimensional framework for comprehensive urban data management and intelligent decision-making (Yu et al., 2025), designed to support governance by a range of stakeholders, including: metropolitan administrations, municipal unions, and multi-utility companies.

The applications of the City Information Modeling (CIM) framework are primarily strategic and scenario-oriented, as it is designed to support strategic decision-making processes for the governance of urban transformations. In contemporary city and territorial management, there is an increasing need to represent the complexity of urban environments through the development of digital platforms capable of integrating multiple spatial and administrative scales. Such platforms function as powerful instruments for scenario simulation, facilitating cost reduction, improving efficiency, and enhancing the overall quality of urban systems. Despite its growing relevance, the availability of tested and operational CIM models remains limited worldwide. Therefore, there is an urgent need to develop methodologies and tools capable of estimating key parameters essential for effective and sustainable urban management (Mozuriunaite & Haiyan, 2021). This research falls within the emerging themes of urban surveying, aiming to define a language grounded in graphic-symbolic codification, capable of describing diverse and heterogeneous cognitive levels of relevance to the city, and designed as an interactive language for dynamic representation environments. (Garzino et al., 2021).

While City Information Modeling is not a new concept, it has recently garnered significant academic attention across various disciplines to deal with future urban challenges. The research presented in this thesis is developed within the framework of the disciplinary scientific area *Area 08 – CEAR-10/A: Drawing*, addressing issues related to methods for visualizing the City Information Modeling (CIM) model according to the information and indicators associated with it. In the context of urban representation and management, its purpose lies in the integration of heterogeneous systems, with the potential to support stakeholders in creating scenarios through a structured documentation system, to support the intervention proposals. The contribution of the disciplines of representation in this thesis encompasses aspects related to surveying knowledge, the creation of multi-relational databases for data management, and the interaction with GIS and BIM systems. On the one hand, synthetic frameworks have been developed to represent complex conceptual elaborations of a logical-deductive nature; at the same time, efforts have been made to make unprocessed data and analytical tools immediately accessible, allowing the various stakeholders involved to conduct diverse analyses and interpretations. The inherently complex structure of the city requires investigation across multiple areas and thematic domains, each connected to a process of partial deconstruction of the overall system. Such an approach cannot be confined within a single type of analysis; rather, it demands, case by case and according to the specificity of the investigation, targeted in-depth studies. Consequently, all the collected information must be properly structured and made consistent through the construction of networks of relationships among data, which can also be queried at later stages. Hence arises the need to employ information systems capable of storing and interrelating the gathered data effectively.

1.2 Objective

City Information Modeling can be understood as a process-oriented approach that aims to meet evolving urban needs, with a forward-looking perspective on the challenges of the future. Within the scope of this research, the concept of CIM will be examined from a semantic perspective, with the objective of developing a documentation system to support intervention proposals. Models that do not support queries and/or interactions cannot be considered semantic 3D city models, but rather simple three-dimensional representations of the territory.

In an urban context characterized by ecological and demographic transitions, oriented towards sustainability, the research seeks to overcome the technical and regulatory limitations of traditional urban models. For this reason, an information-management approach based on City Information Modeling (CIM) is proposed. Such an approach is capable of integrating qualitative and perceptual dimensions of the urban scene and of supporting, in a cross-cutting manner, processes of knowledge, conservation, and transformation of the built environment. Within this framework, the guiding research question is: *"To what extent can a CIM model become a strategic descriptive tool, capable of representing the qualitative complexity of the urban scene and of providing transversal support to decision-making processes?"*.

This question leads to the general objective of the research, which is to define a City Information Modeling framework that can support urban management. The model is developed to integrate heterogeneous information and synthetic indicators in order to interpret, monitor, provide insights, and guide processes of transformation and conservation of urban space in its material, perceptual, and functional dimensions. From this perspective, it becomes essential to investigate the relationships among the various elements that constitute the urban context, thereby reconstructing the typological, morphological, and relational positioning of buildings and spaces within the city. A further objective consists in the development of interpretative and representational tools able to provide a strong informational basis, capable of synthesizing complex and heterogeneous data to inform decisions regarding urban management and transformation. In this way, the passage from raw data to an interpretative and consciously managerial dimension can be accomplished. As part of the research, an in-depth investigation was undertaken to facilitate the consultation of fragmented and unstructured data within digital environments capable of being implemented and queried through different interpretative frameworks. Accordingly, an information system was developed, based on alphanumeric and geographic data integration, linking projects that respond to the emerging needs of both metropolitan and non-metropolitan cities, and connecting alphanumeric and geographic content through customizable pathways of analysis and personalized queries.

Through the implementation of cutting-edge technologies, such as Internet of Things (IoT) sensors and Artificial Intelligence (AI), the long-term objective is to develop a model that functions as a digital twin of urban areas (Li et al., 2022), an innovation that some worldwide cities, among them Bologna (Italy), Singapore, and Helsinki (Finland), have started to develop. Such a model aims to provide real-time responses, insights, and situational awareness, fostering more informed, data-driven, and effective decision-making processes in the management and governance of urban environments.

1.3 Methodological Approach

The research proposes an information-management approach based on City Information Modeling (CIM), conceived as a system capable of integrating the qualitative and perceptual dimensions of the urban scene while supporting, in a cross-cutting manner, processes of knowledge, conservation, and transformation of the built environment. The act of drawing sustains the dialogue among a plurality of actors, competences, disciplines, intermediaries, and urban policies across different interpretative scales. On the one hand, it is necessary to establish synthetic frameworks capable of representing complex conceptual elaborations of a logical and deductive nature; on the other hand, it is equally important to ensure the immediate availability of raw data and analytical tools that allow various stakeholders to perform evaluations and analyses that may not have been anticipated in the initial phase of the research project (Garzino et al., 2021).

Within this framework, the guiding research question is *"To what extent can a CIM model become a strategic descriptive tool, capable of representing the qualitative complexity of the urban scene and of providing transversal support to decision-making processes?"*. This question leads to the general objective of the research, which is to define a City Information Modeling framework that can support urban management. The model is designed to integrate heterogeneous information and synthetic indicators in order to interpret, monitor, and guide processes of transformation and conservation of urban space in its material, perceptual, and functional dimensions. From this perspective, it becomes essential to investigate the relationships among the various elements that constitute the urban context, reconstructing the typological, morphological, and relational positioning of buildings and spaces within the city. A further objective consists in the development of interpretative and representational tools able to provide a strong informational basis, capable of synthesizing complex and heterogeneous data to inform decisions regarding urban management and transformation. In this way, the passage from raw data to an interpretative and consciously managerial dimension can be achieved.

Understanding urban space is a prerequisite for effective CIM modeling, as it provides the reference framework within which qualitative information acquires meaning, coherence, and operational value. To carry out this descriptive process, it is essential to identify the dimensions that define the articulations of the urban scene. The additional research question formulated to address this methodological issue was*: "How is urban space articulated, in order to convey to its users the necessary information - characteristics, elements, and data for its description and management?"*. The research therefore aims to identify those dimensions that, within a unified interpretative framework, are able to correlate various aspects connected both to perceptual experience and to the attribution of managerial meaning. This reflection was developed with a view toward parametric modeling, which CIM implies. From both the perspective of available data and that of geometric modeling and information attribution, the resulting information is subsequently grouped and filtered according to the specific purposes and uses of the model. Within this methodological framework, urban space was analyzed in its different dimensions. *Enclosed space* refers to self-referential spatial configurations in which the space itself carries a high degree of responsibility in defining identity and function. *Unenclosed space* describes conditions in which the urban structure appears fragmented into interrelated and complementary parts but lacks effective control over contextual relationships and spatial contiguities. *Threshold space*, finally, defines those conditions in which a single spatial entity can become either enclosed or unenclosed, where the contact between these two states produces conditions of *tangency* and *intersection*.

In the development of the methodological approach, which was aimed at identifying possible ways in which a CIM model may become both a descriptive and strategic tool capable of representing the qualitative complexity of the urban scene and supporting decision-making and management processes, an additional research question was posed: *Which synthetic indicators can facilitate the documentation and management of urban space, by integrating heterogeneous parameters and supporting both operational and strategic choices?* Twelve (12) descriptive indicators were identified as useful for obtaining a comprehensive picture of the main factors that can provide an interpretative framework of the urban context through the model, which thus already begins to function as a decision-support tool. As often stated, what is not measured is not governed, however it is important to underline that this proposed articulation makes no claim to completeness.

To achieve the descriptive process of parametric modeling through City Information Modeling (CIM), it was necessary to take apart the analyzed urban context into systems, each characterized by the ability to correlate, within the same interpretative framework, various aspects related to perceptual attribution and the attribution of meanings (such as patterns of use, temporal variations, cultural conditioning, etc.). The definition of these systems aimed to develop a model capable of identifying possible methods for the survey of environmental data and the geometric-informative representation of the urban context. The definition of these systems further pursued the objective of describing and identifying the generic, by assigning a set of component elements represented in the main systems, without preconceived hierarchies of value. To recover the descriptive and identificatory value of representation by undertaking the process of representation and documentation of the urban scene through the CIM approach, the following research question was posed: *"How can the elements of the urban scene be represented from both a geometric and informative point of view?"*. Through such informational attributes, CIM systems actually provide a digital environment capable of hosting, organizing, and interacting with all this information by means of the 3D model, which, to a certain extent, may become an access point to the city's informational database. The organization of data sheets thus becomes strategic in terms of model usability, both with regard to standardization, through *shared parameters*, and *Property Sets* (Psets). Once the data sheets had been defined, the methodological research question guiding the definition of the CIM model was: *"How can parameters (descriptors) be correlated with qualitative indicators?"*. To address this question, a *consistency analysis* was carried out, aimed at verifying the internal coherence of the data within the CIM model. This analysis ensures a reliable reading of the parameters and guarantees that the indicators provide results consistent with the condition of the represented urban environment. The procedure is based on a matrix that relates the informative attributes assigned to the objects of the different systems with the synthetic indicators used for interpreting and managing the urban context.

Following this methodological process, the research developed the informative models of three case studies selected for their specific characteristics: Higienópolis, in São Paulo, Brazil, as an example of urban growth and morphological transformation; the historic town of Verucchio, in the province of Rimini, Italy; and the Darsena area in Ferrara, Italy, as an example of an ongoing urban regeneration context. To simulate the CIM-based framework and to verify the possibility of graphically representing the selected indicators within an integrated system, a simulation was carried out to populate and define the set of indicators, translating analytical data into a dynamic visualization connected to the CIM model. From this perspective, the resulting chart represents a first step in establishing the relationship between the indicators and the analyzed urban context. The organization of potentially disaggregated data into a catalogue of codified actions constitutes a systematic method for structuring the collected observations, allowing their reciprocal interactions to be assessed and providing an opportunity for further in-depth study and analysis of the proposed methodology.

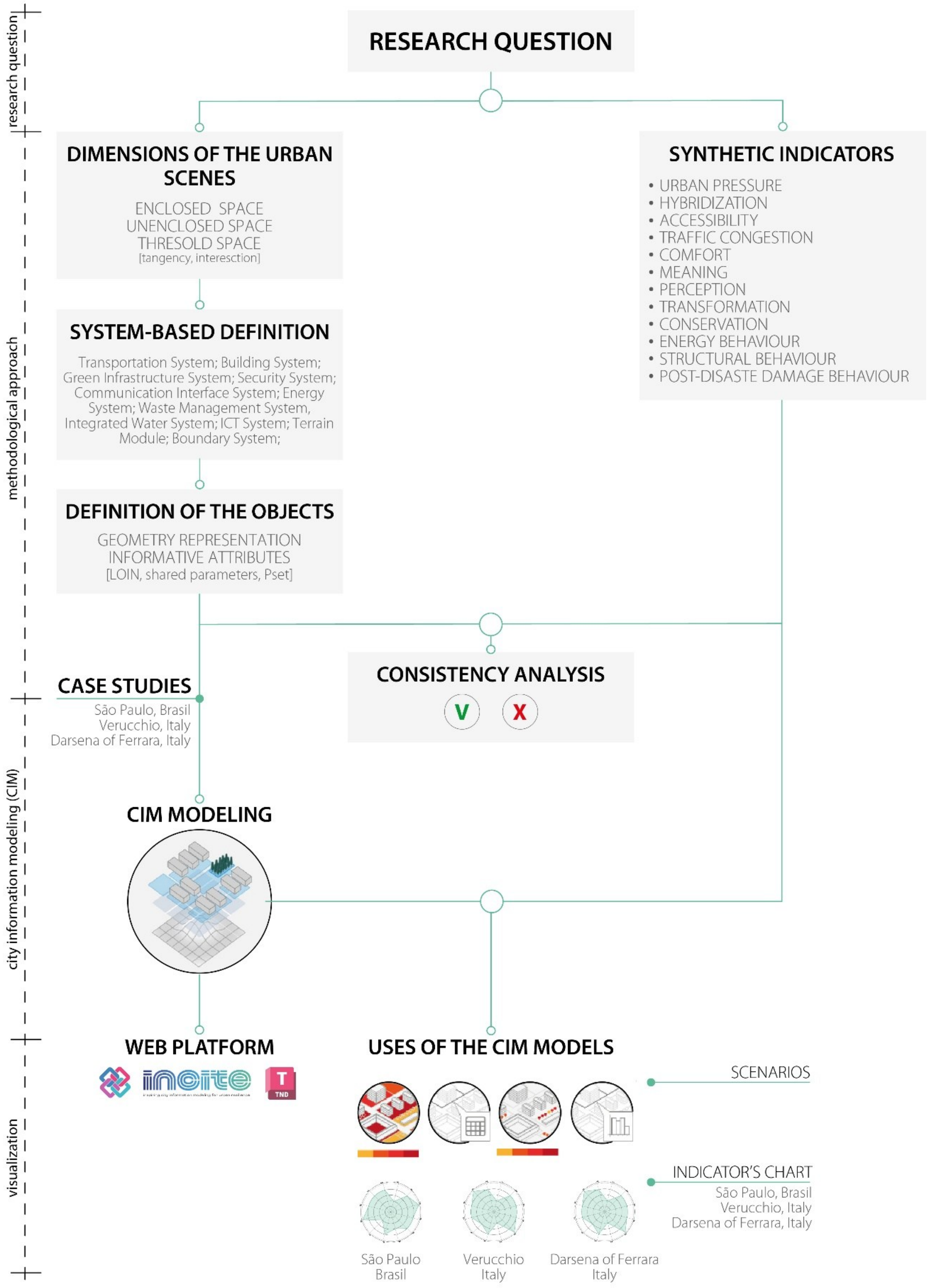

Fig. 1.1- Main steps of research methodology approach.

1.4 Impacts of the Research

In the prospective scenario shaped by the ecological and demographic transitions, whose impacts will become tangible in the coming years, the cross-cutting effects of the research on competence levels and on the simulation of scenario models will become evident. What is crucial, however, is that these models be made available to stakeholders when needed, ensuring their usability at the moment when specific demands arise. A first impact concerns the integration of heterogeneous data sources, currently fragmented and disjointed, into a single georeferenced model: a digital environment that can be expanded and queried through multiple interpretative frameworks. Through this process, the model enables an integrated morphological reading of the urban and territorial context. In this sense, the CIM works as a scientific experimentation environment, where data management and interoperability acquire a cognitive and epistemological value. At the same time, the CIM process introduces a critical reflection on data accuracy and consistency, particularly in relation to the calculation of variation deltas. This approach aims to move beyond the mere three-dimensional representation of the model, towards an awareness-based understanding of geometric coherence, which must comply with specific variation thresholds consistent with the model's purposes and requirements. The impact of the CIM process is also managerial and operational. The ability to integrate territorial and infrastructural data, simulate scenarios, and parametrically represent elements of the urban landscape makes CIM a potentially valuable tool for the programming and maintenance of the built and infrastructural heritage. In this respect, the digital model constitutes a cognitive basis for shared decision-making processes and for future integration with monitoring and management systems. Finally, an additional impact concerns the communicative and cognitive capacity of the model. The CIM enables the immediate and comparative visualization of complex indicators through chromatic representations, gradients, and parametric filters. The research engages with the ecological and demographic transitions, positioning the CIM as a support tool for stakeholders who will be equipped with transversal knowledge concerning data sources and usage typologies. This knowledge is oriented toward strategic planning and fosters the generation of simulation scenarios that can effectively inform decision-making processes.

1.5 Stakeholders

City Information Modeling (CIM) can be understood as a process-oriented approach that aims to meet evolving urban needs, with a forward-looking perspective on the challenges of the future. CIM models, by creating scenarios through a structured documentation system to support intervention proposals, have both strategic and scenario-based functions, enabling stakeholders to make informed strategic decisions and govern transformation processes. The stakeholders to whom this research thesis is addressed, aimed at proposing a methodological approach for managing the urban context in response to the challenges of transition through the City Information Modeling (CIM) process, include: metropolitan administrations, municipal unions, and multi-utility companies.

These are entities that operate at a large implementation scale. An example of a metropolitan area is São Paulo, Brazil, which is of particular interest not only because it is one of the most densely populated areas in the world, but also because it underscores the international applicability of the CIM framework. In this transitional scenario, smaller municipalities, such as Verucchio (RN), Emilia-Romagna, Italy, would be called upon to merge into larger municipal unions, while maintaining the implementing role of the territorial authority. This is because the scale required for urban context management through CIM, although oriented toward local needs, must encompass figures, both in terms of population and territorial dimensions, that enable industrial and managerial investments of this kind. A standard local administration, particularly in a national context such as Italy's, where "small municipalities" with fewer than 5,000 inhabitants account for 69.9% of Italian municipalities[2], would not be able to sustain such investments, either economically or in terms of human resources.

In this context, multi-utility companies, understood as entities managing services distributed across the territory; such as, to take national benchmarks, A2A, IREN, and HERA, could manage their respective asset by integrating information bases across different entities (e.g., water, electricity, gas, transport, etc.) in coordination with public administrations. This would allow them to plan services based on real systems, within a technological framework grounded in the CIM approach.

Fig. 1.2 – Italian multi-utility companies, as entities that manage services distributed throughout the territory, and their user base. From left to right: HERA, IREN and A2A. (Source: gruppohera.it; gruppoiren.it; a2a.it)

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[2] Report iFEL, Fondazione ANCI – Istituto per la Finanza e l'Economia Locale, 2024.

An analysis of the operational domains of these multi-utility companies reveals that their operational areas and urban capital coverage align with the scale, both in terms of territorial dimensions and population basin, at which CIM can provide valuable opportunities for advancing the transition towards the management and planning of services grounded in real needs, through digital modeling frameworks.

1.6 Innovative aspects of this research study

In an urban context characterized by ongoing ecological and demographic transitions and oriented towards sustainability, this research seeks to overcome the technical and regulatory limitations of traditional urban models. The application of integrated digital solutions and protocols to the management of interventions on the city and territory, starting from a parametric modeling approach (City Information Modeling, CIM) and the implementation of information from multiple data sources, represents a field of growing experimentation and academic interest, one of the aspects explored in this research. However, the various experiences conducted so far reveal inefficiencies in the implemented solutions. Therefore, the research aims to propose innovative strategies in several domains: the optimized integration of information sources, which are often available in disaggregated form; the visualization of informational content in three-dimensional environments, which, in the context under investigation, is essential to ensure broad accessibility to the implemented functions; and the application of data acquisition protocols concerning different kinds of information (geometric-spatial, functional, performative, informational, and risk-related). These protocols have to be extended from single, case-specific experiments to more widespread interventions involving the urban environment as a whole, in order to ensure scalability of results and sustainability in data acquisition for model construction, by analyzing and, where available, utilizing existing data sources.

Within this framework, the research introduces innovative aspects aimed at extending the benefits of parametric modeling to the urban scale: namely, the integration of heterogeneous information and synthetic indicators to interpret, monitor, and provide insight into, as well as to guide, processes of transformation and conservation of urban space in its material, perceptual, and functional dimensions. Through the definition of the urban scene and its systems, the study proposes an innovative documentation framework based on the CIM process to support intervention proposals. This framework incorporates a series of indicators designed to respond to the social and environmental challenges of cities and territories. The research also explores new approaches to linking information between different elements and systems, proposing a simulation-based mode of data population. In doing so, it advances a method for visualizing information connected to the model, aimed at supporting the management of territories and urban areas. At this scale of representation, a particularly innovative aspect lies in introducing an analytical procedure to identify a set of component elements represented through key spatial relationships (urban fabric, pathways, skyline) and correlated with various specific features (material, chromatic, functional). The objective is to highlight relationships and criticalities that contribute to a comprehensive reading of the urban landscape, already conceived as a tool to support its management.

It should be emphasized that the proposed framework does not claim to achieve completeness; rather, it aims to introduce an innovative documentation system to support intervention proposals, demonstrating how such simulations can be populated and visualized through an information system connected to the geometric model.

1.7 Expected Results

The research concern within the disciplinary field of representation, exploring the modes of knowledge through its tools and languages. Within the broader research framework, the contribution of representation disciplines encompasses aspects related to surveying, the development of multi-relational databases for information management, and the implementation of GIS and BIM systems through dedicated web-based platforms.

Among the expected outcomes is the demonstration that the City Information Modeling (CIM) process can be understood not merely as a technical instrument but as a method of cognitive inquiry into the urban and territorial context. From this perspective, the informational model, interpreted through a representational point of view, is expected to function as a system capable of generating and conveying knowledge, correlating material and immaterial data, and rendering the complexity of urban phenomena visible.

From an operational standpoint, the development of an experimental CIM model is expected to demonstrate the potential of informational representation as a tool to support both knowledge production and the management of urban context. Such a model is envisaged as a prototype capable of representing not only morphology but also the topological, functional, and perceptual relationships among elements of the built environment, thereby configuring itself as a cognitive and communicative interface for the territory.

1.8 Research Limitations

The research is situated within a transitional framework characterized by a forward-looking vision that focuses on the coming decade, a period during which the most significant effects of the anticipated changes are expected to unfold. Indeed, the organization of heterogeneous data sources, the potential execution of surveys, and the implementation of CIM information modeling require a development phase that implies the non-immediate applicability of the proposed research.

The development of the research across very large urban areas initially represented a limitation, both in terms of the time required and the computational management of data, as the available technologies would not have been capable of handling such an extensive quantity of datasets. Consequently, CIM models were developed for selected significant contexts, chosen for their distinctive features, and were described, analyzed, and developed according to a "zoom-based" logic, in order to produce simulations that could serve as representative of a broader urban and territorial context.

Chapter 2
BACKGROUND

2.1 Towards Sustainability: Transition Scenarios and Strategic Agenda

The transition from traditional forms of urban and territorial governance to new systems centered on sustainability represents a critical issue. Widely acknowledged in the literature is the definition of *sustainable development* set out in the Brundtland Report, Our Common Future, published in 1987 by the World Commission on Environment and Development. Sustainable development is defined therein as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs"[1].

Within this framework, three major transitions: ecological, demographic, and digital, emerge as fundamental and interconnected dimensions of the cross-cutting transformation process that cities and territories are required to undertake. These transitions aim to address current challenges with a forward-looking perspective on the coming decade, when the most significant effects of the anticipated changes are expected to be underway.

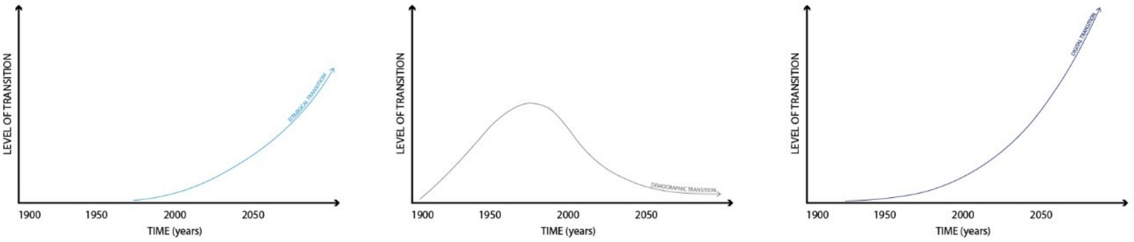

Fig. 2.1 – Transition trends. From left to right: Ecological Transition, Demographic Transition, Digital Transition.

In this context, a prospective vision aligned with the principles of sustainability becomes essential. The themes of ecological, demographic, and digital transition are currently at the center of both European and national strategic planning. Among the key instruments at the European level are the European Green Deal (2019)[2], the Digital Compass 2030[3], and the Next Generation EU

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[1] World Commission on Environment and Development. (1987). *Our common future* (The Brundtland Report). Oxford: Oxford University Pres

[2] European Commission. (2019). *The European Green Deal*. COM(2019) 640 final.

[3] European Commission. (2021). *2030 Digital Compass: The European way for the Digital Decade*. COM(2021) 118 final.

programme (2020)[4], which outline long-term objectives in terms of climate neutrality, digital transformation, and socio-economic resilience. At the national level, these strategic directions are implemented through the National Recovery and Resilience Plan (PNRR)[5], the National Strategy for Digital Transition[6], and the National Strategy for Sustainable Development (SNSvS)[7], together outlining an integrated framework of interventions aimed at fostering innovation, inclusion, and territorial sustainability.

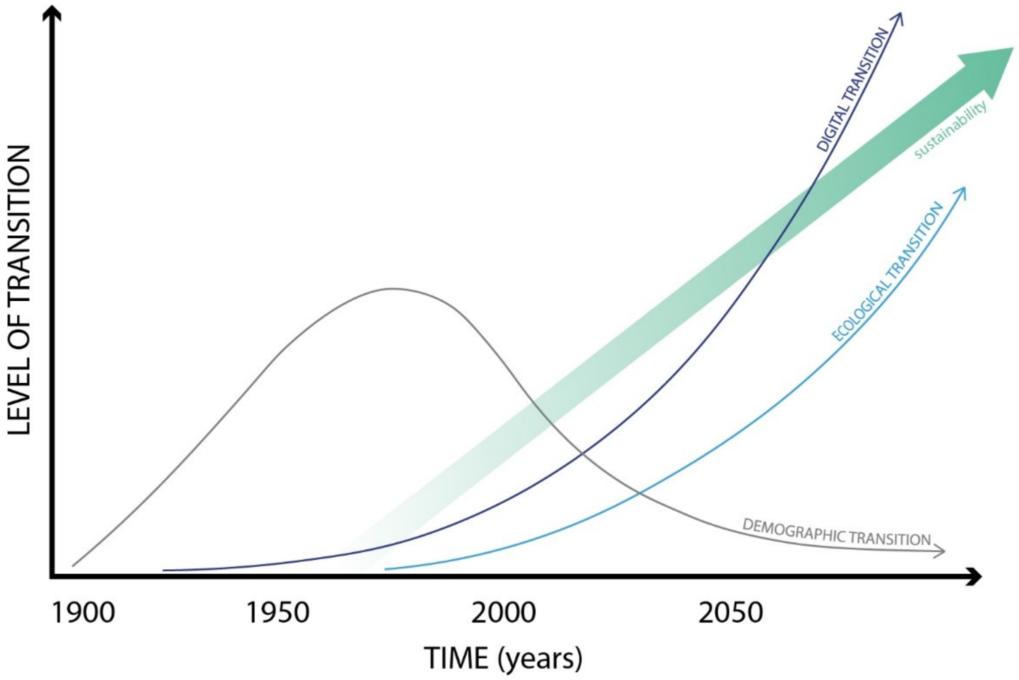

Fig. 2.2 – Trend of the ecological, demographic, and digital transitions in relation to the trajectory toward sustainability

2.1.1 *Ecological Transition*

The intensification of the effects of climate change, marked by increasingly frequent extreme events affecting both Italian and international territories and urban areas, highlights the urgent need to initiate a structural and integrated ecological transition. This transition must be guided by an approach that plays a significant role in territorial governance. The ecological transition is a process that entails the transformation of existing development models toward sustainability, with

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[4] Council of the European Union. (2020). *Council Regulation (EU) 2020/2094 of 14 December 2020 establishing a European Union Recovery Instrument to support the recovery in the aftermath of the COVID-19 crisis*. Official Journal of the European Union, L 433I, 22.12.2020, pp. 23–27.

[5] Presidenza del Consiglio dei Ministri. (2021). *Piano Nazionale di Ripresa e Resilienza (PNRR)* [National Recovery and Resilience Plan].

[6] Ministero per l’Innovazione Tecnologica e la Transizione Digitale. (2022). *Strategia Nazionale per la Transizione Digitale 2026* [National Strategy for Digital Transition 2026].

[7] Ministero dell’Ambiente e della Sicurezza Energetica. (2022). *Strategia Nazionale per lo Sviluppo Sostenibile (SNSvS)* [National Strategy for Sustainable Development].

the aim of tackling environmental and climate challenges while simultaneously safeguarding quality of life, economic competitiveness, and the sustainability of ecosystems. According to the *European Green Deal*, it constitutes "the set of transformations necessary to make Europe climate-neutral by 2050." At the national level, the Italian Ministry of Ecological Transition defines it as "the shift toward an economic and productive system that does not compromise the environment, health, or future generations."[8]

From this perspective, the ecological transition necessarily involves a profound rethinking of infrastructure models and land management practices, particularly in light of the impacts that recent flood events have had on Italian territory (Sharma et al., 2021). It is therefore essential to adopt models capable of supporting strategic decision-making in the representation, analysis, and management of land and related infrastructure (Okonta et al., 2025). Environmental scenario simulation, combined with the assessment of seismic and energy vulnerability, constitutes a set of fundamental tools for promoting sustainable resource management and effectively addressing the challenges of the ecological transition.

2.1.2 *Demographic Transition*

Demographic transition is a structural phenomenon of European relevance, with Italy being particularly affected. It is a cross-cutting issue that encompasses economic, social, and territorial dimensions, and therefore requires an integrated and systemic interpretive approach. The most recent data (ISTAT, 2023)[9] confirm a progressive decline in birth rates and fertility levels, accompanied by a pronounced ageing of the population and increasing territorial imbalances. These dynamics have significant implications for the social and economic sustainability of the national system (Giorgetti, 2025)[10]. In this context, it is important to mention the *ageing factor*, employed in European projection models to estimate age-related public expenditure (pensions, healthcare, and social assistance). This factor enables a more precise identification of needs in terms of infrastructure and employees, with the most significant effects expected in the early 2040s (European Commission, 2024)[11]. At the same time, the real-estate market is also undergoing a transition, increasingly oriented towards the conversion of public real estate assets

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[8] Ministero della Transizione Ecologica. (2021). *Definizione e obiettivi della transizione ecologica.*[Definition and objectives of the ecological transition].

[9] ISTAT. (2023). *Rapporto annuale 2023: La situazione del Paese* [Annual report 2023: The situation of the country]. Istituto Nazionale di Statistica.

[10] Giorgetti, G. (2025). *Audizione del ministro Giorgetti sugli effetti economici e sociali derivanti dalla transizione demografica* [Hearing of Minister Giorgetti on the economic and social effects of the demographic transition]. Camera dei Deputati – Commissione d'inchiesta sulla transizione demografica.

[11] European Commission. (2024). *The 2024 Ageing Report: Economic and budgetary projections for the EU Member States (2022–2070)*. Publications Office of the European Union.

into social housing. This shift aim at address emerging forms of housing demand linked to demographic and territorial changes. These trends influence key economic variables, including those affected by changes in workforce dynamics, such as the levels of specialised skills (CENSIS, 2023)[12]. In this scenario of demographic transition, affecting both the population and skill profiles, it becomes essential to develop systems capable of compensating for the progressive loss of technical know-how at the territorial level. Digital tools and information models must therefore support the development of operational strategies through the generation of knowledge-based scenarios enabled by structured data and querying processes.

2.1.3 *Digital Transition*

The digital transition is a structural transformation process that entails the widespread integration of technologies within economic, social, and territorial systems. It constitutes a strategic asset in the contemporary landscape, acting as a catalyst for the transformation of traditional management and decision-making models (European Commission, 2021)[13]. At the same time, it represents an opportunity to develop innovative models characterized by systems that are accessible even to individuals without highly specialized expertise, with the aim of strengthening the operational capacity of local areas and enhancing their resilience in response to emerging challenges (Batty, 2018). From this perspective, the adoption of advanced digital technologies, such as: artificial intelligence, sensor systems, and territorial information models, makes it possible to reduce reliance on traditional vertical competencies, thereby fostering the emergence of more adaptable and widespread digital and transversal skills (Balsmeier & Woerter, 2019).

In this context, the digital transition supports the development of solutions such as *City Information Modeling,* conceived as an integrated digital tool for territorial representation and as a documentation system to support intervention proposals (Gil, 2020).

2.2 City Information Modeling as a Prospective Approach to Urban Transition Challenges

Urban areas, both metropolitan cities and towns municipalities are confronting multifaceted challenges, within a scenario marked by ecological and demographic transitions. Conventional urban governance approaches frequently prove inadequate in addressing these complex issues, constrained by fragmented data silos and the lack of a unified data-driven governance framework (Gil et al., 2011; Soltanifard et al., 2024). To bridge this gap, City Information Modeling (CIM)

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[12] Fondazione CENSIS. (2023). *La frattura generazionale e la perdita di competenze nel mercato del lavoro italiano* [The generational divide and the loss of skills in the Italian labour market]. Censis.

[13] European Commission. (2021). *2030 Digital Compass: The European way for the Digital Decade*. COM(2021) 118 final.

is emerging as a digital solution, providing a multidimensional framework for comprehensive urban data management and intelligent decision-making (Yu et al., 2025). The long-term objective is the development of a model that serves as a digital twin of urban areas (Li et al., 2022), designed to support governance by a range of stakeholders, including metropolitan administrations, municipal unions, and multi-utility companies. There is an increasing need to represent the complexity of urban environments through the creation of digital platforms capable of managing multiple spatial and administrative scales. These platforms serve as powerful tools for scenario simulation, enabling cost reductions and enhancing overall urban quality. Despite its growing relevance, there is a lack of tested and operational CIM models woldwide. Consequently, there is an urgent need to develop tools capable of estimating key parameters for effective urban management (Mozuriunaite & Haiyan, 2021).

While City Information Modeling is not a new concept, it has recently garnered significant academic attention across various disciplines to deal with future urban challenges. In the context of urban representation and management, its purpose lies in the integration of heterogeneous systems, with the potential to support stakeholders in creating scenarios through a structured documentation system, to support the intervention proposals. From this perspective, digital transition represents a critical opportunity for urban managers. By combining information of existing databases, often stored across disparate databases, and integrating technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI), digital management enables a more holistic approach. This approach facilitates the joint consideration of urban facilities quality and user behavior, offering the necessary informational layers to render the built environment adaptive to human needs (Pasquinelli et al., 2016). Within this framework, the paradigm of City Information Modeling can be understood as a process-oriented approach that aims to meet evolving urban needs, with a forward-looking perspective on the challenges of the future.

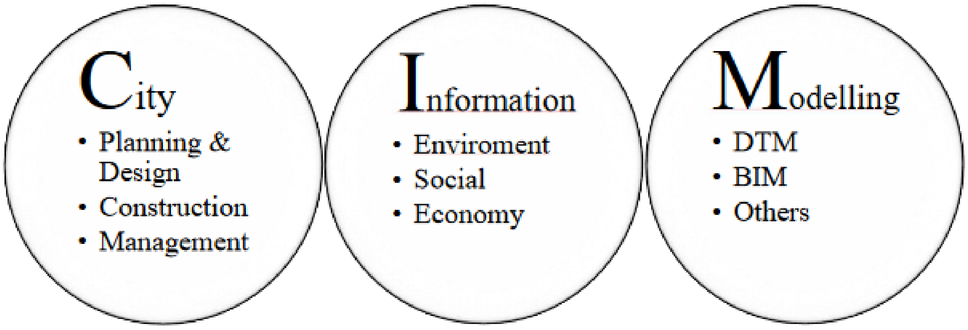


Fig. 2.3 – The understanding of CIM composition from the semantic perspective. (Source: Mozuriunaite, 2021).

Fig. 2.4 – RoofScape project, Rotterdam, Netherlands. The platform displays a 3D urban model with thematic informational analysis of building rooftops, visualized through a color-coded scale based on different parameters and design scenarios. (Source: MVRDV, 2022).

2.2.1 *Background of CIM*

Currently, a 3D City Model is often 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). These digital representations are widely used to store, visualize, and interact with urban data derived from real-world environments, encompassing terrain, buildings, vegetation, roads, and transportation systems. A key characteristic of virtual 3D city models lies in their ability to integrate heterogeneous geospatial data into a unified and coherent structure, thereby supporting the development and management of complex urban information environments (Billen et al., 2014; Döllner et al., 2006; Zhu et al., 2009).

Since the mid-2000s, the term City Information Modeling (CIM) has gained increasing recognition (Gil et al., 2011; Hamilton et al., 2005; E. Thompson, 2023). Nevertheless, a lack of academic consensus persists regarding a clear and universally accepted definition of CIM (Souza & Bueno, 2022; Z. Xu et al., 2021). Initially, CIM was conceived as a conceptual extension of Building Information Modeling (BIM), adapted to the urban scale (Montenegro & Duarte, 2009; Stojanovski, 2018). However, CIM is now understood as more than a mere aggregation of individual BIM models. It represents a higher-level framework encompassing infrastructure networks, administrative systems, and human activities. CIM facilitates the visualization, analysis, and monitoring of urban environments, thus supporting project development and planning at both local and regional scales. Consequently, CIM is characterized by the multidisciplinary integration of various spatial data models (Dantas et al., 2019).

Furthermore, CIM is often conceptualized either as a three-dimensional extension of Geographic Information Systems (GIS) (Stojanovski, 2013) or as a hybrid integration of BIM and GIS technologies (Melo et al., 2019; Souza & Bueno, 2022; X. Xu et al., 2014). Although the definition of CIM remains under continuous refinement and debate “the CIM concept is under constant discussion and transformation” (Souza & Bueno, 2022) it is generally understood as a three-dimensional urban model constructed from comprehensive city information data (Zhang, 2024).

In recent years, the CIM paradigm has evolved into a complex and integrated system incorporating BIM, GIS, and cutting-edge technologies, such as the Internet of Things (IoT) and Artificial Intelligence (AI) (Y. Wang et al., 2021; Z. Wang et al., 2020). Unlike isolated technological solutions, CIM establishes a cyber-physical system that enables cross-domain data interoperability and advanced computational simulations. This integration supports the development of dynamic digital twins capable of 3D visualization, real-time interaction, and predictive analytics for urban systems. The technical architecture underlying CIM enhances decision-making processes in fields such as the urban environment and emergency management, through data fusion mechanisms and AI-driven analytical pipelines (Yu et al., 2025).

As noted by Amorim (2015), the CIM concept entails coordinated action among all stakeholders involved in the management of urban development, including conception, planning, execution, operation, monitoring, maintenance, and renovation. These processes are managed within a centralized and shared digital environment: the CIM model. Collaboration and interoperability thus represent the foundational conceptual pillars of the CIM paradigm. Almeida and Andrade (2018) further expand on the definition of CIM, framing it as a computation-based knowledge model that integrates processes, public policies, and technologies to facilitate cooperation among multiple stakeholders in the pursuit of sustainable, participatory, and competitive cities.

The conceptual evolution of digital cities has catalyzed the systematic digitization of urban infrastructure and environmental systems, marking a paradigm shift towards data-centric urban governance. Through the progressive integration of BIM and GIS technologies and the advancement of computational ontologies, CIM has emerged as both an academically recognized and industrially adopted paradigm (Cocchia, 2014; Dameri & Cocchia, 2013).

According to Yu et al. (2025), City Information Modeling (CIM) constitutes a holistic and data-driven paradigm for urban management. It represents a comprehensive digital framework that integrates advanced technologies such as BIM and GIS, designed to address the inherent complexity and dynamic demands of urban environments, thereby fostering intelligent and sustainable urban development (Z. Wang et al., 2020; X. Xu et al., 2014; Xue et al., 2021). The implementation of CIM enables urban managers to access integrated and multidimensional datasets, promote cross-sectoral collaboration, and support informed, data-driven decision-making processes.

Within the scope of this research, the concept of CIM will be examined from a semantic perspective, with the objective of developing a documentation system to support intervention proposals. The motivation at the base for employing such models lies in their ability to enable the extraction of information directly from the urban model (e.g., how many inhabitants live in a given block? What are the construction years and building techniques of the structures?). Models that do not support queries and/or interactions cannot be considered semantic 3D city models, but rather simple three-dimensional representations of the territory.

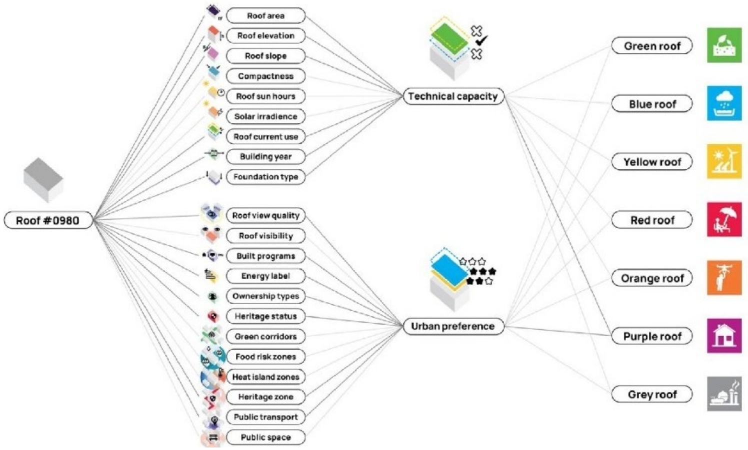
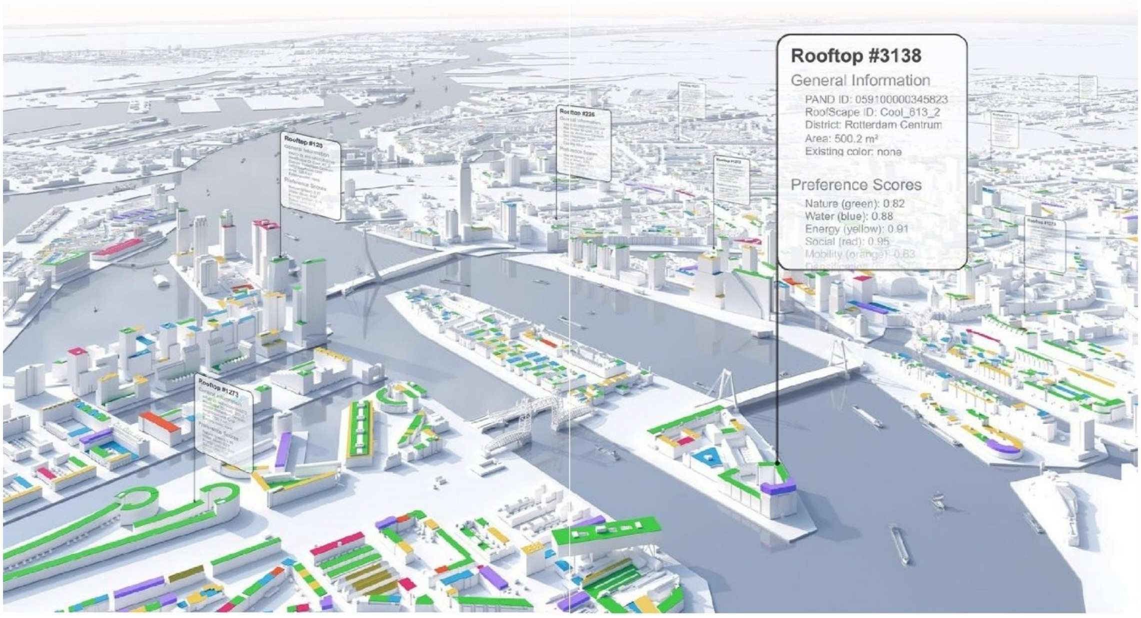


Fig. 2.5 – Decision-making diagram from the RoofScape project, integrating technical capacity and urban preference parameters to classify building rooftops and suggest potential roof typologie. (Source: MVRDV, 2022).


Rooftop #3138

General Information

PAND ID: 0591000000345823
RoofScape ID: Cool_613_2
District: Rotterdam Centrum
Area: 500.2 m²
Existing color: none

Preference Scores

Nature (green): 0.82
Water (blue): 0.88
Energy (yellow): 0.91
Social (red): 0.95
Mobility (orange): 0.63

Fig. 2.6 – RoofScape visualization applied to the city of Rotterdam, showing thematic classification of building rooftops and detailed informational panels integrated within the 3D urban model. (Source: MVRDV, 2022).

2.2.2 *City Information Modeling within GIS and BIM Frameworks*

The visualization of three-dimensional urban environments facilitates the resolution of urban planning and design challenges, supports decision-making processes, and enhances collaboration and communication among stakeholders (Hamilton et al., 2005). The rise of City Information Modelling (CIM) stems from this need and has been progressively enriched by the rapid advancement of information and storage technologies (Mozuriunaite & Haiyan, 2021). However, the multiplicity of modelling approaches has hindered the establishment of a unified methodological paradigm, comparing to what has occurred for GIS and BIM systems (F. M. La Russa, 2023). Consequently, the recent international debate on the definition of City Information Modelling reveals the difficulty in identifying the specific features that distinguish a CIM model from a 3D GIS or from a BIM model extended to the urban scale. According to Xue et al. (2021), the interpretive key lies in the meaning attributed to the "I" of *Information* within CIM, as compared to GIS and BIM. The term City Information Modelling refers to the technologies and practices used to develop digital models that maximise their potential for urban and spatial analysis (Mozuriunaite & Haiyan, 2021; Xue et al., 2021). CIM models may therefore be understood as BIM processes applied to the urban context, therefore as a three-dimensional semantic expansion of GIS models (Stojanovski, 2013). As noted by Xu et al. (2014), one of the main challenges of CIM lies in the management of information modelling, since such models handle both internal and external data, which are semantically connected. It is important to note that 3D urban models developed within BIM environments and subsequently visualized in GIS platforms (and vice versa) do not meet the definitional criteria of CIM. In these cases, geometries and information are not able to interact or modify one another beyond basic visualization or querying functionalities. These types of urban 3D models, also known as *GeoBIM*[14], primarily focus on interoperability between standard BIM and GIS formats (IFC and CityGML) (Della Scala et al., 2023).

Although the early developments of CIM were identified in applications combining point cloud data acquired through instrumental surveys with georeferenced 3D models in GIS environments (Julin et al., 2018), the information in such models is typically organised in layers within two-dimensional geometries (Lu et al., 2017). This highlights a fundamental distinction between GIS

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[14] The term *GeoBIM* refers to the integration of GIS and BIM, conceived as a response to the informational fragmentation between the building scale and the territorial scale. This integration enables the representation and analysis of the entire built environment, from individual buildings to the urban context, within a unified informational framework. *City Information Modeling* (CIM) goes beyond the integration of GIS and BIM, positioning itself as a conceptually broader tool for managing the urban context. This approach also requires a critical reflection on the role of scale in the representation and analysis of urban assets.

and CIM: City Information Modelling considers urban scenarios entities in causal relation to one another (as in BIM), rather than solely based on spatial proximity or georeferencing (F. M. La Russa, 2023). BIM, on the other hand, focuses on information at the architectural scale, supporting the design, management, and conservation of a building (Osello, 2015). In CIM, the relationships between individual architectural units and the information tied to the three-dimensional urban context are taken into consideration. (X. Xu et al., 2014). A 3D city model is defined as spatio-semantically coherent when there is a univocal relationship between each element and its host object, both in geometric and semantic terms. Conceptually, these models are structured similarly to BIM models, which rely on families and parameters (Arroyo Ohori et al., 2022). On the basis of these relationships, which emerge within the urban scene, the semantic enrichment of modelled components is defined (for example, identifying a façade and determining whether it corresponds to the main frontage facing the street).

The literature reveals that the integration of Geographic Information Systems (GIS) and Building Information Modelling (BIM) into a unified model, capable of analysing an urban area at different scales (both geometrically and informationally), and for various objectives, represents one of the major challenges (Jovanović et al., 2020; Ying et al., 2020). On one side, there are systems that represent territorial and urban data predominantly in two dimensions; on the other, systems that describe individual buildings and their construction components in detailed geometric and informational terms.

Mozuriunaite & Haiyan (2021) describes the evolution of CIM systems through four main phases. The first phase involves the combination of GIS technologies and digital modelling, with the goal of creating a unified and coherent urban information model (such as GeoBIM models). The second phase concerns the enhancement of user interaction with these models, enabled by technologies like Augmented Reality and Virtual Reality, which facilitate more effective consultation, both on-site and remotely. The third phase is characterized by the integration of the Internet of Things, aiming to embrace the concept of the Digital Twin at the urban scale. The fourth phase, involves the application of artificial intelligence algorithms, with the aim of further improving the creation and management through the CIM model, reducing associated costs while increasing the quality of the outcomes.

2.3 Technology Foundation of CIM

In the evolution of CIM, a key role is played by the technological integration of BIM, GIS, and other cutting-edge technologies, such as IoT networks, big data analytics, and artificial intelligence (Yu et al., 2025), which are currently attracting growing interest in the international scenario.

The development of CIM models entails the creation of a synergistic technological ecosystem: interoperability between BIM and GIS enables multidimensional urban representations; IoT sensor networks allow real-time data acquisition; while big data and AI driven analytics, combined with distributed computing frameworks, facilitate predictive modelling and the optimisation of decision-making processes. These models are characterised by properties, rules, and attributes that confer a certain degree of "intelligence." Indeed, there is a growing interest in Information Technology (IT) tools designed to produce integrated data management systems, both graphical and non-graphical, concerning to the built environment (Del Giudice et al., 2017). This interdisciplinary integration has the potential to shape an enabling digital infrastructure, which is a prerequisite for the definition of the urban digital twin: a key component in the development of smart cities.

This study addresses the framework for defining the information modelling of CIM models, from both geometric and semantic perspectives. However, it is considered important to also mention cutting-edge technologies that could potentially be implemented in the process, in order to emphasise the importance of a forward-looking approach. These technologies, in fact, offer possible avenues for integration within the CIM context and represent a well-recognised area of development in the scholarly literature.

The following section outlines the key enabling technologies that can be integrated into the CIM model.

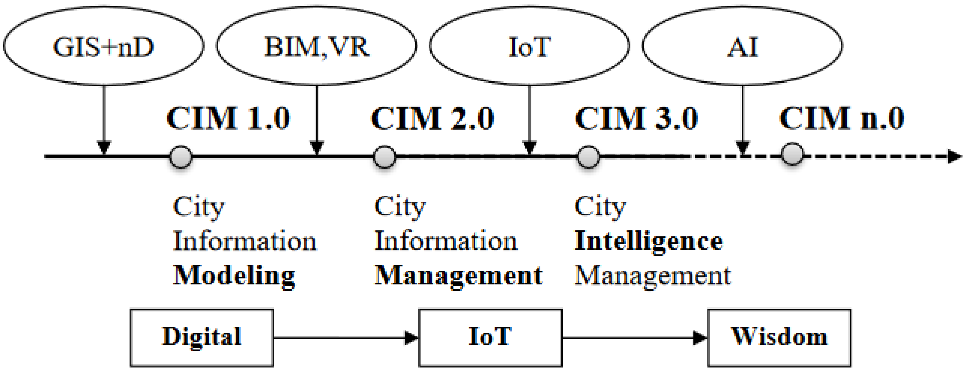

Fig. 2.7 – Stages of CIM's development and application. (Source: Mozuriunaite, 2021).

2.3.1 *Building Information Modeling (BIM)*

A three-dimensional model of the urban context is spatially and semantically consistent when geometric and semantic relationships exist among its objects (Arroyo Ohori et al., 2022). Building Information Modeling (BIM) constitutes a parametric and semantic modeling system capable of meeting the requirements for urban management. BIM is a system that demonstrates the ability to manage the fragmented but interconnected information needed in the building workflow within an "all-in-one" environment. It cannot be ignored when controlling the "shaping" of buildings and cities and especially when the design aspires to be "regenerative." At the core of this interaction lies the Model: a virtual representation of a real-world element, which simultaneously serves both as the object of the interaction and as the medium through which it the interaction takes places (Bianchini et al., 2021). Through BIM, by associating a graphical model with a repository of structured information, each digital object becomes the direct counterpart of a real object and stores its semantic annotations (Scandurra, 2020). Each element can be enriched with additional content to represent not only its quantitative properties (such as geometry) but also its qualitative attributes, including materials, physical parameters, performance characteristics, and more. BIM systems effectively provide a digital environment capable of hosting, organizing, and managing all this information through the 3D model, which, to some extent, can function as a gateway to the building's information database (Bianchini & Nicastro, 2018).

Today, the term BIM refers to a type of architectural modeling considered advanced from an informational standpoint. Thanks to its parametric modeling features, which attribute intrinsic meaning and relational properties to objects and to the set in which they are embedded, BIM plays a strategic role in the development of City Information Modeling (CIM). The resulting three-dimensional representation consists of a digital model consistent with the attributed information, thereby becoming the visual tool that enables data integration and querying. Through the model, the information can be georeferenced (Di Luggo & Scandurra, 2016). By implementing multidimensional data schemas in addition to geometric modeling, BIM enables the structuring of a rich data substrate for urban computational analyses (Yu et al., 2025).

Despite the considerable advantages that BIM brings to CIM, several critical issues hinder its full potential. Among these is the lack of standardized data formats, heterogeneous scales of representation, and inconsistent protocols between BIM and other systems, which significantly obstruct smooth data exchange and collaborative analysis (Nguyen & Adhikari, 2023). This interoperability issue greatly limits the effectiveness of integrated urban management systems. Although the integration of BIM within CIM is increasingly recognized, ensuring its effective implementation and optimization remains a significant challenge for future developments (Heidari et al., 2023).

2.3.2 *Geographic Information System (GIS)*

The Geographic Information System (GIS) is a geospatial information system for documenting, analysing, and representing territory, integrating data storage with cartographic and analytical visualisation tools in the form of cartograms, charts, and tables. Batty et al., (2012) describe it as an essential component of the digital infrastructures of contemporary cities, emphasising its technical role in managing geographic information and in developing urban simulation and decision-support systems.

GIS platforms are primarily two-dimensional, and geographic data are framed within projection and coordinate systems to accurately represent the territory. It maps the geographical location and topology of territorial entities, providing data management and modelling for advanced cartography (Del Giudice et al., 2014). At an operational level, GIS enables the overlay of multiple informational layers, offering a multidimensional representation of space and supporting complex spatial analyses (Goodchild, 2009).

Recent developments have expanded its capabilities, making it possible to perform three-dimensional modelling of the territory, with the aim of enhancing the semantic and spatial relationships between data (Scandurra, 2020).

Within CIM (City Information Modeling) frameworks, GIS constitutes the essential foundation for the geospatial structuring of the urban model. By integrating informational layers from heterogeneous sources with operational datasets, GIS emerges as a system capable of improving the efficiency and accuracy of urban planning.

Nevertheless, GIS continues to face significant challenges in managing large volumes of data and in keeping information up to date. As a result, it stands as a strategic platform for integration with other information systems, consolidating its key role in the development of CIM models.

2.3.3 *Internet of Things (IoT)*

The emergence of Internet of Things (IoT) applications has introduced a wide range of innovative digital solutions (Banfi et al., 2022). In particular, by enabling the real-time monitoring of diverse and dynamic urban elements through extensive networks of interconnected sensors and smart devices, IoT represents a key driver of advancement within the City Information Modeling (CIM) framework. By capturing and processing real-time data on critical urban metrics such as traffic flow, energy consumption, and environmental changes, IoT supports the development of more responsive and data-driven urban management strategies (Gil et al., 2010). Through such applications, IoT not only enhances the operational efficiency of urban systems but also provides the foundations for sustainable and intelligent urban development, thereby reinforcing its critical role in the evolution of CIM (Yu et al., 2025).

The implementation of IoT within CIM, however, entails substantial challenges, particularly concerning data security and privacy, due to the large-scale collection of sensitive information via urban sensor networks. Ensuring the accuracy and reliability of sensor data is equally critical, as inaccuracies may compromise the validity of decision-making processes. Moreover, the integration of heterogeneous IoT systems presents technical obstacles related to interoperability, alongside the need for standardized communication protocols to facilitate seamless data exchange (Souza & Bueno, 2022; B. Wang & Tian, 2021).

Despite these challenges, IoT technologies offer considerable potential for the further development of CIM. Although the present research does not employ data derived from IoT-based systems, it is nonetheless essential to acknowledge these areas of innovation, as their technological integration into CIM frameworks will be inevitable in the future. This is particularly relevant given the opportunities they provide for enhancing the management of urban systems, especially within the broader context of smart city development.

2.3.4 *Big Data Analytics*

In a complex context such as the urban environment, characterized by an ever-growing production of data required to generate awareness and support informed decision-making, which in turn drives operational actions, the need to organize such data so as to make it comprehensible and facilitate its use in decision-making processes emerges with particular urgency. From a forward-looking perspective, data analytics holds the potential to integrate with City Information Modeling (CIM), thereby enhancing the intelligence and operational efficiency of urban management systems. By synthesizing information from sensor networks and other ICT-based data collection systems, the integration of Big Data Analytics into CIM can steer the management of urban operations towards a data-driven approach capable of addressing complex urban challenges more effectively (Fang et al., 2024). Reliance solely on isolated data sources, in fact, does not allow for a coherent overview of the urban ecosystem.

Data analytics is distinguished by its capacity to integrate large volumes of real-time data and compare them with historical databases, thereby improving urban governance and the effectiveness of strategic actions (Yu et al., 2025). However, the widespread implementation of Big Data Analytics within CIM faces several significant challenges, including: the heterogeneity of urban data sources, which results in inconsistencies in formats and standards; the exponential growth of data volume; and the need to ensure high computational performance to meet the demands of real-time analysis. The potential of Big Data Analytics in driving intelligent and sustainable urban management represents a development area that, in the long-term, will be indispensable in the evolution of CIM models. Although no computational procedures related to big data are applied in the present research, it is deemed appropriate to mention this topic, given its scientific relevance and the strategic role it is expected to play within the technological framework in the coming years.

2.3.5 *Artificial Intelligence (AI)*

Artificial Intelligence (AI) is progressively emerging as a foundational technology which, in a future development scenario, when integrated into City Information Modelling (CIM), can significantly enhance the management of the urban context by supporting operators in the automation of repetitive tasks. In this scenario, the integration of AI will increase the efficiency of urban data processing, thereby enabling a more intelligent and detailed management of the city (Ashwini et al., 2022; Herath & Mittal, 2022). AI applications to be employed in future CIM implementations will predominantly utilize machine learning, deep learning, and data mining techniques, with the aim of analysing extensive urban datasets, providing forward-looking insights into urban development, and generating optimised solutions (Yu et al., 2025).

The significant progresses in artificial intelligence entail mention in the context of this research, as the development potential offered by its integration into urban management processes will require a three-dimensional support system, the CIM model, which constitutes the focus of this thesis.

2.4 Overview of International Standards for the Development and Adoption of CIM

The progressive application of City Information Modeling (CIM) within urban processes entails a parallel evolution of international standards, which will play a key role in its adoption. Nowadays, there is no specific reference standard for CIM; however, as a multidisciplinary system based on the management of information relating to different assets, it aims to ensure interoperability and sustainability within the urban context. The following sections present the international standards published to date that are considered fundamental for the future development of CIM, which will require further evolution. ISO 19650[15] constitutes a fundamental reference for information management in the construction sector, as it defines a structured framework steering the organization, digitization, and management of data throughout the entire asset life cycle. The goal of this standard is ensuring interoperability among systems and stakeholders, as well as fostering sustainability in urban development. In Italy, the principles and recommendations of ISO 19650 are applied through UNI 11337[16], which regulates the digital

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[15] International Organization for Standardization. (2018). *ISO 19650-1:2018* – Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM), Information management using building information modelling, Part 1: Concepts and principles. ISO.

[16] UNI 11337 Ente Nazionale Italiano di Unificazione. (2017). *UNI 11337:2017* – Digital management of building information processes – Part 1: Models, documents, and information objects for building products and processes. UNI.

management of information processes in the construction sector, covering both buildings and infrastructure.

In the long term, from a forward-looking perspective, standards such as ISO 30162:2022[17] and ISO 30173:2023[18], which address, respectively, Internet of Things (IoT) technologies and digital twins, are closely related to City Information Modeling. Regarding smart cities and sustainable urban development, ISO 37120[19] and ISO 37106[20] provide guidelines for data sharing, system interoperability, and urban resilience.

Taken as a whole, these standards can contribute to the integration of City Information Modeling processes into traditional practices, supporting stakeholders in adapting to future challenges and emerging technologies. The table below presents the reference framework of the standards analyzed, highlighting their impact on implementation.

Standard Name	Relevant Field	Standard Overview
ISO 37120	Urban Sustainability	Focuses on urban sustainability and the quality of life by providing standardized indicators and a data management framework.
ISO 19650	BIM	Defines the information management for buildings and civil engineering works through the organization and digitization of data, including BIM.
UNI 11337* (Italy)	BIM	Defines the information management for buildings and civil engineering works through the organization and digitization of data, including BIM.
ISO/IEC 30146:2019	Information Technology	Defines a framework of evaluation indicators for ICT adoption in smart cities, detailing each indicator’s name, description, classification, and measurement method.
ISO 37106	Smart Cities and Sustainable Cities	Sustainable cities and communities-guidance on establishing smart city operating models for sustainable communities.
SO/IEC 30162:2022	IoT	IoT - compatibility requirements and a model for devices within industrial IoT systems.
ISO/IEC 30173:2023	Digital Twin	Digital twin - concepts and terminology.

Table 1: Key milestones in the development of CIM standards. (Source: Yu, 2025). *author’s addition relative to the source.

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[17] International Organization for Standardization & International Electrotechnical Commission. (2022). *ISO/IEC 30162:2022* – Internet of things (IoT), Compatibility requirements and model for devices within industrial IoT systems. ISO/IEC.

[18] International Organization for Standardization & International Electrotechnical Commission. (2023). *ISO/IEC 30173:2023*, Digital twin, Concepts and terminology. ISO/IEC.

[19] International Organization for Standardization. (2018). *ISO 37120:2018* – Sustainable cities and communities, Indicators for city services and quality of life. ISO.

[20] International Organization for Standardization. (2021). *ISO 37106:2021* – Sustainable cities and communities, Guidance on establishing smart city operating models for sustainable communities. ISO.

2.5 The Representation in CIM: Geometric Modeling, Semantic Structuring, and Information Requirement Definition

The construction of a consistent and rigorous multidisciplinary database represents not only a key task, but also a process that requires the cooperation of diverse expertise in order to propose interpretations that transcend the limits of individual disciplines. One of the distinguishing features of virtual 3D city models is their ability to visually integrate heterogeneous geoinformation into a unified framework. This capability enables the creation and management of complex urban information environments (Bianchini et al., 2021). The applications of 3D city models cover almost all disciplines, making their generation and management a topic of considerable scientific relevance (F. M. La Russa, 2023).

The construction of a CIM (City Information Model) entails an interpretative effort concerning the semantic structuring of its elements. This ontological and subjective step goes beyond the simple geometric identification of objects. The modeller must, in fact, move from the real to the digital continuum (Inzerillo et al., 2016), navigating a hierarchical and additive environment in which all digital objects must find their place within the parametric domain.

In the context of this research, the focus is on semantic 3D city models. The motivation for semantic 3D city models lies in their capacity to enable the extraction of information from the model (for example, determining the number of inhabitants in a city block or the construction years and techniques of its buildings). Models that do not allow queries and/or interactions cannot be defined as semantic 3D city models, but rather as 3D representations of a territory. Given the wide variety of 3D city model types, it became necessary to establish an international standard for defining their data structure from a semantic perspective, ensuring that even when models are generated from different data and processes, they are structured in a consistent manner (F. La Russa et al., 2021).

The predominantly geometric nature of Levels of Detail (LOD) is partly due to the fact that current applications of 3D city models tend to focus more on geometry and texturing than on the semantic content of objects. However, the growing importance of CIM in urban context management, similarly to the role of BIM (Building Information Modeling) in the construction sector, necessitates a reconsideration of the concept of Level of Development (LOD) for such models. In the context of City Information Modeling, LOD plays a central role in structuring and progressively defining digital information related to the urban scene. As in BIM, LOD in CIM encompasses not only geometric representation but also the degree of completeness of the information associated with digital objects. The Italian standard UNI 11337-4:2017 defines LOD as “Level of Development” (not merely “level of detail”), articulated in seven progressive stages (A–G) that govern both the geometric and the informational components. This goes hand in hand with the concept of Level of Information Need (LOIN), introduced by UNI EN 17412-1:2021, which specifies that the quantity and quality of required information must be defined according to the intended use of the model, thus avoiding unnecessary excesses of detail. An attempt at standardisation was made through the CityGML format, which identifies five Levels of Detail (LOD) in 3D representation: from LOD0 (ground footprint) to LOD4 (buildings modeled both internally and externally), and employs a set of classes to describe urban features. However, this organisation has been found to contain ambiguities arising from advances in data acquisition and modelling techniques, which sometimes allow for the representation of only a portion of the model. This issue has been extensively discussed in the literature.[21]

Fig. 2.8 – The five LODs in CityGML for the exterior of a building. (Source: Biljecki, 2017).

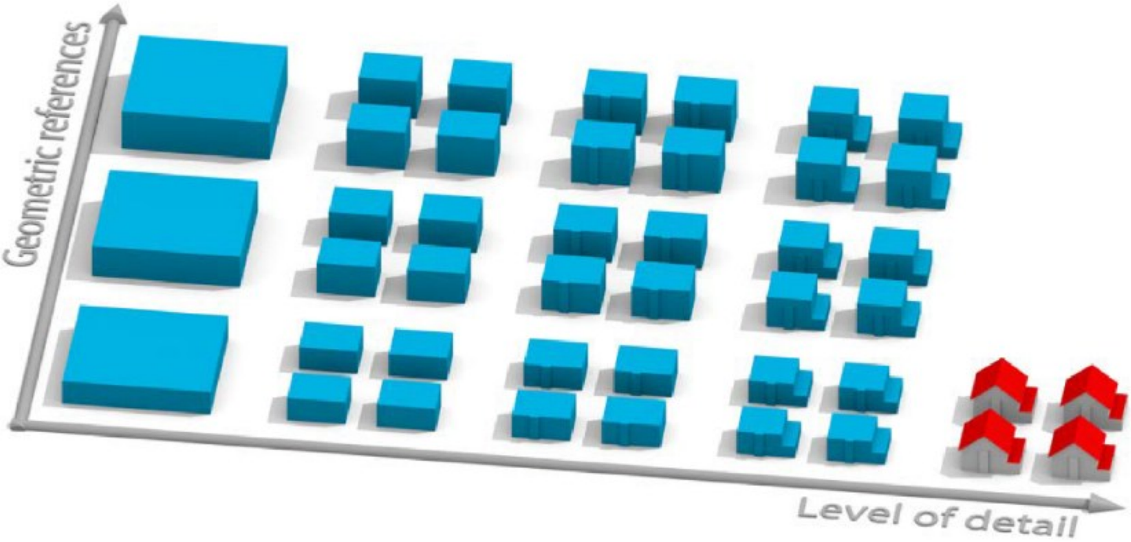

Fig. 2.9 – The orthogonal relationship between the LOD and geometric reference concepts. (Source: Biljecki, 2017).

According to Biljecki et al., (2016), the application of the concepts of LOD and LOIN in the context of CIM remains in a phase of standardisation and consolidation. In this research, a reflection is proposed on the geometric and informational definition of parametric objects

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[21] For further details: Deng et al., 2016; Fan et al., 2014; Guercke et al., 2011

representing urban models. CIM is not conceived as the aggregation of all BIM models within a district or urban area. Instead, the representation of the urban scene entails a distinct approach to the management of geometries and the associated information. Accordingly, a metadata structure is proposed, based on discretised topological families, whose primary value lies in the informational attributes that enrich them.

2.6 Open Standards for Digital Interoperability in City Information Modeling

BIM datasets are emerging as a promising and valuable source for 3D city models and their management. Fundamentally, a BIM model is a database; therefore, schedules and other information can be extracted and employed for a variety of purposes (Del Giudice et al., 2017).

The development of City Information Modeling (CIM) requires the exchange of models (i.e., information) among different software applications and tools, which inevitably leads to data and feature losses. To enhance stakeholder involvement, interoperability, and interactivity, there is a need to integrate CIM models with semantic web platforms through an Open BIM approach based on open standards (Iadanza et al., 2019), thereby enabling end users to access information using a standard web browser. Therefore, open standards are developed with exchange formats to establish interoperability among different tools.

The two most prominent data formats in the architecture, engineering, and construction (AEC) sector, and in the geospatial domain respectively, are the buildingSMART standard Industry Foundation Classes (IFC)[22] and the Open Geospatial Consortium (OGC) standard CityGML[23] (Biljecki et al., 2021). Both CityGML and IFC represent different aspects of 3D models, including semantics, geometry, topology, and appearance. However, they differ significantly in how they store and represent such data (Salheb et al., 2020).

The Industry Foundation Classes (IFC) is an international openBIM standard and format for the exchange of BIM data. It is recognised by ISO 16739-1:2024[24] and provides a highly detailed semantic model for 3D buildings (Eastman et al., 2011). The IFC architecture follows an entity–relationship model based on express schemas. It consists of hundreds of entities organised hierarchically through object inheritance relationships. The most common file format is IFC-SPF, which uses STEP encoding, which is a plain-text that is human-readable and more compact than XML (Salheb et al., 2020).

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[22] buildingSMART, Industry Foundation Classes (IFC). https://www.buildingsmart.org/standards/bsi-standards/industry-foundation-classes/

[23] Open Geospatial Consortium, OGC City Geography Markup Language (CityGML). https://www.ogc.org/standards/citygml/

[24] International Organization for Standardization. (2024). *ISO 16739-1:2024* - Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries – Part 1.

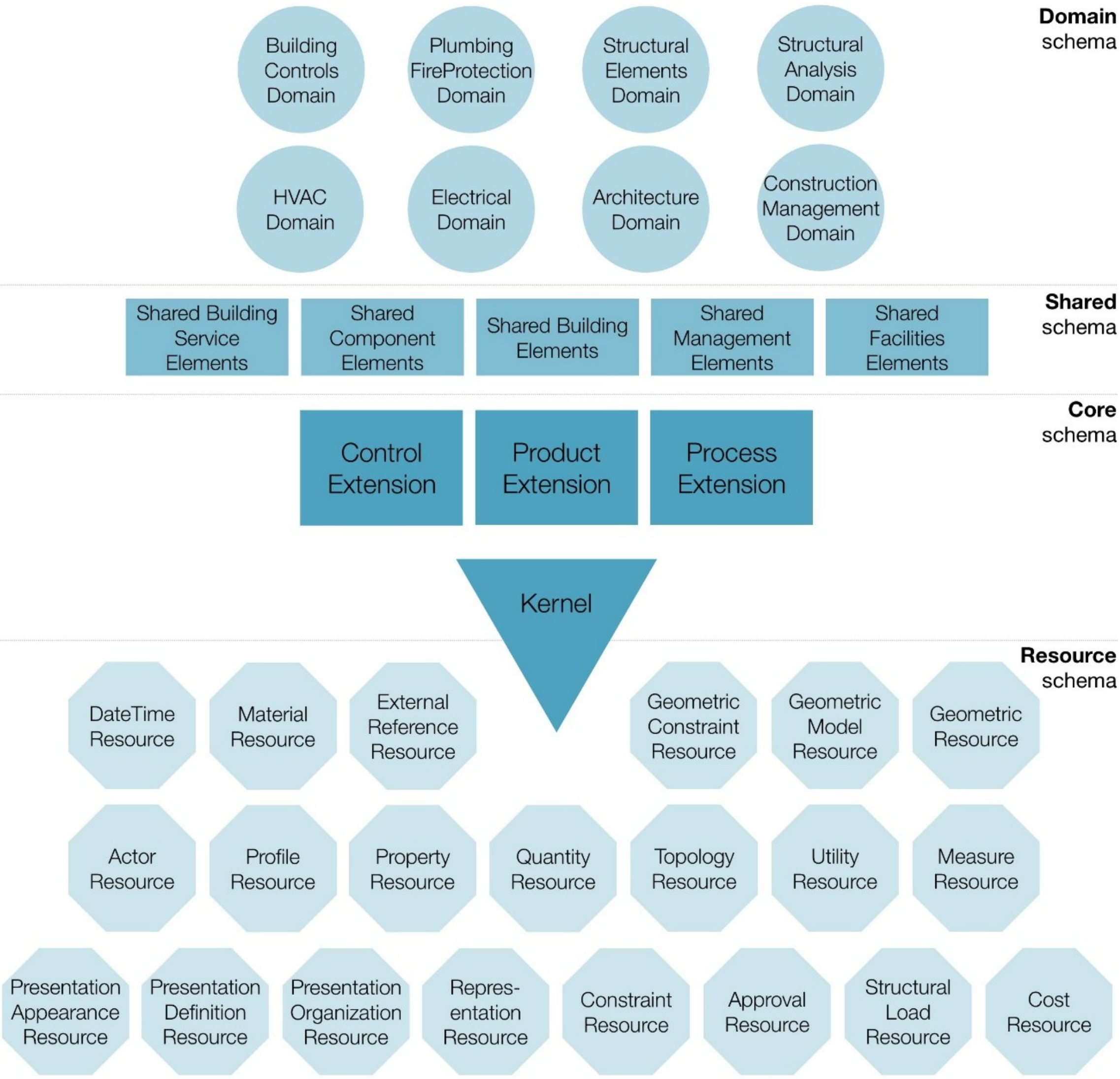

Fig. 2.10 – IFC schema: Organisation of IFC classes. From top to bottom: *Core schema*: classes that constitute the basic structure, fundamental relationships, and shared concepts, and are required for subsequent discipline-specific definitions (e.g., IfcActor, IfcTask, IfcElement); *Shared schema*: classes that describe more specific relationships and objects, shared across multiple disciplines (e.g., IfcBeam, IfcColumn, IfcDoor, IfcFastener, IfcFurniture); *Domain schema:* classes belonging to specific disciplines that cannot be further specialised by other classes (e.g., IfcAlarm, IfcCoil, IfcStructuralAction); *Resource schema:* supporting classes that cannot exist independently but only in reference to one or more classes from the other schemas (e.g., IfcDate, IfcPoint, IfcAddress, IfcMaterial). (Source: https://www.buildingsmartitalia.org/).

CityGML is an open standard model and exchange format for storing and exchanging virtual 3D models of cities and landscapes, developed by the Open Geospatial Consortium (OGC) and ISO/TC211 (Usman, 2021). CityGML is an application schema of GML 3 based on XML. It provides a common definition of basic entities, attributes, and relationships in a 3D city model. Its tree-based data structure creates a hierarchical representation that extends down to individual features and attributes (Salheb et al., 2020). The standard defines a data model that enables the semantic representation of 3D city models.

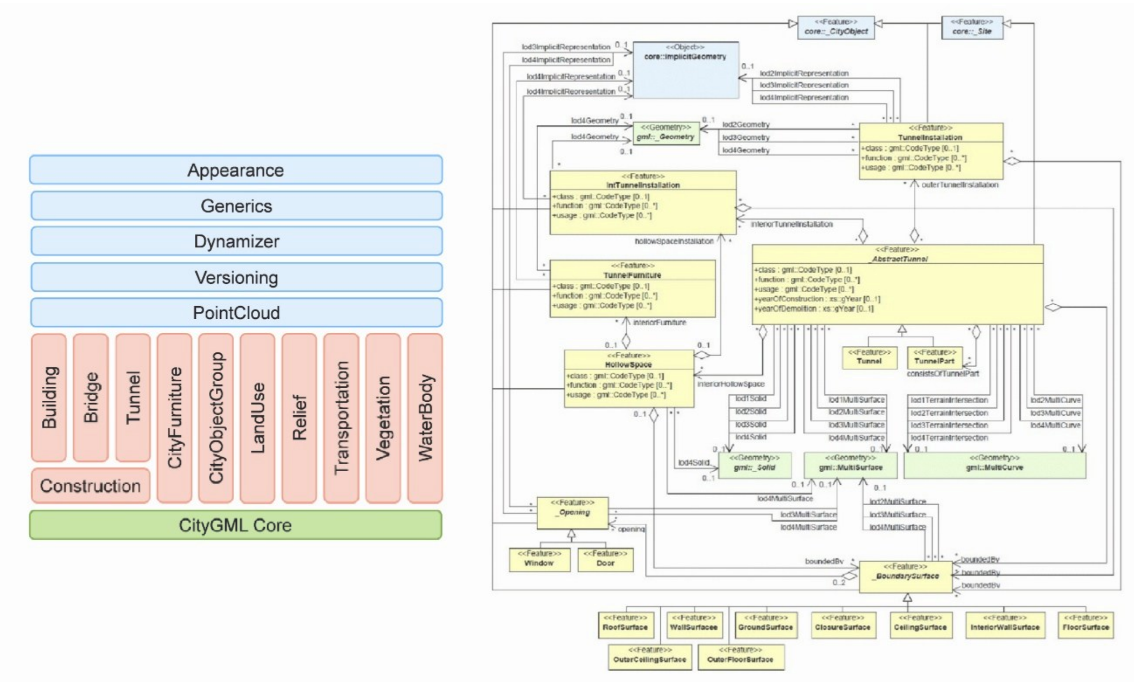

Fig. 2.11 – Left: The modules of the CityGML data model. (Source: Arroyo, 2022). Right: The CityGML data model. (Source: https://www.ogc.org/standards/citygml/).

The development of CIM models, and the consequent Open BIM approach, implies the convergence of models toward a single integrated urban model, standardising them in either the IFC or CityGML format. Biljecki et al., (2021) conducted research aimed at converting IFC into CityGML, with the goal of leveraging the advantages of both formats, including the development of additional layers. However, this XML-based encoding method is not among the most accessible, as it is not human-readable, has a rigid hierarchical structure, and is poorly suited for the web. On the other hend, Salheb et al., (2020) tested a basic framework for conversion from CityGML to IFC. Although the IFC format is relatively rigid, recent developments in IFC4 allow for the management of classes related to the urban context. According with Salheb et al., (2020), converting models to IFC can be beneficial for creating complete BIM models for buildings that require one. Another potential application is the creation of simplified BIM models of buildings, which can then be further developed using BIM software to produce thematic building representations.

Nevertheless, although both IFC and CityGML are capable of rich semantic and geometric representations, they are not natively suited for web visualisation or for integration with databases and IoT networks. In particular, both rely on hierarchical encodings (STEP for IFC and XML for CityGML) that are not optimised for lightweight, browser-compatible environments (Ledoux et al., 2019). This limitation has driven the development of alternative representations, particularly in JavaScript Object Notation (JSON): a format inherently compatible with web technologies and application programming interfaces (APIs). JSON is a lightweight, text-based data interchange format widely adopted for its simplicity, readability, and compatibility with all major programming languages and platforms. Its use in the context of 3D urban modelling has led to the creation of formats such as CityJSON, a simplified alternative to CityGML that preserves its semantic expressiveness while streamlining its structure, thus enhancing usability in web applications (Ledoux et al., 2019). Similarly, experimental initiatives have emerged to convert IFC into JSON to enable BIM data visualisation and interaction within browsers, leveraging libraries such as IFC.js (Stouffs et al., 2018). While IFC and CityGML remain foundational standards for modelling and data exchange in the BIM and GIS domains, JSON, although not yet standardised, is increasingly recognised as a key enabling technology for City Information Modeling, particularly regarding open data, platform integration, and user accessibility.

Chapter 3
METHODOLOGICAL APPROACH

3.1 The Construction of the Methodological Model

This chapter illustrates the methodological model developed in order to coherently address the research questions posed. In an urban context characterized by ecological and demographic transitions, oriented towards sustainability, the research seeks to overcome the technical and regulatory limitations of traditional urban models. For this reason, an information-management approach based on City Information Modeling (CIM) is proposed. Such an approach is capable of integrating qualitative and perceptual dimensions of the urban scene and of supporting, in a cross-cutting manner, processes of knowledge, conservation, and transformation of the built environment. Within this framework, the guiding research question is: *"To what extent can a CIM model become a strategic descriptive tool, capable of representing the qualitative complexity of the urban scene and of providing transversal support to decision-making processes?"*.

This question leads to the general objective of the research, which is to define a City Information Modeling framework that can support urban management. The model is developed to integrate heterogeneous information and synthetic indicators in order to interpret, monitor, provide insights, and guide processes of transformation and conservation of urban space in its material, perceptual, and functional dimensions. From this perspective, it becomes essential to investigate the relationships among the various elements that constitute the urban context, thereby reconstructing the typological, morphological, and relational positioning of buildings and spaces within the city. A further objective consists in the development of interpretative and representational tools able to provide a strong informational basis, capable of synthesizing complex and heterogeneous data to inform decisions regarding urban management and transformation. In this way, the passage from raw data to an interpretative and consciously managerial dimension can be accomplished.

Understanding urban space is a prerequisite for effective CIM modeling, as it provides the frame of reference within which qualitative information acquires meaning, coherence, and operational value. To address this topic, a more thorough analysis is needed. In the following sections, more research questions are formulated in support of the development of the thesis. It thus becomes important, first of all, to clarify the meaning of certain key terms and concepts that constitute the basic framework within which the research is situated.

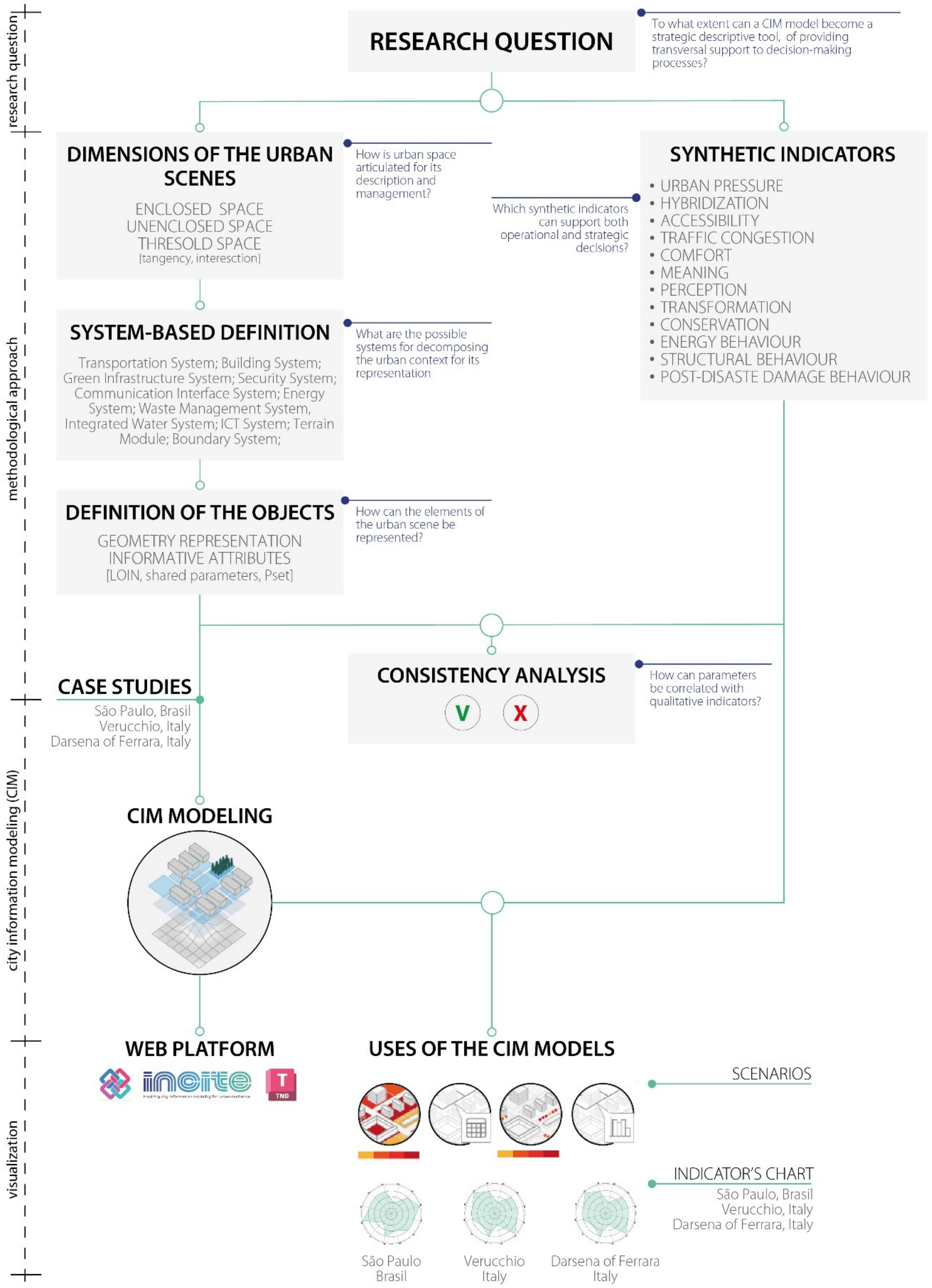

Fig. 3.1 – Main stages of the research methodology, together with the corresponding research questions.

3.2 The Dimensions of the Urban Scene: Enclosed Space, Unenclosed Space and Thereshold Space

Understanding urban space is a prerequisite for effective CIM modeling, as it provides the reference framework within which qualitative information acquires meaning, coherence, and operational value. To carry out this descriptive process, it is essential to identify the dimensions that define the articulations of the urban scene. The additional research question formulated to address this methodological issue was: *"How is urban space articulated, in order to convey to its users the necessary information - characteristics, elements, and data for its description and management?"*. The research aims to identify dimensions defined by their ability to correlate, within the same interpretative framework, various aspects connected both to perceptual action and to the attribution of managerial meanings (habits of use, temporal variations, cultural influences, etc.). This reflection was also developed with a view toward parametric modeling, which CIM implies. Both from the perspective of available data and from that of geometric modeling and information attribution, the resulting information is subsequently grouped and filtered according to the specific purposes and uses of the model.

On one hand, there is a dimension constituted by self-referential spaces, where space itself is highly charged with responsibility: *enclosed space*. Defined by the acceptance of *interiority*, enclosed space is without freedom, but everything within it is organized through a hierarchy of phenomena: one enters through a door, there is a corridor, a designated function, a capacity, a relationship, and so forth. It identifies those areas which, though not necessarily confined within a built volume, are regulated by rules of use related to behavioral systems characterized by a strong sense of meaning and belonging.

On the other hand, there is the dimension of *unenclosed space*, where the structure of the urban context appears fragmented into interrelated and complementary parts, yet lacking effective control over contextual relationships and spatial contiguities. These dimensions are vast and devoid of clear references. Our system of perception and interpretation is shaped according to logics functional to survival. Our routes are deduced through the construction of a mental map generated by instinct and subsequently layered with experience. In such conditions, behavioral models, often characterized by *distraction*[1], as well as concepts of ownership linked to collective use and public perception, activate modes of inhabiting space that differ from the *interiority of external space* as indicated by Consonni[2]. Conceptually, unenclosed space is defined by practices of use, understood as consolidated habits, which change as soon as the domestic threshold is

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[1] For further detalis: Walter Benjamin, *Immagini di città*, Torino 1971, Einaudi.

[2] For further details: Giancarlo Consonni, *L'internità dell'esterno. Scritti sull'abitare e il costruire,* Milano 1989, CLUP.

crossed, both in relation to the quality of details and to the identification elements that typically foster the sense of belonging associated with private interior spaces.

In the urban scene, as translated into CIM-based modeling, there are not two distinct entities (enclosed versus unenclosed space), but rather a single space that can become either enclosed or unenclosed, where their contact creates situations of *threshold space*, which implies conditions of *tangency* and *intersection*.

Within this tangential relationship, margins (fences, boundaries, property lines, protective barriers) represent the first element of contact and perhaps the most impactful on the urban scene at ground level. This is the invention of the boundary, the identification of an inside and an outside relative to the limit. It is the moment of rupture that shifts the relationship between the indeterminacy of unenclosed space and the conception of a defined domain: enclosed space. Such devices acquire cultural and social significance depending on territorial contexts, and through their absence/presence and morphology, they are capable of expressing many distinctive features typical of relational environments (Balzani, 1995). Walking through the landscape, the wall reveals itself as a "persistent ruin": an ancient formula that enabled the thickening and sedimentation of matter. Historically, the wall has been consistently entrusted with a discriminating role, as an element aimed at the precise identification of a recognizable and measurable limit. Relentlessly, humankind has built walls to organize and divide the space and territories it occupies (Gobbo, 2020). The wall, as the bearer of an imaginary, embodies the physical dimension of division, the limit between parts. Paraphrasing Étienne Balibar[3], the wall, in its representation and presence, thus becomes the very definition of the boundary. Concepts such as *property*, *protection*, and *freedom*, which regulate many social convictions, can be correlated to the model and to the type of fencing, depending on the place, the neighborhood, and the geographical setting under examination.

To describe and understand the implications inherent in boundary elements, a more complex and articulated language is required than the common perception of the wall solely as an image of exclusion. The boundary of enclosed space may, under certain circumstances, be understood as an *osmotic membrane*. Terms such as surface, accumulation, proximity, interface, and interaction can all shift meaning when applied to the boundary, to its role as a porous structure, an intermediate buffer between parts[4]. The concept of *absorption* spans across various scientific

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[3] For further details: Étienne Balibar, *Nous, citoyens d'Europe? Les frontières, l'État, le people*, La Découverte, Paris 2001.

[4] For further details: Simone Gobbo, *L'innocenza del muro*, Quodlibet, 2020.

domains[5]. Generally, this behavior can be interpreted in two ways: an active meaning, with respect to the wall as an architectural feature capable of attenuating the shock waves of two opposing forces; or a passive meaning, whereby the wall is itself absorbed into the urban fabric. Consider, for example, the building envelope, which plays a significant perceptual role in the urban scene. It is not simply a boundary, but a dynamic interface capable of mediating the relationship between users and the external environment, even fostering processes of perceptual introspection. In this sense, the perception of light and shadow does not convey the idea of an insurmountable barrier but rather that of a relational filter. Similarly, a fence can be interpreted as an osmotic membrane, characterized by varying degrees of permeability between enclosed and unenclosed spaces, thereby becoming a coherent reflection of the urban image.

In the urban scene, there are also situations in which enclosed and unenclosed spaces have a relationship of *intersection*. A paradigmatic case is that of arcades: inter-exterior spaces. On the one hand, they belong to and are managed by the building owner; on the other, they are characterized by practices of use and behaviors typical of unenclosed space.

3.3 Synthetic Indicators for Documenting and Managing the Urban Context

In the development of the research methodology, aimed at identifying possible ways in which a CIM model may become both a descriptive and strategic tool, capable of representing the qualitative complexity of the urban scene and supporting decision-making and management processes in a transversal manner, an additional research question was posed: *Which synthetic indicators can facilitate the documentation and management of urban space, by integrating heterogeneous parameters and supporting both operational and strategic choices?*

From the literature review and the analysis of case studies, 12 descriptive indicators emerged as useful for obtaining a clear picture of the main factors that can provide an interpretative framework of the urban context through the model, which thus already begins to function as a decision-support tool. Indeed, what is not measured is often not governed (Orii et al., 2020).

Each indicator was assigned a score from 1 to 5 in order to construct a coherent profile of the urban context under investigation. A low score indicates a negative condition. The indicators were subsequently correlated using a Kiviat Chart (or radar chart), a graphical tool that enables the two-dimensional visualization of multiple quantitative variables, each represented along axes radiating from a common origin.

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[5] “Chemical absorbation”: In chemistry, the term refers to the process by which a substance passes from a solution to the surface of a solid. This phenomenon involves the accumulation of chemical species in the vicinity of the interface between the two phases, resulting from both physical and chemical interactions. *The Hutchhinson Encyclopedia*, Hodder & Stoughton, 2002.

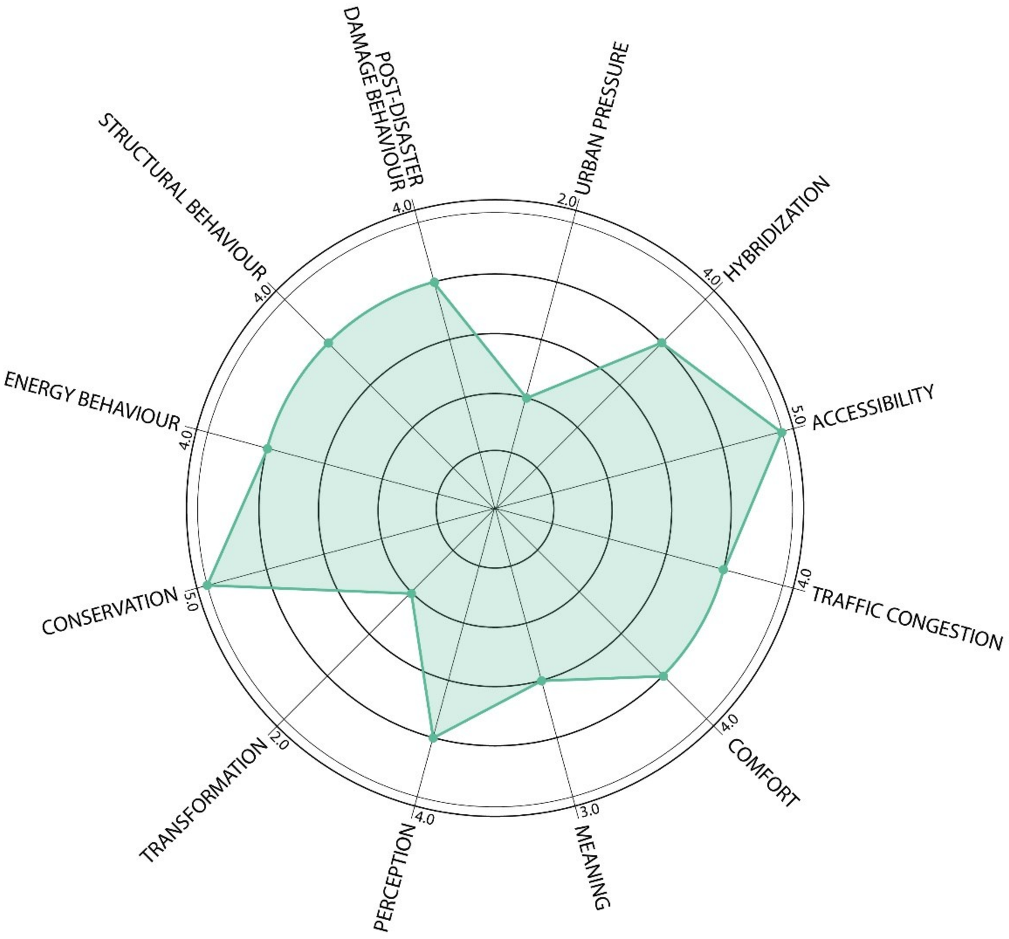

Fig. 3.2 – Example of the representation of the proposed synthetic indicators.

Location, primary functions, density and frequency, effects on both specific situations and on the continuity of façades or pathways, the passage of time, variations in lighting, patterns of use, and conservation conditions can all be documented and described through dedicated information maps, which convey data collected at different moments.

It is important to underline that this proposed articulation, which makes no claim to completeness, is intended to serve two main purposes:

- To construct maps or frameworks in which the representation of environmental data, unconstrained by the limiting content of urban zoning, allows for the identification of the widest possible range of factors at play. This is achieved through a simple language, easily compatible with design criteria in use, and particularly adaptable to variations and the diversity of places;
- To provide the opportunity to approach the theme of complexity through a process of decomposition and dismantling into parts, while preserving sufficient flexibility to reveal hierarchies of elements and devices that are not always identifiable by scale (spatial

relationships), marginal location, or functional selection (patterns of use, infrastructural connections).

3.3.1 *Defining the Synthetic Indicators*

The following section describes the indicators identified in this dissertation, which represent a fundamental step in constructing a system of cross-cutting references. The definition of these indicators is intended to capture the whole, describing the urban scene through the construction of a spatio-temporal framework in which the landscape is mechanically encompassed, yet where the observer is typically not considered. The aim is to provide, through these investigative criteria, a framework that can support the monitoring and simulation of decisions related to urban regeneration (Balzani, 1995).

Urban Pressure

It measures the impact caried out by the expansion and density of settlements within the urban and territorial context[6]. In certain context, exemplified in this thesis by the case of Higienópolis (São Paulo, Brazil), unprecedented transformations have been triggered by the anthropocentric orientation of socioeconomic growth. The massive scale of urban expansion directly affects not only demographic dynamics but also cultural contexts and minor architectures, as in the case of Vila Penteado, which appear subordinated to the surrounding urban fabric. Factors of subjection are also included, generating a set of introspective relationships between the façades of buildings and the smaller-scale built structures in adjacent areas. These factors also give rise to specific conditions related to overshadowing (reflected shadows) and to microclimatic constraints (Balzani, 1995). The analysis of this indicator becomes more comprehensive when conducted across a historical series, as it reveals the impact exerted by urban expansion and settlement density resulting from urban pressure.

Hybridization

Numerous transformations challenge the urban context in its evolution toward advanced modernity. The adaptation of buildings and urban spaces to contemporary requirements of space,

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[6] An approach widely recognized in the literature for an initial assessment of urban pressure is the ratio between the resident population and the urbanized area. Despite its simplicity, this measure allows for an immediate understanding of the intensity of anthropic impact on the territory. For further details: Jaeger et al., *Urban permeation of landscapes and sprawl per capita: New measures of urban sprawl. Ecological Indicators*, 2010.

$$Urban\ Pressure = \frac{Resident\ Population\ in\ the\ Study\ Area}{Urbanized\ Area\ (ha)}$$

light, ventilation, and mobility can affect the integrity and quality of the built environment. These processes naturally manifest themselves in the form of homogenization, differentiation, and, above all, hybridization, since the very concept of the city has historically been constructed as a hybrid social product. The monitoring of these phenomena is therefore essential to ensure the quality and sustainability of the urban context. In this case, the indicator reflects the degree of hybridization within the urban space under consideration.

Accessibility

The study of urban accessibility[7] is based on a survey of morphological conditions, taking into account not only dimensional and proportional factors but also patterns of use (safety-related factors), the frequency of devices, and assessments regarding the overall psycho-physical energy expenditure.

In this thesis, the accessibility indicator performs a dual role: on the one hand, it is understood as one of the main preconditions of social inclusion[8], representing the possibility, even for people with reduced or impaired motor or sensory abilities, to experience the urban environment under conditions of adequate safety and autonomy; on the other hand, it is linked to the temporal dimension of urban space. Within a micro-intermodal fabric at the human scale (where the main exchanges occur between pedestrian and bicycle, pedestrian and metro, pedestrian and car, pedestrian and bus), it measures people's experience of space in relation to travel and use times. Particular attention is given to the notion of urban proximity, defined as the degree of accessibility and nearness among services, resources, and urban functions (housing, workplaces, public transport, green spaces, schools, etc.). This allows for an evaluation of how much a neighborhood or district can provide the main activities of daily life within a walkable or easily reachable distance, thereby fostering models of compact, sustainable, and livable cities (Alonso et al., 2018). Moreover, accessibility is addressed as a multiscalar concept in relational terms: each environmental element constitutes a link in a chain of relationships, where, if even one of these links presents problems of access, the accessibility of the entire system is compromised (Lauria, 2023).

Traffic Congestion

Congestion represents one of the main critical issues in urban mobility systems. It is analyzed by correlating the demand for vehicular travel with the capacity of the road network, with direct

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[7] For further detail: Marcello Balzani, *Metodiche per il rilievo dei dati ambientali e rappresentazione del paesaggio. La costa romagnola*, 1995, p.134.

[8] For further details: Antonio Lauria et al., *Spazio pubblico e vita in città. Sei sfide per una società che cambia*, 2020.

repercussions on travel times and on the overall efficiency of transport flows. In this sense, congestion also constitutes a source of external noise which, from a sensory perspective, contributes to shaping the quality of the urban environment, delineating its profiles and influencing mobility and social interaction at multiple levels. The traffic congestion indicator, therefore, emerges as a transversal parameter that links the load on the road network with the increase in noise levels and the consequent impact on population comfort[9].

Comfort

The shift in lifestyles, linked to the growing awareness triggered by the COVID-19 pandemic, has placed renewed emphasis on the quality of housing and of open urban spaces, which have become essential components of individual well-being. This transformation is beginning to manifest its effects in urban regeneration processes, increasingly oriented towards fostering *vitality* and *livability*. These characteristics are fundamental to the performance of the different types of urban activities, necessary, voluntary, and social, that constitute the life in cities (Gehl, 1991)[10]. Urban vitality represents a subjective value that refers to the idea of a recreational city, associated with pleasure, art, and culture in the form of attraction and entertainment. Livability, by contrast, evokes the well-being of everyday life, encompassing opportunities for social engagement within the habitual practices of existence (Cicalò, 2009). In this perspective, Edward T. Hall's contribution on urban proxemics[11], proves particularly relevant: interpersonal distances, influenced by the configuration of public spaces, directly affect the modalities of social interaction and the degree of perceived comfort. These opportunities depend not only on the climatic and environmental characteristics of the intervention site but also on the formal requirements and physio-perceptual qualities of the urban space, including safety, comfort, and the degree of control[12] exercisable by its users (Lauria et al., 2020). Within this framework, concepts such as way-finding[13] and urban diversity[14] play a crucial role in shaping the degree of livability, with implications at spatial, social, and economic levels. The concept of "quality of life" (Q.d.V.)[15]

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[9] For further details of the impacts of urban mobility: Alonso et al., *CityScope: A Data-Driven Interactive Simulation Tool for Urban Design*, 2018

[10] For further details: Jan Gehl, *Vita in città*, 1991.

[11] For further details: Edward Thomas Hall, *La dimensione nascosta*, 1973.

[12] For further details: Antonio Lauria, *La pedonalità urbana. Percezione extra-visiva, orientamento, mobilità*, 1994; Antonio Lauria, *Persone 'Reali' e Progettazione dell'Ambiente Costruito: L'Accessibilità come Risorsa per la Qualità Ambientale*, 2023.

[13] For further details: Kevin Lynch, *The Inage of the City*, 1960.

[14] For further details: Jacobs, *The Death and Life of Great American Cities*, 1961.

[15] For further details: In *Come si misura la "qualità della vita" di una città*, 1986, Giovanni Koenig express the concept of "quality of life" into a more precise and measurable dimension, defined through the comparison between the overall environmental benefits and the generalized costs of access, according to the following ratio:

was further refined by (Koenig, 1986), who framed it within a measurable dimension, defined through the comparison between the overall environmental benefits and the generalized costs of access.

In this thesis, the comfort indicator is proposed with the aim of representing well-being in relation to the quality of housing, by considering the main requirements of communicability, orientation and wayfinding, and safety, which the urban environment should guarantee in order to mitigate conditions of physical and perceptual conflict.

Meaning

To understand the urban environment in its dimensions of scale, time, and complexity, Kevin Lynch's reflection[16] remains highly relevant: *"one should not only consider the city as an entity in itself, but also as it is perceived by its inhabitants"*. An environmental image must hold meaning for the observer, whether practical or emotional, and it is not easily altered through mere physical manipulation. The meaning indicator proposed in this dissertation aims to measure *affection*, understood as an affective and emotional dimension. The purpose is to highlight the affective value of places, where shared hopes and pleasures, as well as the sense of community, find tangible expression. In such contexts, where the environment is clearly organized and distinctly recognizable, citizens, by identifying with it, are encouraged to cherish and protect it.

Perception

Perceptive processes aim to identify the main visual relationships that often underlie the establishment of cognitive habits in relation to the urban environment. Perception plays a decisive role in shaping a series of dominant images of the urban scene, taking into account the prevailing perspectival effects determined by the configuration of the urban path, as well as the rhythm of the solid–void relationship and the interplay of vertical and horizontal features. Among the possible phenomenological relations that emerge between user/observer and the urban context, a very common psychological condition is *distraction*.[17] The urban scene is frequently perceived in a distracted manner by citizens, who, while experiencing it, are often absorbed in other thoughts related to practical intentions, such as the destination to reach or the people to meet. In this context, unenclosed space, lacking referential elements and limits, acts upon the subject in a subtle and unconscious way, influencing behavior without full awareness. This differs from the attention

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$$Q.d.V = \frac{overall\ richness\ of\ the\ environment}{generalized\ cost\ of\ access}$$

[16] For further details: Kevin Lynch, *The Inage of the City*, 1960.

[17] For further details: Walter Benjamin, *Immagini di città*, Torino 1971, Einaudi.

that is typically activated when entering a building: a defined and referential space. The dynamic dimension of urban scene perception is also relevant: under conditions of movement[18], the environment produces a sequence of visual stirring.

The perception indicator, dominated by vision, therefore emphasizes the perception of the urban scene and landscape, with the aim of representing *qualities* (that is, differences and underlying reasons) without preconceptions or hierarchies of values.[19] Through this indicator, the research seeks to identify a useful reference that can link the descriptive qualifications observed and subsequently represent them according to specific synthetic criteria.

Transformation

The urban transformation indicator is proposed as an analytical tool to support the monitoring of morphological and functional changes within the urban fabric. By integrating the temporal dimension, the indicator makes it possible to document transformation processes from a dual perspective: retrospectively, to analyze modifications that have already occurred, and prospectively, to estimate the intrinsic propensity for change of a plot, block, or neighborhood[20]. This approach is framed within the context of urban regeneration, where anticipating the evolutionary dynamics of the territory becomes a strategic element for informed and conscious planning.

Conservation

Tradition constitutes the dimension of continuity over time, ensuring the transmission and recognition of cultural, material, or symbolic elements that persist through transformations. It functions as a stable reference, linking past and present through repetition, recurrence, and analogy. Alongside the concept of tradition, conservation introduces an additional dimension, characterized by a conscious choice: an intentional act that entails the decision to preserve certain elements while excluding others. To conserve means to establish priorities, to safeguard what is considered meaningful, and to measure the value attributed to what endures in relation to what is not preserved. The concept of conservation, understood here as an indicator, makes it possible to identify and make visible the presence of a shared orientation toward the safeguarding of architectural heritage. Conservation thus becomes a useful parameter for understanding the

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[18] For further details: Appleyard et al., *The view from the road,* 1964

[19] For further details: Gordon Cullen, *Townscape*, 1961.

[20] For further details: "*Cities are never complete, never at equilibrium, always in transition. The challenge is to understand the processes of urban change in a way that enables us to simulate and anticipate transformation",* Michael Batty, *Cities and Complexity: Understanding Cities with Cellular Automata, Agent-Based Models, and Fractals*, 2005

relationship between memory, tradition, and future, showing how the distinction between having and not having, preserving or letting go, proves decisive in defining collective meaning.

Energy Behaviour

By analyzing the classification of building typologies through a rapid urban-scale approach, it is possible to initiate a knowledge-based process aimed at providing preliminary estimates of buildings' energy performance[21]. Within this framework, simplified assessment models make it possible to link typological features to representative energy parameters, thereby forming the basis for the definition of a synthetic index of urban energy performance.

The proposed index is intended to integrate and synthesize the information required to identify and anticipate the energy behavior of a building stock, thus supporting the informed planning of energy retrofit programs. Beyond describing the current state, this tool also enables the simulation of the expected effects of refurbishment interventions, thereby offering decision-making support in the definition of intervention strategies.

Structural Behaviour

By analyzing the classification of building typologies through a rapid urban-scale approach, it is possible to initiate an exploratory process that may subsequently be refined through more detailed, instrument-based methods[22]. Within this framework, typological models for assessing the expected level of damage establish correlations among several factors: ground displacement, represented by subsidence maps; the indexing of structural typologies, derived from reference building types; and the application of simplified models for damage classification.

The proposed indicator is intended to synthesize this information into a representative value of the structural performance of buildings within a given urban sector. Such a measure proves particularly useful in supporting the planning of extraordinary maintenance interventions and, more broadly, in guiding strategies for risk management and urban regeneration.

Post-Disaster Damage Behaviour

Within the field of studies on the vulnerability and resilience of complex systems, a particularly relevant approach is represented by the concept of "after the damages" behavior, which is used to assess risk vulnerability[23]. This notion focuses not only on exposure and the probability of

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[21] For further details: Vincenzo Vodola et al., *A Methodology for Fast Simulation of Energy Retrofitting Scenarios of Social Building Stock*, 2022.

[22] For further details: Ferretti et al., *Seismic Vulnerability Assessment of Masonry and RC Building Stocks: A Simplified Methodology*, 2024.

[23] For further details: According to UNDRR (United Nations Office for Disaster Risk Reduction) and other institutions, such as the Italian Civil Protection, the most widely used formula is:

damage, but above all on the capacity of a system to react, reorganize, and recover following a disastrous event. The ability to enhance the safety of people and ecosystems in relation to potential risk sources, whether natural or anthropogenic, constitutes one of the main challenges for territorial resilience (Maietti et al., 2022).

Risk management makes it possible to identify the causes of uncertainty and the potential impacts of disasters in contexts of anthropic and environmental fragility, thereby implementing actions to minimize the effects of such events (Dallas, 2006). Risk management can indeed provide strategic opportunities, but only if risks are properly identified and their consequences controlled.

The improvement of governance in addressing both natural and anthropogenic disasters, aimed, for instance, at reducing population exposure to fire and seismic risks, constitutes a fundamental aspect for enhancing the overall efficiency of the system. Within this framework, particular attention is also devoted to the safeguarding of architectural heritage, with the purpose of preserving memory, which represents a cornerstone of place identity and community belonging. Such heritage is an essential legacy for future generations in building a sustainable future (Cocchi & Leoni, 2021).

The indicator of post-disaster damage behaviour is thus conceived as a dynamic measure, one that does not merely describe the pre-existing condition of fragility, but rather the sequence of processes activated in the post-event phase. It seeks to overcome the traditional static conception of vulnerability by highlighting the processual and transformative dimension of resilience. Among the dimensions feeding into the indicator are: recovery time, recovery quality, and the relative level of functionality achieved (total, partial, or transformative restoration); as well as adaptive capacity, understood as the ability to introduce structural and innovative changes in order to reduce vulnerability to future critical events.

3.4 System-Based Definition for the Parametric Representation of Urban Contexts

To achieve the descriptive process of parametric modeling through City Information Modeling (CIM), it was necessary to take apart the analyzed urban context into systems, each characterized by the ability to correlate, within the same interpretative framework, various aspects related to perceptual attribution and the attribution of meanings (such as patterns of use, temporal variations, cultural conditioning, etc.). The descriptive and interpretative potential, in direct relation to urban space, refines the visual tool for perceiving the qualities of places, beyond value judgments and

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$$Risk = \frac{Hazard\ x\ Exposure\ x\ Vulnerability}{Capacity}$$

types of the models shaped by stronger or weaker aesthetic assumptions. According to this perspective, the attribution of value categories within the urban scene does not correspond to the intrinsic value of the object itself, but rather to the way it perceptually resonates within space.[24]

The definition of these systems aimed to develop a model capable of identifying possible methods for the survey of environmental data and the geometric-informative representation of the urban context. This process is conceived as a dynamic qualification designed to open a set of connections, seeking to transfer into representation all the complexities that shape the relationships among the components of the urban scene, without exclusions or field limitations. Accordingly, this contribution advances an articulated sequence of systems aimed at describing the urban scene, with the purpose of fostering changes in the management approach to the urban context.

The definition of these systems further pursued the objective of describing and identifying the generic, by assigning a set of component elements represented in the main systems, without preconceived hierarchies of value. This choice was intended to recover the *qualities* (the diversity and ration) of the greatest possible number of actors involved in the complexity of the urban scene. Moreover, through the organization into systems, the aim was to overcome the strictly functional categorization of the objects that make up the urban scene, proposing instead an approach that enables systems to be interrogated in a manner responsive to the needs of stakeholders, particularly in relation to the management of urban space.

Within the urban scene, objects exist in either an active or passive dimension. These dimensions are intrinsic to socially relevant objects and depend on the type of interaction between individuals and the objects themselves. This distinction, for example, is reflected in indicators of accessibility, comfort, and perception, which together define the urban context. In enclosed spaces, all objects tend to possess an active dimension, since they are physically engaged by touch. In unenclosed spaces, however, objects assume differentiated roles: some are directly touched, some are touched only by certain individuals (e.g., waste bins), while others are never touched, thus inhabiting a passive dimension. Objects in unenclosed spaces also possess varying signaling capacities: some have tactile self-signaling, others acoustic, and others chromatic. Indeed, in the urban scene, most objects are not mimetic but self-signaling, designed to emerge and capture attention.

The model is designed to generate scenarios in which systems define the requirements and objects, with their informational attributes, respond to representational needs. Stakeholders, for instance, might ask: What do we want to achieve in this street? If the answer is to enhance the pedestrian system, then the system of walkability must be reinforced, not merely by adding more benches,

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[24] For further details: For further details: Gordon Cullen, *Townscape*, 1961 and of Pierluigi Giordani, *Introduzione*, in the book of Gordon Cullen, *Il paesaggio urbano*, 1976.

but by improving parameters that align with a specific indicator, according to stakeholder needs. All objects are associated with different systems, and this correspondence is integrable across them. For example, a bench can be included both in the pedestrian mobility system and in the green system, depending on the indicator through which the model is being interrogated. In this way, querying the model by system makes it possible to filter and visualize all the objects (families) correlated with that particular system.

The systems proposed in this research are presented below, together with the proposed categories of objects. **Transportation System** [urban roads, sidewalks, parkings, benches, bollards, traffic signs, streetlights, traffic light, bus stop, planting bed, Street kiosk, open spaces]; **Building System** [buildings (volume), building envelope (vertical perimeter walls, roof), external frames, projection systems]; **Green Infrastructure System** [trees, benches, planting bed, open spaces]; **Security System** [camera poles]; **Communication Interface System** [advertising signs, commercial signage, billboards, street kiosk]; **Energy System** [street lights, poles]; **Waste Management System** [litter bins, refuse bins], **Integrated Water System** [potable water, stormwater, wastewater]; **ICT System** [sensors, wi-fi, antennas]; **Terrain Module** [topographic solid]; **Boundary System** [walls, fence, access].

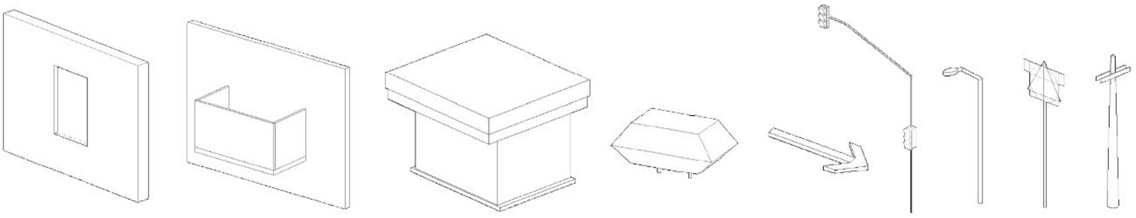

Fig. 3.3 – Example of a few parametric families modeled and implemented within the CIM models.

It is evident that the proposed articulation does not claim to be exhaustive; rather, it serves as a framework for the organization and design of the CIM model. Indeed, within the model there exists a “hidden” system, consisting of the *category of absence*, which is intrinsic to process of identifying the model itself.

3.5 Typological Definition of Objects and Structuring of Data Sheets

To undertake the process of representation and documentation of the urban scene through the CIM approach, the following research question was posed: *“How can the elements of the urban scene be represented from both a geometric and informative point of view?”*.

The objective was to recover the descriptive and identificatory value of representation, where, before making any obligatory reference to the attribution of value judgments, the process began with the development of a methodology aimed at acquiring characters, elements, and information capable of describing the general context (Balzani, 1995). This attempt is introduced by an analytical procedure based on surveying, with the intent of identifying a set of component elements represented within the main systems.

The objects of the urban scene, within the CIM model, are translated into 3D elements that, in Autodesk Revit, are called *families*. Any element is additionally augmented with further content, *parameters*, in order to convey not only its quantitative properties (i.e., geometry) but also its qualitative ones (such as materials, physical parameters, performance, etc.) (Bianchini et al., 2021). These represent the second distinctive feature of the type of modeling associated with CIM. Through such informational attributes, CIM systems actually provide a digital environment capable of hosting, organizing, and interacting with all this information by means of the 3D model, which, to a certain extent, may become an access point to the city's informational database. All information related to the model, both graphic and technical, are defined by parameters. Geometrically, this means that a dimensional variation does not consist of a local modification of the graphic data but of a variation in the parameter representing that specific dimension; the update then occurs simultaneously and automatically across the entire data sheet, while preserving relationships with other instances. The same applies to technical data. Thus, any value that can be compiled within a type is a parameter. A parameter may clearly be numerical, textual, or graphic in nature, among others, and in essence represents the repository for all information associated with the project (URLs, images, descriptions, currency, visibility, length, volume, area, angle, material, density, etc.) (Scandurra, 2020).

To geometrically modeled objects, it is potentially possible to assign any type of information. In this research, therefore, data sheets were developed for each modeled family, which were necessary for the definition of typological families. In these sheets, information are organized by groups, depending on the domain. In this way, according to the requirements of the model, different stakeholders may implement family information or create schedules and filters by querying specific parameters or groups of parameters within the different systems.

This does not mean that all information must be compiled throughout the entire model. Rather, informational requirements gain importance in relation to organizational processes and the data necessary to meet strategic objectives. The concept of Level of Information Need (LOIN), derived from BIM, refers precisely to the level of detail and the quantity of information required depending on the purpose of the model. The requested information are structured around five fundamental questions: Who: who needs the information?; What: what specific information is required for the task?; When: at what stage or temporal moment is this information needed?;

Where: where should this information be located or used within the project?; Why: what is the purpose of this information and how does it support decision-making?.

Depending on the purpose of the model and the information required in the decision-making process, the level of detail varies, ensuring that only the pertinent and useful information are delivered at the appropriate time. The organization of data sheets thus becomes strategic in terms of model usability, both with regard to standardization, through *shared parameters*, which, as the term itself suggests, may be the same across multiple models, thereby defining a standard to be followed; and in view of subsequent implementation in open-standard platforms. While in the modeling phase it is possible to manage and modify informational attributes directly in the authoring software, for export into the open IFC format it is necessary to develop *Property Sets* (Psets). These consist of a structured set of attributes regulated by the IFC standard. They represent a fundamental tool for interoperability and the exchange of information among software platforms and stakeholders involved in the process.

Within this analytical process, the definition of data sheets is proposed as a cataloging and census activity of the elements that can be reported and located in the urban scene with codified references. The associated attributes constitute descriptive legends. Locations, primary functions, density and frequency, effects of details and of continuity along façades or paths, temporal actions, variations of light, habits and criteria of use, and conservation conditions may all be documented, described as informative parameters, and represented through appropriate informational maps. In this way, it becomes possible to highlight a reading of the urban landscape already structured to serve as a support for proposals of intervention or control.

Reference is made to the appendix at the end of the chapter, where: Table 2 and Table 3 are reported. These correspond, respectively, to the file of shared parameters, containing the information parameters implemented in the models, and to the Pset file used for export in the open IFC format.

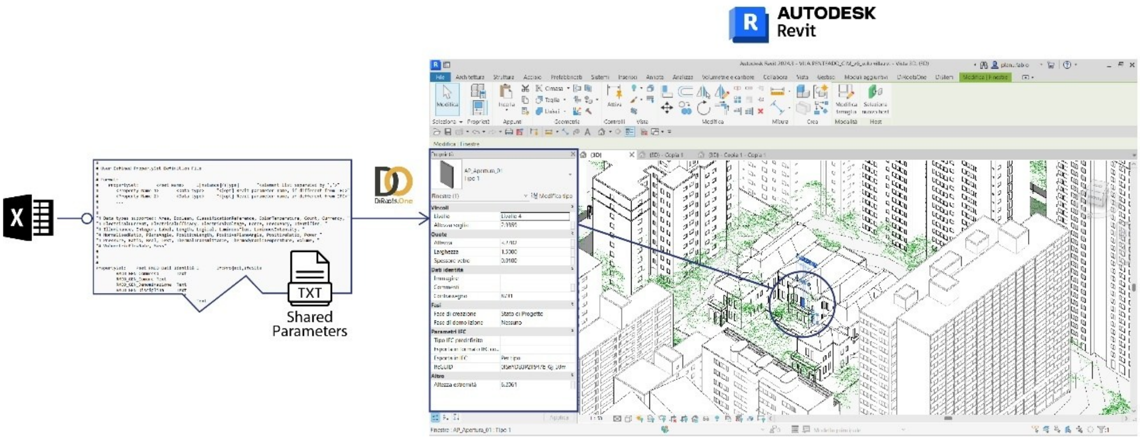

Fig. 3.3 – Implementation process of shared parameters from Excel into Revit using the DiRoots plugin.

3.6 Consistency Analysis

Once the data sheets had been defined, the methodological research question guiding the definition of the CIM model was: *"How can parameters (descriptors) be correlated with qualitative indicators?"*. To address this question, a *consistency analysis* was carried out, aimed at verifying the internal coherence of the data within the CIM model. This analysis ensures a reliable reading of the parameters and guarantees that the indicators provide results consistent with the condition of the represented urban environment. The procedure is based on a matrix that relates the informative attributes assigned to the objects of the different systems with the synthetic indicators used for interpreting and managing the urban context, as described in paragraph 3.3. By linking informative parameters that meet specific requirements to the indicators, the various systems, through the CIM model, constitute a documentation framework capable of supporting intervention proposals. Through these indicators, the model, thanks to the informative parameters that organize data into schedules and false-color visualizations, becomes a tool able to assist in the transformation of scenarios.

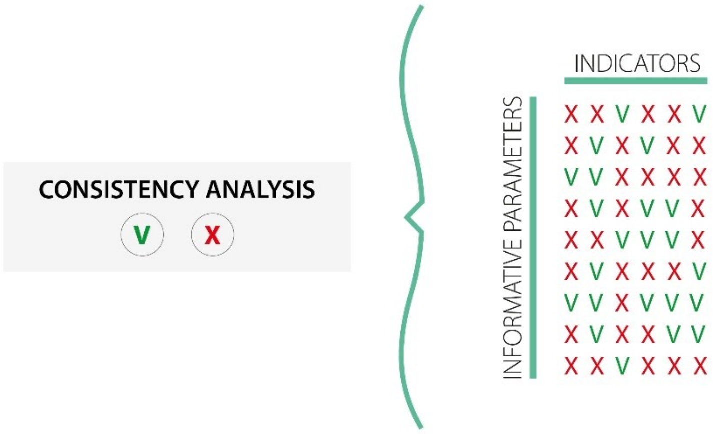

Fig. 3.4 – Consistency analysis: concept.

3.7 Chapter Appendix

Table 2: Shared parameters implemented in the CIM models. The table shown is the output of an Excel file that can be imported into Revit through dedicated plugins such as DiRoots.

SUMMARY OF INFORMATION PARAMETERS

Attribute list

PARAMETER GROUP NAME [Pset]: IDENTIFICATION PARAMETERS

P. NAME	DESCRIPTION	EXAMPLE	TYPE	TIPOLOGY	SYSTEM
Building code	Indicates the building code.		Instance	Text	Building System, Boundary System
Database link	Link to the existing database containing building data.	Link to the Emilia-Romagna Region webGIS database	Instance	URL	Building System, Green Infrastructure System, Transportation System, Integrated Water System
Botanical family	-	Horse-chestnut family, etc.	Instance	Text	Green Infrastructure System
Common name	-	Plane tree, walnut, etc.	Instance	Text	Green Infrastructure System

PARAMETER GROUP NAME [Pset]: MORPHOLOGICAL PARAMETERS

P. NAME	DESCRIPTION	EXAMPLE	TYPE	TIPOLOGY	SYSTEM
Volumetric articulation	Indicates the volumetric articulation of the building	Openings, loggias, balconies, etc.	Instance	Text	Building System
Building height	Indicate the number of floors	1, 2, 3, etc.	Instance	Text	Building System
Roof type	Indicate the type of roof	Flat, pitched, etc.	Instance	Text	Building System
Opening pattern	Indicate the arrangement of openings on the façade	Vertical, horizontal, isolated, etc.	Instance	Text	Building System
Wall pattern/texture	Indicates the wall pattern or texture	Vertical, horizontal, square, etc.	Instance	Text	Building System
Presence of chimneys	Indicates whether chimneys are present on the roof	Yes, no	Instance	Text	Building System
Projection / Recess	Indicates the depth or protrusion of the element	Projecting, recessed, flush with façade	Instance	Text	Building System
Parapet type	Indicates the type of parapet	Railing, solid, glass, mixed, etc.	Instance	Text	Building System
Shape and bearing	Trunk/canopy relationship, solid/void ratio		Instance	Text	Green Infrastructure System
Genus characteristics	-	Evergreen, deciduous	Instance	Text	Green Infrastructure System
Usage effects	-	Isolated, rows, clusters, borders	Instance	Text	Green Infrastructure System
Element morphology	Indicate the shape	Could be a predefined list (e.g. InfraWorks)	Instance	Text	Transportation System, Security System, Communication Interface System, Energy System, Waste Management System, ICT System, Boundary System
Light color	-	White, yellow, orange	Instance	Text	Energy System
Presence of sidewalk	Indicates whether a sidewalk is present	Predefined list (e.g. InfraWorks)	Instance	Text	Transportation System
Number of lanes			Instance	Text	Transportation System
Property boundary type	Indicates the type of boundary enclosure	Railing, low wall with railing, metal mesh, etc.	Instance	Text	Building System
Access protection type	-	Handrail, railing, low wall	Instance	Text	Building System, Boundary System
Crossing type	-	At grade, raised, etc.	Instance	Text	Transportation System

Junction (edge) type	Indicates the type of crossing or curb junction	Curb, ramp, continuous, step, etc.	Instance	Text	Transportation System
Parking type	-	On-street, square, multilevel, etc.	Instance	Text	Transportation System
Parking layout	-	Parallel, angled, perpendicular, mixed	Instance	Text	Transportation System
Elevation relative to street	-	At grade, elevated, underground	Instance	Text	Transportation System
Presence of vegetation	-	Yes, no	Instance	Text	Green Infrastructure System, Terrain Module
Presence of lighting	-	Yes, no	Instance	Text	Green Infrastructure System
Morphological genesis	-	Historical, spontaneous, designed, residual, etc.	Instance	Text	Green Infrastructure System, Terrain Module

PARAMETER GROUP NAME [Pset]: TYPOLOGICAL PARAMETERS

P. NAME	DESCRIPTION	EXAMPLE	TYPE	TIPOLOGY	SYSTEM
Building typology	Indicates the building type category	Detached, row, tower, terraced, courtyard	Instance	Text	Building System
Planimetric relation	Indicates the building's plan relation	Simple, combined, stepped, etc.	Instance	Text	Building System
Main use	Indicate the main function	Residential, commercial, educational, etc.	Instance	Text	Building System
Ground floor use	Indicate the degree of openness or relation to urban space	Closed, mixed, open and integrated, etc.	Instance	Text	Building System
Configuration	Indicates the compositional organization	Symmetrical, asymmetrical, modular, free, etc	Instance	Text	Building System
Window type	Indicate the window family (e.g., Revit family)	Window, door, fixed glazing, etc.	Instance	Text	Building System
Shading system	Indicate the window shading system type		Instance	Text	Building System
Room use	Indicates the functional relevance of the window	Residential, commercial, services, etc..	Instance	Text	Building System
Type of external frontage	Indicates the type of external opening	Loggia, balcony	Instance	Text	Building System
Functional furniture classification	Indicate what the object is	Bench, lamppost, bin, etc.	Instance	Text	Transportation System, Green Infrastructure System, Security System, Communication Interface System, Energy System, Waste Management System, ICT System
Functional furniture role	Indicates what it does or its purpose	Seating, lighting, barrier, protection, etc.	Instance	Text	Transportation System, Green Infrastructure System, Security System, Communication Interface System, Energy System, Waste Management System, ICT System
Illuminated sign	Indicates whether the sign is illuminated	Yes, no	Instance	Text	Communication Interface System
Functional street class	Indicates the functional category of the street	Main, secondary, local, service, etc.	Instance	Text	Transportation System
Mobility type	Indicates the prevalent mobility type	Vehicular, pedestrian, cycle, mixed, etc.	Instance	Text	Transportation System
Maximum speed	-		Instance	Text	Transportation System
Fence height	Indicates the indicative height of the fence	In meters	Instance	Text	Boundary System
Access hierarchy	Indicates whether access is to the plot or building	Plot, building, etc.	Instance	Text	Boundary System
Access mode	Indicates access type	Vehicular, pedestrian, mixed, etc..	Instance	Text	Boundary System

Access road class	Indicates from which road entry occurs	Main road, secondary road, private road, etc.	Instance	Text	Boundary System
Connection type	-	Stairs, ramp, steps	Instance	Text	Boundary System
Entrance type	-	With porch, covered path, unprotected, etc.	Instance	Text	Boundary System
Access level difference	Indicates if access is at first floor, ground floor, etc.	1st floor, GF, etc..	Instance	Text	Building System, Boundary System
Crossing signage	-	Vertical, horizontal, both, etc.	Instance	Text	Transportation System
User category	-	Public, private, condominium, service, etc.	Instance	Text	Transportation System
Parking regulation	-	Free, paid, reserved, etc.	Instance	Text	Transportation System
Average parking duration	-	Short (loading/unloading), medium, long	Instance	Text	Transportation System
Open space type	Indicates the type of open space	Square, courtyard, widened area, etc.	Instance	Text	Green Infrastructure System
Typological vocation	Indicates the main use of the open space	Gathering, transit, events, etc..	Instance	Text	Green Infrastructure System
Presence of equipment	-	Yes, no	Instance	Boolean	Green Infrastructure System

PARAMETER GROUP NAME [Pset]: TECHNOLOGICAL PARAMETERS

P. NAME	DESCRIPTION	EXAMPLE	TYPE	TIPOLOGY	SYSTEM
Structural type	Indicate the structural system	Steel, Concrete, etc.	Instance	Text	Building System, Transportation System, Boundary System
Construction period	Indicate the construction period		Instance	Text	Building System, Transportation System, Boundary System
Materials	Indicate the materials used		Instance	Text	Building System, Transportation System, Boundary System, Green Infrastructure System, Security System, Communication Interface System, Energy System
Color	Indicate predominant colors		Instance	Text	Building System, Transportation System, Boundary System, Green Infrastructure System, Security System, Communication Interface System, Energy System
Surface treatment	Indicate the surface finish type	Smooth, rough, decorated, etc.	Instance	Text	Building System, Transportation System, Boundary System, Green Infrastructure System, Security System, Communication Interface System, Energy System
Permeability level (resilience)	Indicates permeability level to assess resilience	High, medium, low	Instance	Text	Green Infrastructure System, Terrain Module

PARAMETER GROUP NAME [Pset]: PERCEPTUAL PARAMETERS

P. NAME	DESCRIPTION	EXAMPLE	TYPE	TIPOLOGY	SYSTEM
Presence of advertising	Indicates if the building supports advertising signs	Yes, No	Instance	Boolean	Building System, Communication Interface System
Urban relevance	Indicates visual and perceptual prominence in context	Urban front, perspective axis, corner, etc	Instance	Text	Building System, Boundary System
Presence of urban art	Indicates if urban art or participatory interventions exist	Yes, No	Instance	Boolean	Building System, Boundary System
Visibility	Degree of visibility within the urban context	High, medium, low, etc.	Instance	Text	Boundary System, Transportation System,

					Security ystem, Communication Interface System, Energy System, ICT System
Relation to urban space	Indicates which category of urban space it is linked to	e.g., lampposts linked to public pathways	Instance	Text	Transportation System, Building System, Green Infrastructure Syste, Security System, Communication Interface System, Energy System, Waste Management System, ICT System, Boundary System
Open space perception	-	Open, intimate, enclosed, sequential, etc.	Instance	Text	Green Infrastructure System

PARAMETER GROUP NAME [Pset]: SOCIAL PARAMETERS

P. NAME	DESCRIPTION	EXAMPLE	TYPE	TIPOLOGY	SYSTEM
Number of inhabitants	Number of residents or users of a building	Numeric value or range	Instance	Text	Building System
Accessibility to nearby services	Average distance to basic services (school, health, transport, etc.)	Average distance or qualitative value (high, medium, low)	Instance	Text	Building System
User type	Predominant user type	Elderly, students, families, etc..	Instance	Text	Building System, Green Infrastructure System
Perceived safety	Level of perceived safety	Numeric or qualitative value	Instance	Text	Building System, Green Infrastructure System, Transportation System
Vacancy rate	Indicates the vacancy rate	Percentage value	Instance	Text	Building System
Cultural belonging value	Indicates whether the object has community cultural value	Yes, no	Instance	Boolean	Building System, Green Infrastructure System
Potential for collective functions	Indicates ability to host collective uses	Yes, no	Instance	Boolean	Building System, Green Infrastructure System
Perception of night lighting	Indicates perception related to perceived safety	Numeric or qualitative value	Instance	Text	Transportation System, Energy System
Accessibility for disabled persons	Indicates if architectural barriers are removed	Yes, no	Instance	Boolean	Boundary System, Building System, Green Infrastructure System
Disability signage	-	Yes, no	Instance	Boolean	Transportation System
Integration with public transport	-	Yes, no	Instance	Boolean	Transportation System
Average permanence duration	-	Time indicator	Instance	Text	Green Infrastructure System
Symbolic community place	-	Yes, no	Instance	Boolean	Green Infrastructure System

PARAMETER GROUP NAME [Pset]: ENERGY PERFORMANCE PARAMETERS

P. NAME	DESCRIPTION	EXAMPLE	TYPE	TIPOLOGY	SYSTEM
Energy class	Building’s energy rating	A, B, C, etc.	Instance	Text	Building System
Energy performance	Annual energy consumption	9999 KWh/m²/year	Instance	Text	Building System
Natural lighting quality	Percentage of surfaces with direct daylight		Instance	Text	Building System
Climate zone	Indicate the climate zone		Instance	Text	Building System
Presence of renewable energy systems	Indicate presence of renewable energy systems	Yes, no	Instance	Boolean	Building System

PARAMETER GROUP NAME [Pset]: CONVERSATION PARAMETERS

P. NAME	DESCRIPTION	EXAMPLE	TYPE	TIPOLOGY	SYSTEM
Presence of incongruous elements	Indicates whether incongruous elements exist in the urban scene	Yes, No (e.g., air conditioning units)	Instance	Boolean	Building System, Green Infrastructure System, Boundary System

Subject to interventions	-	Yes, no	Instance	Boolean	Building System, Green Infrastructure System, Boundary System,
Rebuilt or replaced	-	Yes, no	Instance	Boolean	Building System, Boundary System, Transportation System, Security ystem, Communication Interface System, Energy System, ICT System
Temporal transformation index	Indicates how many times the object has undergone major replacement	1, 2, 3, none, etc.	Instance	Text	Building System, Boundary System, Transportation System, Security ystem, Communication Interface System, Energy System, ICT System
Possible uses	List of possible restoration uses		Instance	Text	Building System
Coherence with original use	Indicates whether the original function is preserved	Yes, no	Instance	Boolean	Building System
Protected	Indicates whether the building is under protection constraints	Yes, no	Instance	Boolean	Building System, Boundary System, Green Infrastructure System
Possible morphological configurations	Indicates possible options (InfraWorks-style list)	Menu type InfraWorks	Instance	Text	Building System, Transportation System, Green Infrastructure System, Security System, Communication Interface System, Energy Sytem, Waste Management System, ICT System, Boundary System
Possible material configurations	Indicates possible options (InfraWorks-style list)	Menu type InfraWorks	Instance	Text	Building System, Transportation System, Green Infrastructure System, Security System, Communication Interface System, Energy Sytem, Waste Management System, ICT System, Boundary System
Possible color configurations	Indicates possible options (InfraWorks-style list)	Menu type InfraWorks	Instance	Text	Building System, Transportation System, Green Infrastructure System, Security System, Communication Interface System, Energy Sytem, Waste Management System, ICT System, Boundary System
Possible surface treatments	Indicates possible options (InfraWorks-style list)	Menu type InfraWorks	Instance	Text	Building System, Transportation System, Green Infrastructure System, Security System, Communication Interface System, Energy Sytem, Waste Management System, ICT System, Boundary System
Volumetric coherence	Indicates whether volumetry was preserved	Yes, no	Instance	Boolean	Building Sysytem
Conservation status	Indicates preservation state	High, medium, low	Instance	Text	Building System, Transportation System, Green Infrastructure System, Boundary System

PARAMETER GROUP NAME [Pset]: MANAGEMENT PARAMETERS

P. NAME	DESCRIPTION	EXAMPLE	TYPE	TIPOLOGY	SYSTEM
Ownership	Indicates ownership of the building or urban object	Public, private, mixed	Instance	Text	Building System, Transportation System, Green Infrastructure System, Boundary System

Managing entity	Indicates who manages it	Municipality, company, consortium, private, etc.	Instance	Text	Building System, Transportation System, Green Infrastructure System
Usage regime	Indicates the usage regime	Public use, concession, lease	Instance	Text	Building System, Green Infrastructure System
Risk of plant interference	-		Instance	Text	Green Infrastructure System
Parking occupancy count	-		Instance	Text	Transportation System
Access schedule	-	Libero, limitato, temporaneo	Instance	Text	Green Infrastructure System
Seasonal use	-	Estiva, invenale, perenne, ecc.	Instance	Text	Green Infrastructure System

PARAMETER GROUP NAME [Pset]: SEISMIC VULNERABILITY PARAMETERS

P. NAME	DESCRIPTION	EXAMPLE	TYPE	TIPOLOGY	SYSTEM
Building size class	-	Single-family, row, multi-family, apartment blocks	Instance	Text	Building System
Construction period class	-	Year of construction grouped by class	Instance	Text	Building System
Last renovation	-	Year of last renovation	Instance	Text	Building System
Structural type	-	Masonry, etc.	Instance	Text	Building System
Foundation type	-		Instance	Text	Building System
Building height above ground	-	in meters	Instance	Text	Building System
Building height above ground	-	in meters	Instance	Text	Building System
Damage category	From 0 to 5	Resulting from calculation	Instance	Text	Building System
Design subsidence (mm)	In millimeters		Instance	Text	Building System
Design angular distortion	Ratio		Instance	Text	Building System
Neutral axis position (equivalent beam)	Meters		Instance	Text	Building System
Design deformation	Percentage %		Instance	Text	Building System

Table 3: Pset for exporting CIM model information in the open IFC format.

SUMMARY OF INFORMATION PARAMETERS

Attribute list - IFC

PARAMETER NAME	TYPE	PSET CATEGORY	TIPOLOGY
Building code	Instance	All IfcEntity	Text
Database link	Instance	All IfcEntity	URL
Botanical family	Instance	All IfcEntity	Text
Common name	Instance	All IfcEntity	Text

PARAMETER GROUP NAME [Pset]: MORPHOLOGICAL PARAMETERS

PARAMETER NAME	TYPE	PSET CATEGORY	TIPOLOGY
Volumetric articulation	Instance	All IfcEntity	Text
Building height	Instance	All IfcEntity	Text
Roof type	Instance	All IfcEntity	Text
Opening pattern	Instance	All IfcEntity	Text
Wall pattern/texture	Instance	All IfcEntity	Text
Presence of chimneys	Instance	All IfcEntity	Text
Projection / Recess	Instance	All IfcEntity	Text
Parapet type	Instance	All IfcEntity	Text
Shape and bearing	Instance	All IfcEntity	Text
Genus characteristics	Instance	All IfcEntity	Text
Usage effects	Instance	All IfcEntity	Text
Element morphology	Instance	All IfcEntity	Text
Light color	Instance	All IfcEntity	Text
Presence of sidewalk	Instance	All IfcEntity	Text
Number of lanes	Instance	All IfcEntity	Text
Property boundary type	Instance	All IfcEntity	Text
Access protection type	Instance	All IfcEntity	Text
Crossing type	Instance	All IfcEntity	Text
Junction (edge) type	Instance	All IfcEntity	Text
Parking type	Instance	All IfcEntity	Text
Parking layout	Instance	All IfcEntity	Text
Elevation relative to street	Instance	All IfcEntity	Text
Presence of vegetation	Instance	All IfcEntity	Text
Presence of lighting	Instance	All IfcEntity	Text
Morphological genesis	Instance	All IfcEntity	Text

PARAMETER GROUP NAME [Pset]: TYPOLOGICAL PARAMETERS

PARAMETER NAME	TYPE	PSET CATEGORY	TIPOLOGY
Building typology	Instance	All IfcEntity	Text
Planimetric relation	Instance	All IfcEntity	Text
Main use	Instance	All IfcEntity	Text
Ground floor use	Instance	All IfcEntity	Text
Configuration	Instance	All IfcEntity	Text
Window type	Instance	All IfcEntity	Text
Shading system	Instance	All IfcEntity	Text
Room use	Instance	All IfcEntity	Text
Type of external frontage	Instance	All IfcEntity	Text
Functional furniture classification	Instance	All IfcEntity	Text
Functional furniture role	Instance	All IfcEntity	Text
Illuminated sign	Instance	All IfcEntity	Text
Functional street class	Instance	All IfcEntity	Text
Mobility type	Instance	All IfcEntity	Text
Maximum speed	Instance	All IfcEntity	Text
Fence height	Instance	All IfcEntity	Text
Access hierarchy	Instance	All IfcEntity	Text
Access mode	Instance	All IfcEntity	Text
Access road class	Instance	All IfcEntity	Text
Connection type	Instance	All IfcEntity	Text
Entrance type	Instance	All IfcEntity	Text
Access level difference	Instance	All IfcEntity	Text
Crossing signage	Instance	All IfcEntity	Text
User category	Instance	All IfcEntity	Text
Parking regulation	Instance	All IfcEntity	Text
Average parking duration	Instance	All IfcEntity	Text

Open space type	Instance	All IfcEntity	Text
Typological vocation	Instance	All IfcEntity	Text
Presence of equipment	Instance	All IfcEntity	Boolean

PARAMETER GROUP NAME [Pset]: TECHNOLOGICAL PARAMETERS

PARAMETER NAME	TYPE	PSET CATEGORY	TIPOLOGY
Structural type	Instance	All IfcEntity	Text
Construction period	Instance	All IfcEntity	Text
Materials	Instance	All IfcEntity	Text
Color	Instance	All IfcEntity	Text
Surface treatment	Instance	All IfcEntity	Text
Permeability level (resilience)	Instance	All IfcEntity	Text

PARAMETER GROUP NAME [Pset]: PERCEPTUAL PARAMETERS IN THE URBAN SCENE

PARAMETER NAME	TYPE	PSET CATEGORY	TIPOLOGY
Presence of advertising	Instance	All IfcEntity	Boolean
Urban relevance	Instance	All IfcEntity	Text
Presence of urban art	Instance	All IfcEntity	Boolean
Visibility	Instance	All IfcEntity	Text
Relation to urban space	Instance	All IfcEntity	Text
Open space perception	Instance	All IfcEntity	Text

PARAMETER GROUP NAME [Pset]: SOCIAL PARAMETERS

PARAMETER NAME	TYPE	PSET CATEGORY	TIPOLOGY
Number of inhabitants	Instance	All IfcEntity	Text
Accessibility to nearby services	Instance	All IfcEntity	Text
User type	Instance	All IfcEntity	Text
Perceived safety	Instance	All IfcEntity	Text
Vacancy rate	Instance	All IfcEntity	Text
Cultural belonging value	Instance	All IfcEntity	Boolean
Potential for collective functions	Instance	All IfcEntity	Boolean
Perception of night lighting	Instance	All IfcEntity	Text
Accessibility for disabled persons	Instance	All IfcEntity	Boolean
Disability signage	Instance	All IfcEntity	Boolean
Integration with public transport	Instance	All IfcEntity	Boolean
Average permanence duration	Instance	All IfcEntity	Text
Symbolic community place	Instance	All IfcEntity	Boolean

PARAMETER GROUP NAME [Pset]: ENERGY PERFORMANCE PARAMETERS

PARAMETER NAME	TYPE	PSET CATEGORY	TIPOLOGY
Energy class	Instance	All IfcEntity	Text
Energy performance	Instance	All IfcEntity	Text
Natural lighting quality	Instance	All IfcEntity	Text
Climate zone	Instance	All IfcEntity	Text
Presence of renewable energy systems	Instance	All IfcEntity	Boolean

PARAMETER GROUP NAME [Pset]: CONSERVATION PARAMETERS

PARAMETER NAME	TYPE	PSET CATEGORY	TIPOLOGY
Presence of incongruous elements	Instance	All IfcEntity	Boolean
Subject to interventions	Instance	All IfcEntity	Boolean
Rebuilt or replaced	Instance	All IfcEntity	Boolean
Temporal transformation index	Instance	All IfcEntity	Text
Possible uses	Instance	All IfcEntity	Text
Coherence with original use	Instance	All IfcEntity	Boolean
Protected	Instance	All IfcEntity	Boolean
Possible morphological configurations	Instance	All IfcEntity	Text
Possible material configurations	Instance	All IfcEntity	Text
Possible color configurations	Instance	All IfcEntity	Text
Possible surface treatments	Instance	All IfcEntity	Text
Volumetric coherence	Instance	All IfcEntity	Boolean
Conservation status	Instance	All IfcEntity	Text

PARAMETER GROUP NAME [Pset]: Management PARAMETERS

PARAMETER NAME	TYPE	PSET CATEGORY	TIPOLOGY
Ownership	Instance	All IfcEntity	Text
Managing entity	Instance	All IfcEntity	Text
Usage regime	Instance	All IfcEntity	Text

Risk of plant interference	Instance	All IfcEntity	Text
Parking occupancy count	Instance	All IfcEntity	Text
Access schedule	Instance	All IfcEntity	Text
Seasonal use	Instance	All IfcEntity	Text

PARAMETER GROUP NAME [Pset]: SEISMIC VULNERABILITY PARAMETERS

PARAMETER NAME	TYPE	PSET CATEGORY	TIPOLOGY
Building size class	Instance	All IfcEntity	Text
Construction period class	Instance	All IfcEntity	Text
Last renovation	Instance	All IfcEntity	Text
Structural type	Instance	All IfcEntity	Text
Foundation type	Instance	All IfcEntity	Text
Building height above ground	Instance	All IfcEntity	Text
Building height above ground	Instance	All IfcEntity	Text
Damage category	Instance	All IfcEntity	Text
Design subsidence (mm)	Instance	All IfcEntity	Text
Design angular distortion	Instance	All IfcEntity	Text
Neutral axis position (equivalent beam)	Instance	All IfcEntity	Text
Design deformation	Instance	All IfcEntity	Text

Table 4: Consistency Analysis

	URBAN PRESSURE	HYBRIDIZATION	ACCESSIBILITY	TRAFFIC CONGESTION	COMFORT	MEANING	PERCEPTION	TRANSFORMATION	CONSERVATION	ENERGY BEHAVIOUR	STRUCTURAL BEHAVIOUR	POST-DISASTER DAMAGE BEHAVIOR
PARAMETER GROUP NAME [Pset]: IDENTIFICATION PARAMETERS												
PARAMETER NAME												
Building code	X	X	X	X	X	X	X	X	X	X	X	X
Database link	X	X	X	X	X	X	X	X	X	X	X	X
Botanical family	X	X	X	X	X	X	X	X	X	X	X	X
Common name	X	X	X	X	X	X	X	X	X	X	X	V
PARAMETER GROUP NAME [Pset]: IDENTIFICATION PARAMETERS												
PARAMETER NAME												
Volumetric articulation	V	V	X	X	X	V	V	X	X	V	V	X
Building height	V	X	X	X	X	X	V	V	X	V	V	V
Roof type	V	X	X	X	X	X	V	X	X	V	V	X
Opening pattern	X	X	X	X	X	V	V	X	X	V	V	X
Wall pattern/texture	X	X	X	X	X	X	V	X	X	X	X	X
Presence of chimneys	X	X	X	X	X	X	V	X	X	V	V	X
Projection / Recess	X	X	X	X	X	X	V	X	X	X	V	X
Parapet type	V	X	X	X	X	X	V	X	X	X	X	X
Shape and bearing	V	X	X	X	V	X	X	X	X	X	V	X
Genus characteristics	X	X	X	X	V	X	X	X	X	V	X	X
Usage effects	X	X	X	X	V	X	V	X	X	X	X	X
Element morphology	V	X	X	X	X	X	V	X	X	X	X	X
Light color	V	X	X	X	V	V	V	X	X	X	X	X
Presence of sidewalk	X	X	V	V	V	X	X	X	X	X	X	X
Number of lanes	V	X	X	X	X	X	X	X	X	X	X	V
Property boundary type	V	X	X	X	X	X	V	X	X	X	X	X
Access protection type	V	X	X	X	V	X	X	X	X	X	X	X
Crossing type	V	X	V	V	V	X	X	X	X	X	X	X
Junction (edge) type	V	X	V	V	X	X	X	X	X	X	X	X
Parking type	V	X	X	X	X	X	V	X	X	X	X	X
Parking layout	V	X	X	X	X	X	V	X	X	X	X	X
Elevation relative to street	V	X	V	X	X	X	X	X	X	X	X	X
Presence of vegetation	X	X	X	X	V	X	V	X	X	V	X	X
Presence of lighting	X	X	X	X	V	V	V	X	X	X	X	X
Morphological genesis	X	X	X	X	X	X	X	X	X	X	X	X
PARAMETER GROUP NAME [Pset]: IDENTIFICATION PARAMETERS												
PARAMETER NAME												
Building typology	V	V	X	X	X	X	V	X	X	V	V	X
Planimetric relation	X	V	X	X	X	X	X	X	X	V	V	X
Main use	X	V	X	X	V	X	X	X	X	X	X	V
Ground floor use	X	V	X	X	V	X	X	X	X	X	X	V
Configuration	X	X	X	X	X	X	V	X	X	X	V	X
Window type	X	X	X	X	X	X	V	X	X	X	X	X
Shading system	X	X	X	X	X	X	V	X	X	V	X	X
Room use	X	V	X	X	X	X	X	X	X	V	X	X
Type of external frontage	X	X	X	X	X	X	V	X	X	V	V	X
Functional furniture classification	X	X	X	X	X	X	V	X	X	X	X	X
Functional furniture role	X	X	X	X	X	X	V	X	X	X	X	X
Illuminated sign	V	X	X	X	X	X	V	X	X	X	X	X
Functional street class	V	X	X	V	X	X	X	X	X	X	X	V
Mobility type	V	X	V	V	V	X	X	X	X	X	X	X
Maximum speed	X	X	X	V	X	X	X	X	X	X	X	X
Fence height	V	X	V	X	X	X	V	X	X	X	X	X
Access hierarchy	X	V	V	X	X	X	X	X	X	X	X	V
Access mode	X	V	V	X	X	X	X	X	X	X	X	X
Access road class	X	X	V	X	X	X	V	X	X	X	X	X
Connection type	X	X	V	X	X	X	X	X	X	X	X	X
Entrance type	X	X	V	V	X	X	X	X	X	X	X	X

Access level difference	X	X	V	X	X	X	X	X	X	X	X	V
Crossing signage	X	X	V	V	X	X	X	X	X	X	X	X
User category	V	V	X	X	X	X	X	X	X	X	X	X
Parking regulation	V	X	V	X	X	X	X	X	X	X	X	X
Average parking duration	V	V	X	X	X	X	X	X	X	X	X	X
Open space type	X	X	X	X	V	X	V	X	X	X	X	V
Typological vocation	V	V	X	X	V	X	X	X	X	X	X	X
Presence of equipment	X	X	X	X	V	V	X	X	X	X	X	X

PARAMETER GROUP NAME [Pset]: IDENTIFICATION PARAMETERS

PARAMETER NAME												
Structural type	X	X	X	X	X	X	X	X	V	V	V	V
Construction period	X	X	X	X	X	X	X	X	V	V	V	V
Materials	X	X	X	X	X	X	V	X	V	V	V	X
Color	X	X	X	X	X	X	V	X	V	X	X	X
Surface treatment	X	X	X	X	X	X	V	X	V	X	X	X
Permeability level (resilience)	X	X	X	X	V	X	X	X	X	X	X	V

PARAMETER GROUP NAME [Pset]: IDENTIFICATION PARAMETERS

PARAMETER NAME												
Presence of advertising	V	X	X	X	X	X	V	X	X	X	X	X
Urban relevance	X	V	X	V	X	X	V	X	X	X	X	X
Presence of urban art	X	X	X	X	X	V	V	X	V	X	X	X
Visibility	X	X	X	X	X	X	V	X	X	X	X	X
Relation to urban space	X	V	X	X	X	X	X	X	X	X	X	V
Open space perception	X	X	X	X	V	V	V	X	X	X	X	X

PARAMETER GROUP NAME [Pset]: IDENTIFICATION PARAMETERS

PARAMETER NAME												
Number of inhabitants	V	X	X	X	X	X	X	X	X	X	X	V
Accessibility to nearby services	X	V	X	V	V	X	X	X	X	X	X	X
User type	X	V	X	X	V	V	X	X	X	X	X	X
Perceived safety	X	X	X	X	V	X	X	X	X	X	X	X
Vacancy rate	V	X	X	X	V	V	X	X	X	X	X	X
Cultural belonging value	X	X	X	X	X	V	V	X	V	X	X	X
Potential for collective functions	X	V	X	X	V	V	X	X	X	X	X	X
Perception of night lighting	X	X	X	V	V	X	X	X	X	X	X	X
Accessibility for disabled persons	X	X	V	X	V	X	X	X	X	X	X	X
Disability signage	X	X	V	X	X	X	X	X	X	X	X	X
Integration with public transport	X	X	X	V	X	X	X	X	X	X	X	X
Average permanence duration	X	X	X	X	X	X	X	X	X	X	X	X
Symbolic community place	X	X	X	X	V	V	X	X	X	X	X	X

PARAMETER GROUP NAME [Pset]: IDENTIFICATION PARAMETERS

PARAMETER NAME												
Energy class	X	X	X	X	V	X	X	X	X	V	X	X
Energy performance	X	X	X	X	X	X	X	X	X	V	X	X
Natural lighting quality	V	X	X	X	X	X	X	X	X	V	X	X
Climate zone	X	X	X	X	X	X	X	X	X	V	X	X
Presence of renewable energy systems	X	X	X	X	V	X	X	X	X	V	X	X

PARAMETER GROUP NAME [Pset]: IDENTIFICATION PARAMETERS

PARAMETER NAME												
Presence of incongruous elements	X	X	X	X	X	X	V	X	V	X	X	X
Subject to interventions	X	X	X	X	X	X	X	V	V	X	V	V
Rebuilt or replaced	X	X	X	X	X	X	X	V	V	X	V	X
Temporal transformation index	X	X	X	X	X	X	X	V	V	X	X	V
Possible uses	X	V	X	X	X	X	X	X	V	X	X	X
Coherence with original use	X	V	X	X	X	X	X	X	V	X	X	X
Protected	X	X	X	X	X	V	X	X	V	X	X	X
Possible morphological configurations	X	X	X	X	X	X	X	X	V	X	X	X
Possible material configurations	X	X	X	X	X	X	V	X	V	X	X	X
Possible color configurations	X	X	X	X	X	X	V	X	V	X	X	X
Possible surface treatments	X	X	X	X	X	X	V	X	V	X	X	X
Volumetric coherence	V	X	X	X	X	X	V	V	V	X	X	X
Conservation status	X	X	X	X	V	V	V	X	V	X	X	V

PARAMETER GROUP NAME [Pset]: IDENTIFICATION PARAMETERS

PARAMETER NAME												
Ownership	X	V	X	X	X	V	X	X	V	V	X	X
Managing entity	X	X	X	X	X	X	X	X	X	V	X	X
Usage regime	X	V	X	V	X	X	X	X	X	X	X	X
Risk of plant interference	X	X	X	X	X	X	X	X	X	X	X	V
Parking occupancy count	X	X	V	X	V	X	X	X	X	X	X	X
Access schedule	X	X	X	X	X	X	X	X	X	X	X	X
Seasonal use	V	X	X	X	V	V	X	X	X	V	X	X

PARAMETER GROUP NAME [Pset]: IDENTIFICATION PARAMETERS

PARAMETER NAME												
Building size class	X	X	X	X	X	X	X	X	X	X	X	V
Construction period class	X	X	X	X	X	X	X	X	X	X	X	V
Last renovation	X	X	X	X	X	X	X	X	X	X	X	V
Structural type	X	X	X	X	X	X	X	X	X	X	X	V
Foundation type	X	X	X	X	X	X	X	X	X	X	X	V
Building height above ground	X	X	X	X	X	X	X	X	X	X	X	V
Building height above ground	X	X	X	X	X	X	X	X	X	X	X	V
Damage category	X	X	X	X	X	X	X	X	X	X	X	V
Design subsidence (mm)	X	X	X	X	X	X	X	X	X	X	X	V
Design angular distortion	X	X	X	X	X	X	X	X	X	X	X	V
Neutral axis position (equivalent beam)	X	X	X	X	X	X	X	X	X	X	X	V
Design deformation	X	X	X	X	X	X	X	X	X	X	X	V

Chapter 4
CIM MODELING[1]

4.1 Toward Data Integration for Representing Urban Systems

The transition from traditional methods of city management and planning to modern systems is increasingly driven by the need for efficient resource use, coupled with greater attention to quality of life and the urban environment (Pasquinelli et al., 2016). Challenges related to social, financial, and environmental sustainability compel decision-makers to optimize the management of complex urban systems, a process that relies heavily on the availability and effective use of data. In recent years, metropolitan administrations, municipal unions, and multi-utility companies have shown growing awareness of the importance of adopting innovative technologies for urban documentation and analysis. This shift underscores the necessity of a multidisciplinary and multi-scalar visualization of urban assets, adopting a holistic perspective that integrates both qualitative and quantitative approaches. Such an approach can deepen understanding, facilitate the monitoring of urban transformations, and provide the foundation for more informed management tools (Parrinello et al., 2018). Urban information modeling at multiple scales, from city-wide models to those of individual buildings, has therefore become a central theme in many smart city projects (Del Giudice et al., 2017), reflecting advances in international research across diverse fields.

To initiate meaningful digital transformation, cities must undertake significant efforts to consolidate existing building data scattered across disparate databases. Collecting and structuring data for an entire city or district remains a major challenge, largely because these databases were originally created independently for specific purposes, without consideration for broader information management objectives (F. La Russa et al., 2021). In this context, City Information Modeling (CIM) has attracted growing interest. CIM is widely recognized as a digital representation of the city (Li et al., 2022), enabling the identification of optimal strategies for improving urban environments. It functions as a repository for extensive urban data, encompassing both static models and dynamic objects (X. Xu et al., 2014). By integrating diverse

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[1] All the software referred to in this chapter is either open-source or, when proprietary, accessed through a student license.

data sources, technologies, and analytical tools, CIM provides a comprehensive framework for visualizing, analyzing, and managing urban environments holistically. This approach empowers stakeholders to make informed decisions, optimize resource allocation, and enhance urban livability and sustainability (E. M. Thompson et al., 2016). The literature highlights a viable and cost-effective strategy in the integration of Building Information Modeling (BIM) with Geographic Information Systems (GIS), commonly referred to as the BIM–GIS approach. For the creation of As-Built urban models, the Scan-to-BIM process represents a promising methodology, ensuring accurate representations of the built environment. Within this process, photogrammetric models play a crucial role by improving the morphological accuracy of CIM. These models use photographic images to extract reliable information about the physical features of the urban landscape.

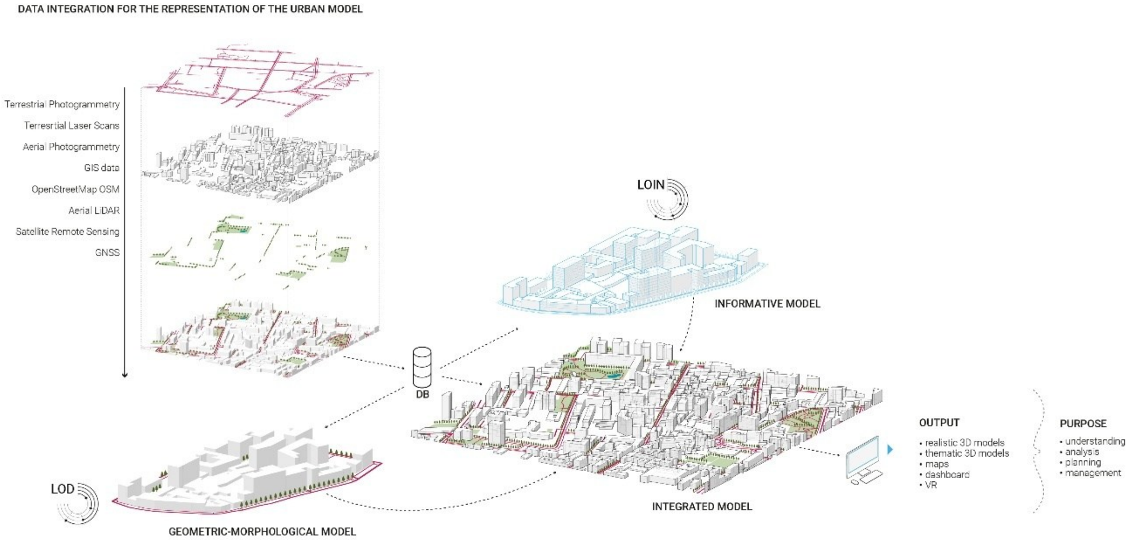

Fig. 4.1 – Concept of the stratification of the knowledge model

In the following chapter, the modeling process adopted in the selected case studies is described, with particular emphasis on the CIM approach developed through different software tools and heterogeneous data sources. The objective is to define an information process, within a BIM environment, for representing the urban context from a CIM perspective. Alongside the discussion of diverse data inputs, the chapter presents the modeling and export procedures designed to enable the use of the model on an open-standard platform, in line with the principles of Open BIM.

4.2 Heterogeneous Data and Diverse Sources as Input Data

Recent innovations in 3D processing and the increasing availability of geospatial data have significantly contributed to the development of more comprehensive solutions for data visualization. Since various data formats are employed to describe urban environments, combining layers from different sources makes it possible to represent three-dimensional urban areas (Hadimlioglu & King, 2019). The 3D reconstruction of urban environments has become a central topic, as multiple disciplines make use of 3D city models for purposes of visualization and simulation. For City Information Modeling (CIM), data enabling the definition and description of territorial areas and the urban scene are essential. As highlighted in the literature, two different modeling approaches can be followed: top-down and bottom-up[2], both of which involve the use of heterogeneous data sources (Planu & Giau, 2024). One of the objectives of the research was to investigate the sustainability of urban parametric modeling. The aim was to define a methodological approach focused on data that are both available and capable of being progressively implemented over time, while at the same time limiting the resources required. This was done in order to achieve a level of detail tailored to the specific requirements of the model, non-homogeneous across the entire urban area of the case studies, yet still capable of demonstrating the potential that progressive implementations may guarantee for future developments, depending on stakeholder needs.

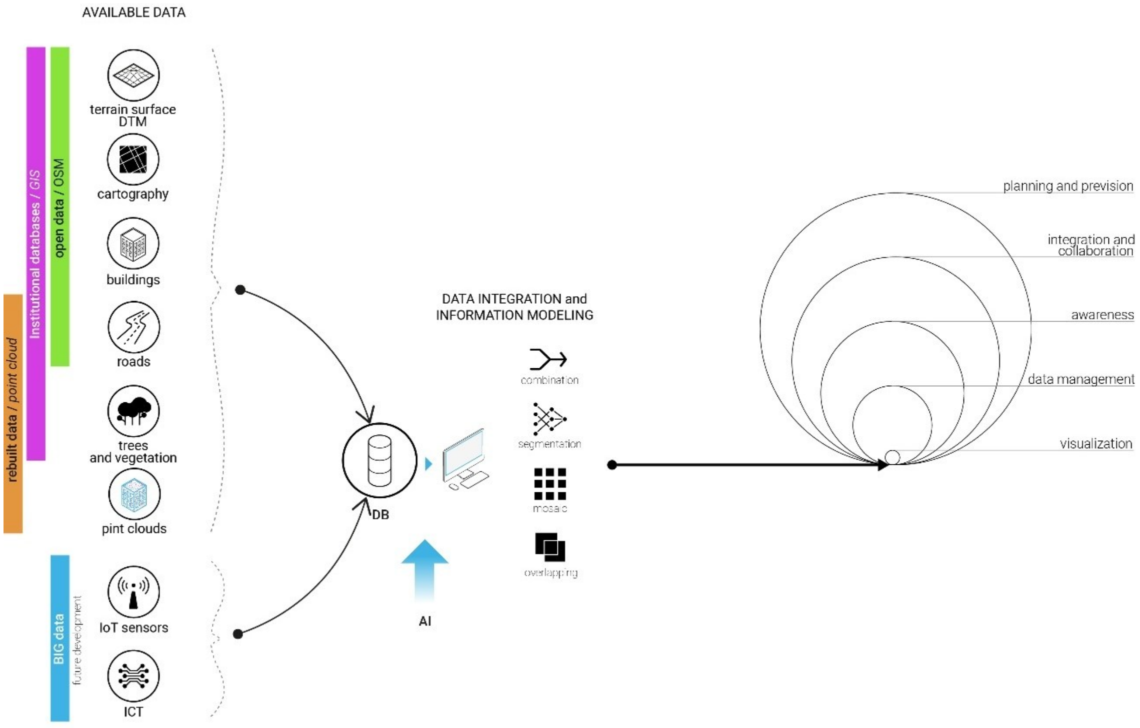

Fig. 4.2 – Concept of data use and integration: sources, uses, representation

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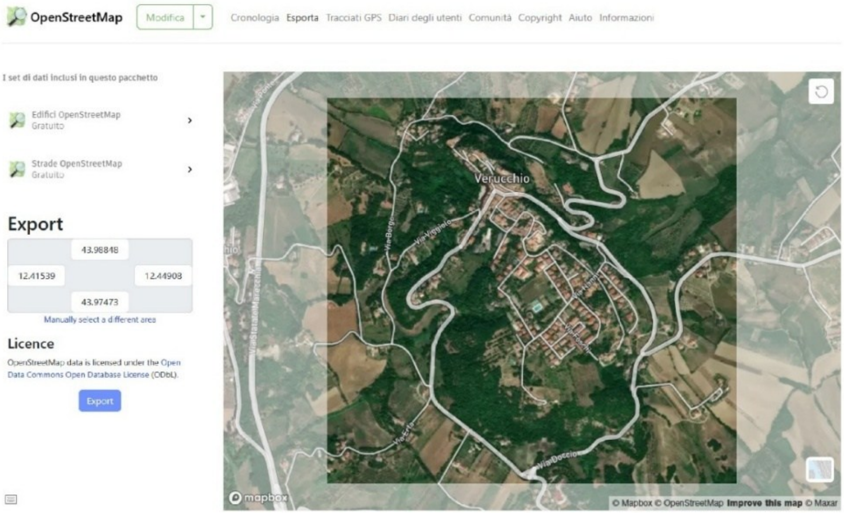
[2] For further details see at: 4.5 Top-Down and Bottom-Up Modeling Approaches

The selected case studies for the research were: Higienópolis, São Paulo, Brazil; Verucchio, Rimini, Italy; and the Darsena of Ferrara, Ferrara, Italy. The datasets identified, and in part used in the subsequent modeling phase depending on specific requirements, were classified according to their source into four categories: open-source data, institutional data, survey data, and data derived through a remote approach.

4.2.1 *Open Source Databases*

Open data represent a vast potential for applications across various sectors, particularly in land management. To date, the largest collection of open access geospatial data is provided by OpenStreetMap (OSM)[3], a collaborative project launched in 2004 to which users may contribute as part of the Volunteer Geographic Information (VGI) community. Data concerning infrastructures, urban areas, and similar features are released under the Open Database License (ODbL) and can serve as a valuable basis for the creation and implementation of 3D city models (F. La Russa & Santagati, 2020). In the literature, several applications have been documented that rely on OSM data to generate city models. Over et al. (2010) and Goetz (2013), investigated the use of OSM data for 3D city reconstruction purposes, where environmental data are visualized and simulations can be conducted (Hadimlioglu & King, 2019). Driven by the availability of high-resolution satellite imagery from Bing, the OSM database has expanded rapidly in recent years, providing vast amounts of geographic data for a wide range of applications. However, as emphasized by Z. Wang & Zipf, (2017), its reliability must be carefully verified. OSM data exhibit an average accuracy sufficient for territorial-scale analyses, but too low for architectural-scale applications (Agius et al., 2018).



I set di dati inclusi in questo pacchetto

Export

43.98848
12.41539
12.44908
43.97473

Licence

OpenStreetMap data is licensed under the Open Data Commons Open Database License (ODbL).

Fig. 4.3 – OpenStreetMap screen showing the Verucchio area selected for the export of cartographic data.

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[3] For further details: openstreetmap.org: https://www.openstreetmap.org/#map=18/43.983291/12.422085

Results demonstrate that urban areas can be effectively visualized in 3D using OpenStreetMap data, provided that data are available (Hadimlioglu & King, 2019). Nonetheless, these data must be integrated into BIM tools in order to optimize them and ensure homogeneity, with the ultimate goal of enabling consultation of both urban and architectural features. The study of OSM data in this research is particularly significant, since tools such as Model Builder in Autodesk Infraworks and Autodesk Forma, further discussed in a later section, also rely on this type of source data when generating the base model.

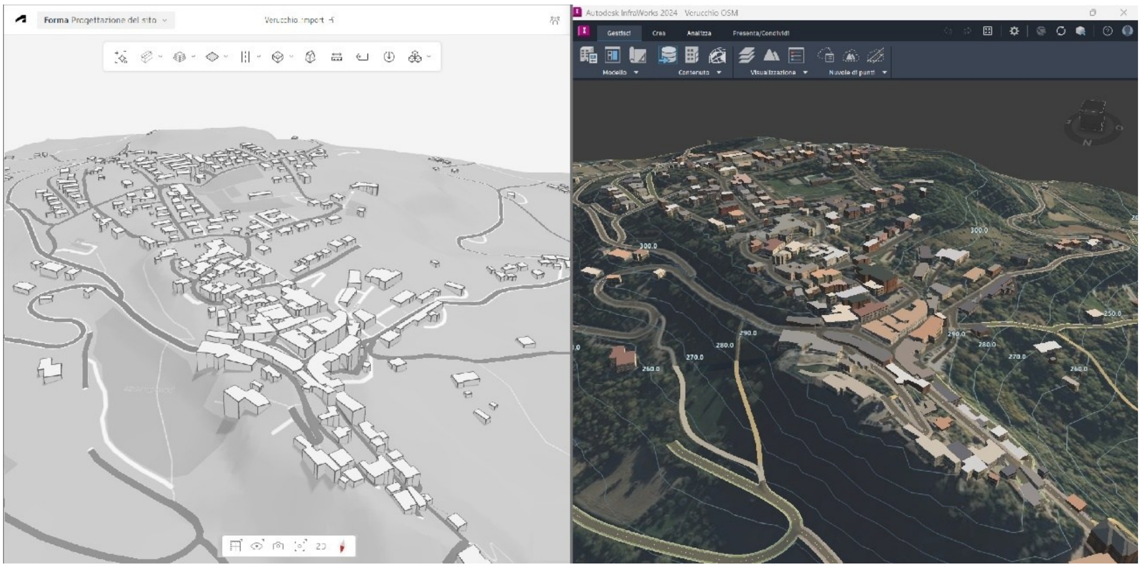

Fig. 4.4 – Construction of the base model of Verucchio in Autodesk Forma (left) and Autodesk InfraWorks (right) derived from OpenStreetMap data.

4.2.2 *Institutional Databases*

With the dual objective of, on the one hand, increasing the representative level of detail, and on the other, assessing the accuracy of OSM data through comparison with institutional data recognized as a shared basis for urban planning, civil protection, environmental monitoring, and infrastructure development, a search was conducted for source data within institutional databases. Among these are: the geoportal of the Emilia-Romagna Region, the Municipality of Ferrara, and the Geographic Information System of the Municipality of São Paulo. These datasets are accessible through web services, which can be integrated into various types of software and, depending on specific needs, can also be directly downloaded from the platforms. Only for the case study of the Municipality of Verucchio did the technical office provide a few CAD data in .dwg format[4].

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[4] The Municipality of Verucchio is gratefully acknowledged.

The *Geoportal of the Emilia-Romagna Region*[5] constitutes the reference digital infrastructure for accessing, consulting, and distributing regional geographic data. It is an interoperable platform, compliant with OGC international standards, capable of integrating cartographic databases, territorial themes, and web-GIS services. Through WMS, WFS, and WMTS services, the portal enables the use of both vector and raster data, and it also includes applications for three-dimensional visualization (RER3dmap) and for the consultation of orthophotos. With its 457 datasets, the Geoportal is not only a technical-administrative tool but also a research infrastructure that ensures access to high-quality spatial data, thereby supporting multidisciplinary applications. The RER3dmap service, accessible via browser, allows users to visualize the datasets from the regional catalogue in a three-dimensional representation. The download section provides extraction and download services for cartographic data from the Emilia-Romagna Region, available in multiple formats (.shp, .dxf, .geojson, .gbd, .gpkg, .kmz). During the download process, the coordinate reference system must be specified. The dataset collection made accessible through the Geoportal is provided by and remains the property of the Emilia-Romagna Region.

For the development of the CIM models in this research, both for the case studies of Verucchio and Ferrara, the following data were downloaded: the digital terrain model (DTM) 5x5, derived from altimetric information from the Regional Technical Map and GIS, as well as .shp files of buildings, roads, and surveyed trees.

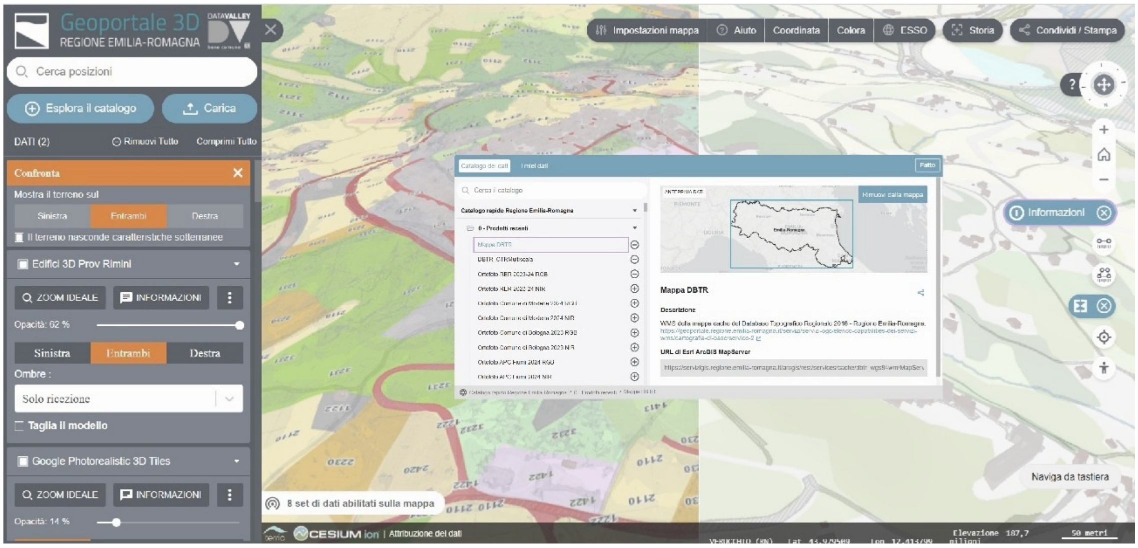

Fig. 4.5 – Interface of the Emilia-Romagna Region 3D Geoportal with the cartographic data catalogue open and a comparative visualization of a portion of Verucchio. (Source: https://mappe.regione.emilia-romagna.it/).

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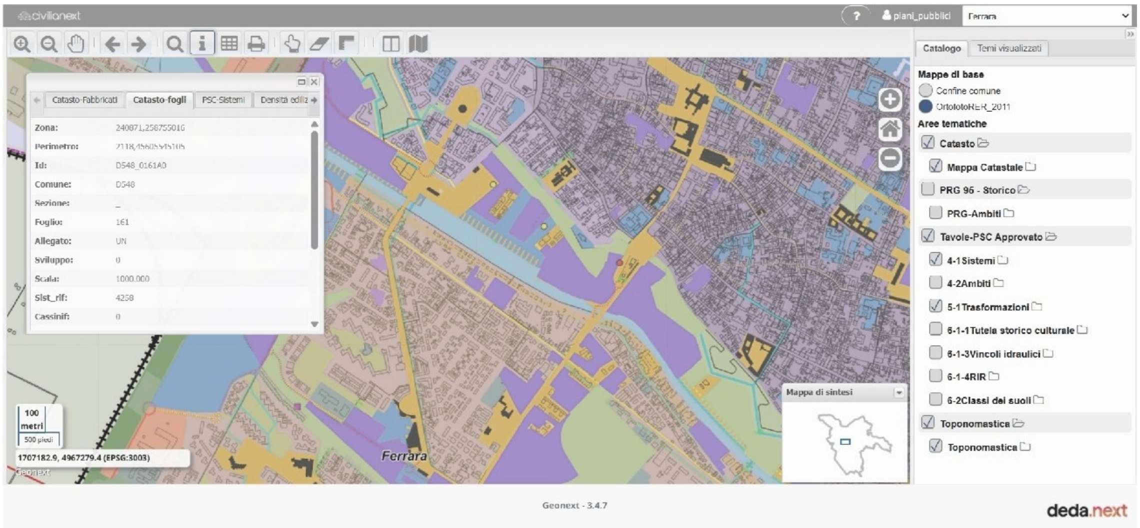
[5] Geoportal of Emilia-Romagna Region: https://mappe.regione.emilia-romagna.it/

The *Geoportal of the Municipality of Ferrara*[6] functions as an interactive digital tool that gathers and makes available data, services, and geographic representations concerning the cultural and natural heritage of the municipal territory. The platform is organized into several sections, among which the "Data" section is particularly significant, as it provides access to the information produced by the municipal administration in the course of its institutional functions. Some datasets are released under open license, freely accessible, downloadable, and reusable, in line with principles of interoperability and public data reuse; other datasets serve purely informational purposes and are subject to usage restrictions. This distinction reflects the portal's dual objective: on the one hand, to promote free and informed access to geographic information; and on the other, to offer a broader catalogue of data, even if sometimes only for restricted consultation. Another key service is the "Maps" section and the Geonext viewer, which allows users to explore institutional maps and navigate within an integrated system of thematic cartographies. Thanks to WMS technology (ISO19128), users can directly view open geographic datasets online. The "Download" section further enables the retrieval of data and corresponding metadata in various formats (.shp, .csv), distributed under the Creative Commons Attribution 4.0 International license (CC BY 4.0).

For the development of the CIM model of the Darsena urban area in Ferrara, .shp files of buildings and tree surveys were downloaded in order to compare datasets of the same category obtained from different sources.



Zona: 240871,258755016
Perimetro: 2118,45605545105
Id: D548_0161A0
Comune: D548
Sezione: _
Foglio: 161
Allegato: UN
Sviluppo: 0
Scala: 1000.000
Sist_rif: 4258
Cassinif: 0

Mappe di base
○ Confine comune
● OrtofotoRER_2011
Aree tematiche
☑ Catasto
  ☑ Mappa Catastale
☐ PRG 95 - Storico
  ☐ PRG-Ambiti
☑ Tavole-PSC Approvato
  ☑ 4-1Sistemi
  ☐ 4-2Ambiti
  ☑ 5-1Trasformazioni
  ☐ 6-1-1Tutela storico culturale
  ☐ 6-1-3Vincoli idraulici
  ☐ 6-1-4RIR
  ☐ 6-2Classi dei suoli
☑ Toponomastica
  ☑ Toponomastica

Fig. 4.6 – Interface of the Municipality of Ferrara Geoportal, showing the cartographic data catalogue and a visualization of the Darsena area within the city. (Source: https://www.comune.ferrara.it/geoportale).

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[6] Geoportal of the Municipality of Ferrara: https://www.comune.ferrara.it/geoportale

The official geoportal of the City of São Paulo, *GeoSampa*[7], launched in 2014 within the framework of the SIG-SP project (Sistema de Informações Geográficas do Município de São Paulo), is promoted by the Coordenadoria de Produção e Análise de Informação (GEOINFO) of the SMUL (Secretaria Municipal de Urbanismo e Licenciamento). The platform, developed using open-source technologies such as GeoServer and OpenLayers, adheres to OGC standards and ensures interoperability and transparency in municipal data management. Through a web interface, it enables navigation of the Mapa Digital da Cidade (MDC), a digital cartographic base derived from an aerial survey conducted in 2004 and updated in 2017 with LiDAR data, including digital surface and terrain models. Over 300 thematic layers are available for query and overlay. From a technical perspective, data are accessible via WMS services (for non-editable raster representations) and WFS services (for direct access and manipulation of vector data). GeoSampa constitutes a centralized database that provides geodata, metadata, aerial photographs, orthophotos, and historical maps, distributed under the Creative Commons Attribution 4.0 International license (CC BY-SA 4.0). The platform supports various reference systems, including SIRGAS2000 (EPSG:31983), officially adopted in Brazil since 2014, SAD69(96) for historical compatibility, and WGS84. Data can be downloaded in multiple formats (.shp, .dxf, .kmz, .gpkg, .pdf, .csv/.xls). Using data obtained from the 2017 aerial survey, in which a laser sensor was mounted on a helicopter, a 3D LiDAR point cloud of the entire city was produced, enabling the representation of both the Digital Terrain Model (DTM) and the Digital Surface Model (DSM). The files, in .laz format, are available for download and online consultation. As the point clouds are classified, they allow segmentation into distinct urban categories, which can also be visualized with false colors, thereby facilitating interpretation during the modeling phase. For the development of the CIM model of Higienópolis, in São Paulo, GeoSampa data were essential: in addition to the LiDAR point clouds of the selected area, .shp files of buildings, trees, boundaries, public lighting, and other urban elements were downloaded, modeled as families, and placed within the model.

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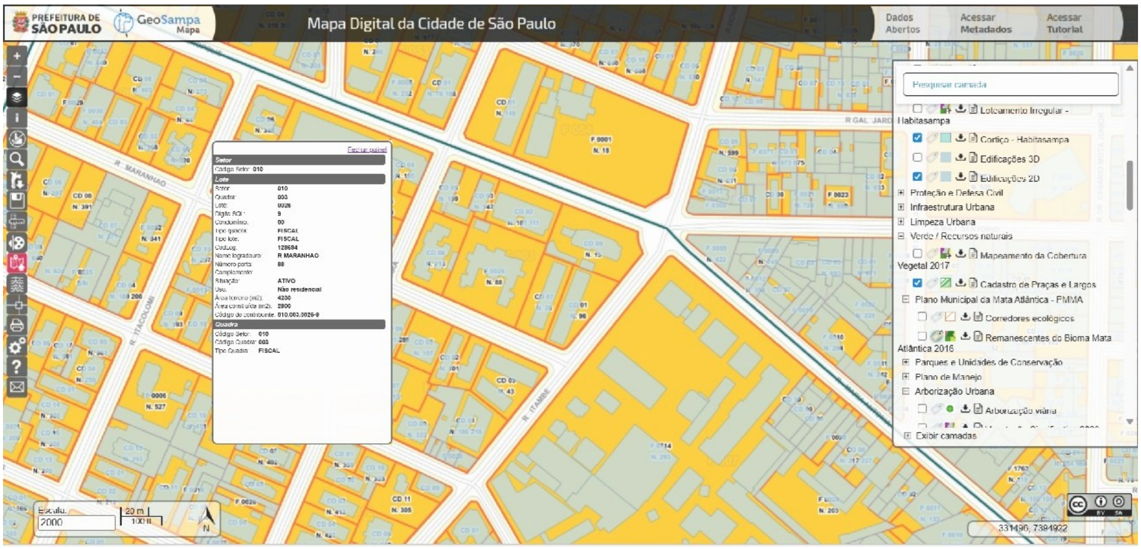
[7] GeoSampa: https://geosampa.prefeitura.sp.gov.br/PaginasPublicas/_SBC.aspx. Credits: Prefeitura do Município de São Paulo, Secretaria Municipal de Urbanismo e Licenciamento – GEOINFO. (s.d.). *GeoSampa: Sistema de informações geográficas do município de São Paulo*. Coordinamento: B. C. Milla, L. P. dos Santos, S. E. de Vasconcelos. Preparazione ed esecuzione: A. M. de Sousa, L. C. Kuada, A. P. da Silva, F. E. N. Waragaya, I. Ribeiro, M. de O. Soares.



Fechar painel

Setor

Código Setor: 010

Lote

Setor: 010
Quadra: 003
Lote: 0026
Dígito SQL: 9
Condomínio: 00
Tipo quadra: FISCAL
Tipo lote: FISCAL
CodLog: 128694
Nome logradouro: R MARANHAO
Número porta: 88
Complemento:
Situação: ATIVO
Uso: Não residencial
Área terreno (m2): 4230
Área construída (m2): 2800
Código do contribuinte: 010.003.0026-9

Quadra

Código Setor: 010
Código Quadra: 003
Tipo Quadra: FISCAL

Pesquisar camada

- ☐ Loteamento Irregular - Habitasampa
- ☑ Cortiço - Habitasampa
- ☐ Edificações 3D
- ☑ Edificações 2D
- ⊞ Proteção e Defesa Civil
- ⊞ Infraestrutura Urbana
- ⊞ Limpeza Urbana
- ⊟ Verde / Recursos naturais
  - ☐ Mapeamento da Cobertura Vegetal 2017
  - ☑ Cadastro de Praças e Largos
  - ⊟ Plano Municipal da Mata Atlântica - PMMA
    - ☐ Corredores ecológicos
    - ☐ Remanescentes do Bioma Mata Atlântica 2016
  - ⊞ Parques e Unidades de Conservação
  - ⊞ Plano de Manejo
  - ⊟ Arborização Urbana
    - ☐ Arborização viária
- ⊞ Exibir camadas

Fig. 4.7 – Interface of GeoSampa, the geoportal of the City of São Paulo, showing the active layer catalogue and a detailed visualization of an urban block of Higienópolis. (Source: https://geosampa.prefeitura.sp.gov.br/)

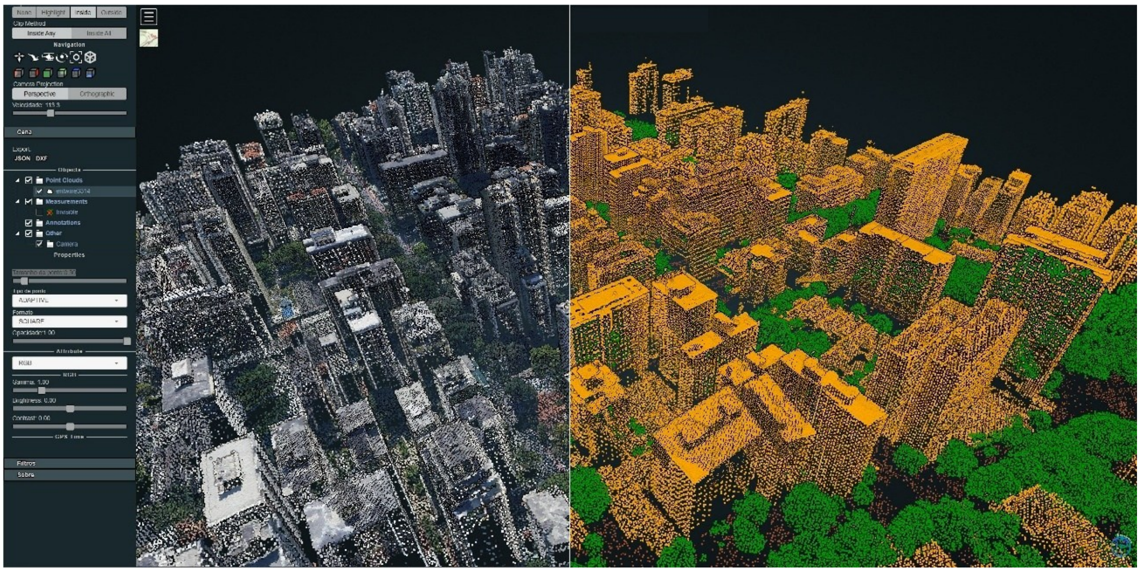


Fig. 4.8 – Interface of GeoSampa, the geoportal of the City of São Paulo, showing a comparative visualization of urban LiDAR point clouds: on the left in photorealistic mode, and on the right with thematic classification of an urban block of Higienópolis. (Source: https://geosampa.prefeitura.sp.gov.br/)

4.2.3 *Urban Surveying Data*

In recent years, the need to develop appropriate documentation activities capable of generating databases for the protection of architectural heritage and the dissemination of cultural values has raised awareness among administrations, development agencies, and municipalities. This has fostered growing interest in the use of innovative technologies for urban documentation and analysis, aimed at more informed territorial management (Parrinello et al., 2018). Urban surveying represents a tool with a dual purpose. On the one hand, it serves as a means of acquiring knowledge of a place through immersion in space and its constituent elements. This cognitive act is able to reveal the structure of the city and its formative logics, highlighting spatial relationships and historical permanence (De Simone, 1982). Surveying thus becomes a document of the testimonies transmitted by history, a primary tool for reading signs and reflecting on them. On the other hand, it functions as both a knowledge system and a structured resource supporting design processes, precisely due to its capacity to outline a methodology concerned with understanding and representing processes of transformation (Balzani, 1995).

Theoretical reflections on urban surveying have found a natural evolution in the field of digital surveying: new technologies, while not replacing the critical approach, extend its cognitive and applicative potential (Bertocci & Bini, 2012; Docci & Maestri, 2009). Traditional survey methods, based on manual operations and direct instruments, have been progressively integrated with instrumental and digital techniques capable of ensuring greater precision and enhanced data management capacity. “Digital surveying” refers to surveys conducted with electronic and computer-based equipment. Three-dimensional digital survey systems make it possible to obtain accurate and detailed models. These technologies are able to capture a huge number of measurements in a very short time, producing a sort of intermediate model between the real and the represented, consisting of a point cloud. Digital surveying does not replace the critical and interpretative approach of traditional methods but rather enhances their outcomes, providing advanced tools for three-dimensional representation, the creation of information models, and the elaboration of scenarios of urban transformation.

For several decades, three-dimensional aerial survey methodologies such as LiDAR and digital photogrammetry have been increasingly employed to acquire the morphology of extensive areas (Mora et al., 2019). In urban areas, the use of “fast survey” tools, capable of capturing a large amount of metrically reliable data in a short time, has significantly stimulated the adoption of integrated acquisition methods for entire portions of historic centers, producing an updated cognitive framework of both individual elements and their surrounding contexts (Parrinello et al., 2018). The configuration of the urban scene requires a combined documentation strategy structured by coverage levels, urban pathways, and analytical objectives, composed of multiple sets of actions: a “static” acquisition of constructive detail, carried out at ground level and focused on environments and urban frontages; a “mobile” acquisition extended along road axes and territorial competences; and an “aerial” action for general control and coordination, aimed at reconstructing and integrating the upper coverage levels and architectural aggregates at the landscape scale. Urban digital surveying relies on the combined use of LiDAR[8] and photographic equipment, procedurally differentiated into terrestrial methods: static application (Terrestrial Laser Scanner) and dynamic acquisition (Mobile Laser Scanner, SLAM[9]), and aerial methods (drones for SfM photogrammetry, LiDAR). This integration ensures complete coverage of the urban context across multiple levels of observation and stratification of the built environment. For proper integration of input data, georeferencing and metric calibration of the model through GPS are fundamental in order to define a single reference system and avoid coordination issue between models. In the urban survey process, laser scanning supports the creation of a highly dense point database focused on urban façades, complemented by photogrammetric point clouds for roofs and upper building sections, and sparse point clouds from mobile scans for areas of lower construction density. These are then integrated through the selection of certified control points across different datasets. The result of the 3D digital survey is a georeferenced three-dimensional digital model of an urban sector, aligned within a unified reference system. These models, point clouds and meshes, constitute only the starting point of a three-dimensional modeling procedure aimed at data processing for interpretation and analysis.

Although urban surveying currently represents the most reliable method for acquiring data on a given urban sector, it must also be acknowledged that survey campaigns are demanding processes, requiring considerable economic resources and time both for data acquisition and for the processing of the often very large datasets involved, which may amount to several terabytes (Tb). From the perspective of the sustainability of the CIM process proposed in this thesis, it is therefore not feasible for metropolitan administrations, municipal unions, and multi-utility companies to carry out instrumental surveys across its entire area of interest. For this reason, the research investigates other already available data sources, adopting an approach oriented towards progressive integrations and implementations, guided by the requirements and needs of model management as expressed by stakeholders.

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[8] LiDAR stands for light detection and ranging, a method of determining three-dimensional (3D) data points using a laser. It is a remote-sensing technique that can be performed with either ground-based systems (terrestrial laser scanning, TLS) or airborne systems (airborne laser scanning, ALS). LiDAR can be deployed from static or moving platforms, including aircraft and vehicle-mounted sensors. (Boardman & Bryan, 2018).

[9] SLAM (Simultaneous Localization and Mapping) reconstructs the scene while simultaneously determining relative position, providing real-time data with a high level of detail and photorealistic rendering.

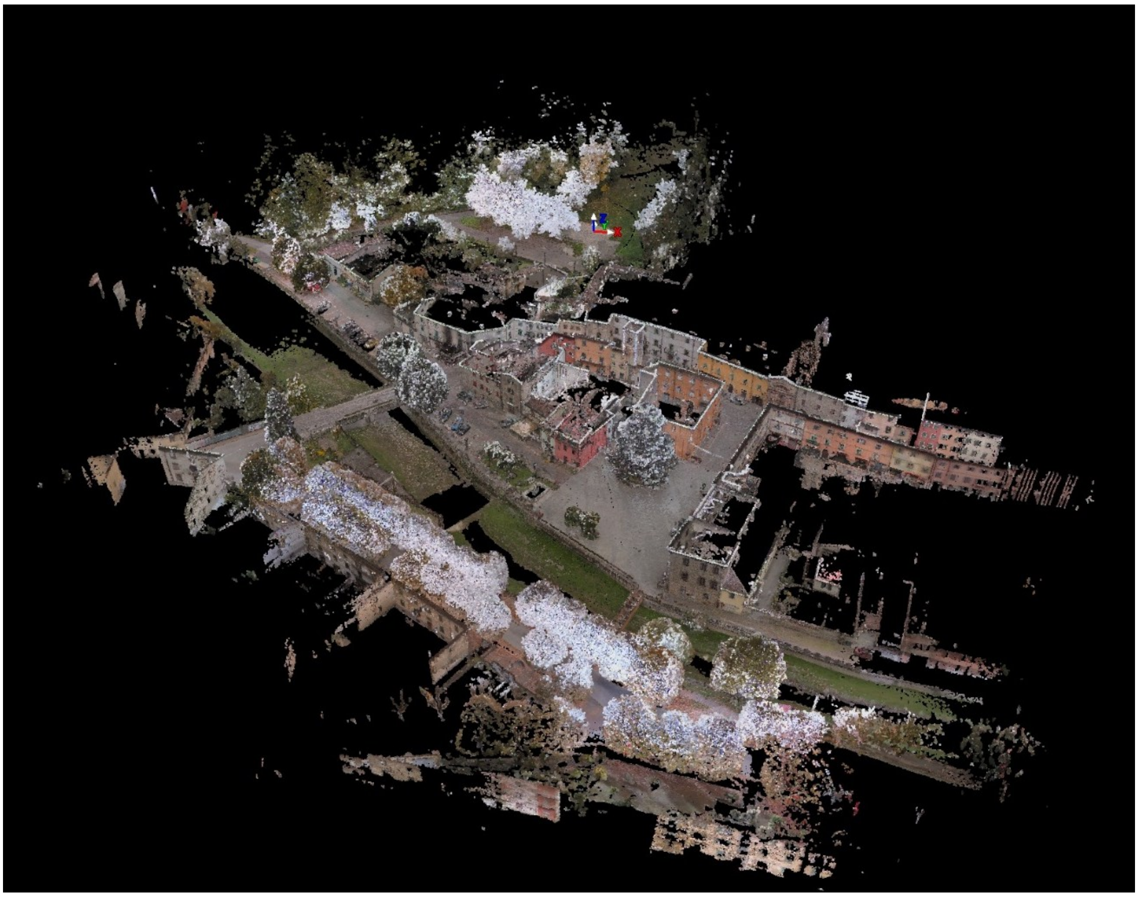

Fig. 4.9 – Example of an urban survey carried out using a SLAM laser scanner in Tredozio (FC), Emilia-Romagna, Italy (Source: INCITE project; credits: Guido Galvani).

4.2.4 *Data Derived Through a Remote Approach*

3D reconstruction of urban environments is a central topic of this research, as numerous disciplines employ 3D city models for visualization and simulation purposes. With recent technological advancements, large corporations such as Apple, Google, and Microsoft have integrated 3D urban visualizations into their mapping services (Hadimlioglu & King, 2019). With the aim of developing sustainable urban models, this research has explored the possibility of simulating a photogrammetric survey at the urban scale in a virtual environment, in order to generate a point cloud from the three-dimensional model available in Google Earth[10]. Google Earth is a geospatial visualization platform that integrates satellite and aerial imagery from various sources (e.g., Landsat, Sentinel, MODIS) (Gorelick et al., 2017; Velastegui-Montoya et al., 2023). The platform is freely accessible for educational and research purposes and is widely used as a basis for preliminary urban studies. The generation of three-dimensional models available in Google Earth relies on automated aerial photogrammetry techniques and advanced computer

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[10] Google Earth: https://earth.google.com/web/

vision algorithms. Aerial images are collected through systematic flights using high-resolution multi-angle cameras, enabling the capture of each urban portion from multiple perspectives. Structure from Motion (SfM) procedures are then employed to identify homologous points across different images and estimate camera orientation parameters, thereby reconstructing the three-dimensional geometry of the scene. Subsequently, Multi-View Stereo (MVS) methods are used to densify the point cloud, producing continuous and topologically consistent surfaces. These surfaces are then textured using the original orthorectified imagery, resulting in a photorealistic outcome. This approach, already consolidated in scientific research on urban modeling (Frueh & Zakhor, 2003; Lafarge & Mallet, 2012), has been implemented by Google on a global scale through distributed computing infrastructures, allowing for the periodic updating of 3D datasets in many high-priority metropolitan areas.

For the preliminary phase of studying methods for data integration, given that surveying an entire urban area is not always feasible due to cost and time constraints, it was decided to simulate an aerial photogrammetric survey. Starting from images extracted from Google Earth, a photo modeling process was conducted for the selected urban section of the case study[11]. The Google Earth data were deemed sufficiently up-to-date for the purposes of this research (Planu & Giau, 2024). Georeferencing and metric accuracy were ensured by means of n.6 known GPS points identifiable in the images. The result is a derived, georeferenced point cloud that constitutes an additional data layer, obtained through a remote approach, and is useful for integration with other datasets in the development of CIM models.

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[11] The process was applied specifically to the case study of the Darsena of Ferrara, Italy.

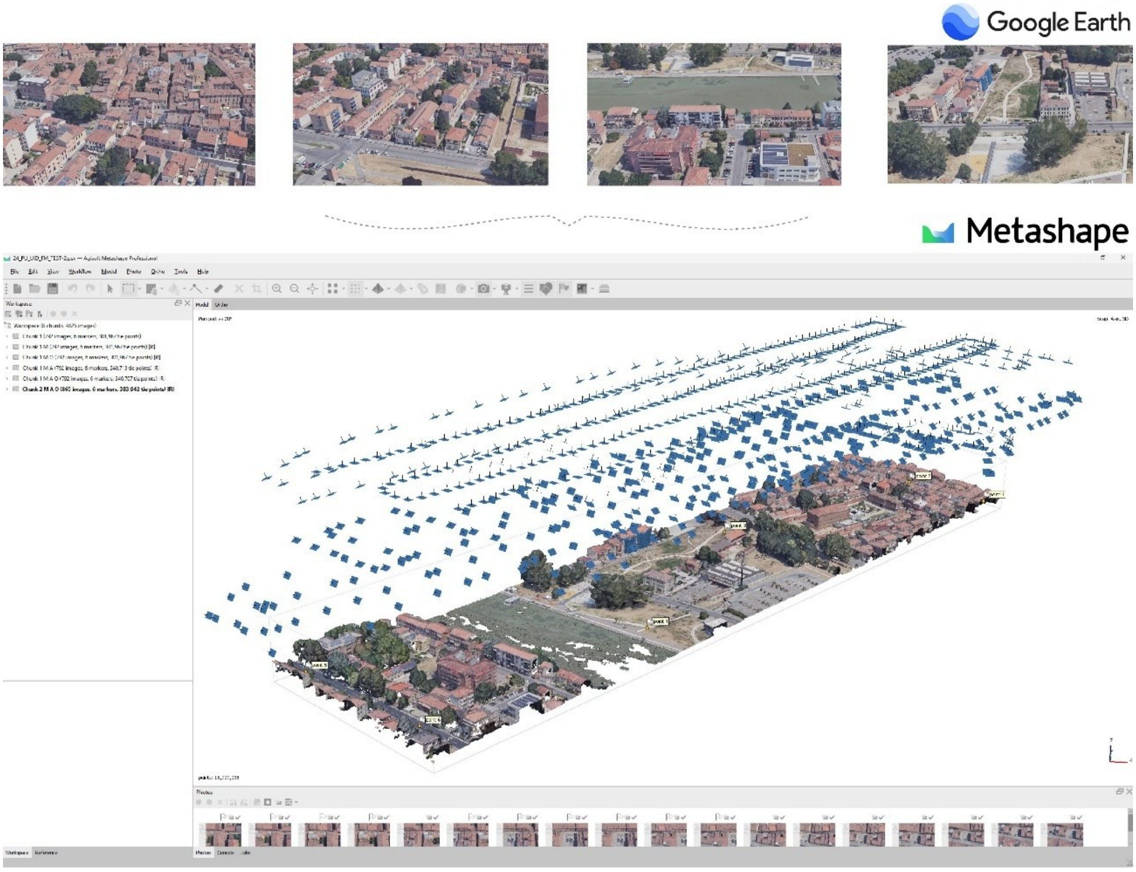

Fig. 4.10 – Photogrammetric reconstruction obtained from images extracted from Google Earth and processed in Agisoft Metashape, showing the distribution of virtual camera positions, the resulting 3D model, and the yellow markers representing the ground control points used to georeference, orient, and scale the model.

4.3 Reference Systems for the Integration of Data

The informational virtualization of the urban context is increasingly linked to deductive processes developed through the combined comparison of heterogeneous information from multiple acquisitions sources, whose integration is essential to achieve documentation that can truly be defined as global (Ratti & Claudel, 2016). For the proper integration of different input data, the definition of a reference system represents a fundamental element, both for the geolocation of source data and, consequently, within the modeling software. This aspect, often underestimated, should instead be considered from the preliminary stages in order to avoid coordination issues in the models (Planu & Giau, 2024).

Every model or set of spatial data, in order to be integrated into a real context, requires a univocal reference framework that ensures geometric consistency and compatibility with other information sources. The adoption of a shared reference system, such as the national cartographic system Roma40/Montemario, or global systems like UTM based on WGS84 (World Geodetic System 1984), makes it possible to accurately position points, surfaces, and volumes within geographic space, thereby ensuring the correct interpretation and usability of the data. The choice of the reference system is not merely a technical issue; rather, it directly affects the quality and reliability of spatial analyses. Correct georeferencing allows interoperability between heterogeneous surveys, comparability of data collected in different periods or contexts, as well as integration with three-dimensional models, official cartography, and geospatial databases.

Within the framework of this research, for the CIM models of the case studies in São Paulo and Verucchio, the WGS84 coordinate system was employed in the following configurations: UTM 23S (EPSG:32723)[12] for the Higienópolis district in São Paulo, and UTM 33N (EPSG:32633) for Verucchio. For the case study of the Darsena in Ferrara, the Roma40/Montemario 1 system (Gauss-Boaga West) was used.

4.4 Preliminary Operations for Input Data

In a context where the virtualization of urban information is increasingly linked to deductive processes developed through the comparison and integration of heterogeneous data from multiple acquisition sources, whose harmonization is essential for the construction of documentation that can be legitimately defined as global (Ratti & Claudel, 2016), the selection of the working environment was primarily determined by the need to preserve the original information without introducing modifications to the operational framework. In order to optimize the modeling process and ensure its coherence and reliability with respect to the various stakeholders and the differentiated uses they may make of the model, this research has established a set of preliminary operations, conceived as preparatory steps for the subsequent development of the actual modeling phase.

4.4.1 *Georeferencing of source data*

For the proper integration of different input data, the definition of the reference system represents an essential element both for the geolocation of the source data and, consequently, within the modeling environment. Once the coordinate system was defined for the models relating to the three case studies, all input data were georeferenced. In some cases, already at the stage of data download, as in the case of the Geoportal of the Emilia-Romagna Region, it was possible to set the desired coordinate system directly. In other cases, through the use of QGIS software, the coordinate system was defined at a later stage, after which the georeferenced files could be

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[12] The acronym EPSG (European Petroleum Survey Group) identifies an international standard that assigns a unique numerical code to each coordinate system and cartographic projection.

exported. For the point clouds downloaded from the GeoSampa portal and the .shp files, since they were already georeferenced according to the selected reference system, no further operation was required beyond verification.

In the perspective of modeling within the Revit environment, this procedure ensures coordination among all input data and provides order and consistency throughout the process. In this way, all data are linked “by shared coordinates,” as they are georeferenced in conformity with the same reference system. It is therefore essential to set the model’s coordinate system correctly before its finalization and the initiation of operational activities. This allows, in the event of subsequent integrations or model updates (for instance, through the addition of a new survey), for the data to be positioned correctly within the workspace, avoiding ambiguities in linking options and enabling immediate interoperability.

4.4.2 *Point Cloud Segmentation and Classification*

3D surveys and recent developments in the field of scan-to-BIM, beginning with the established methodology for generating 3D point cloud models through laser scanning and photogrammetric techniques, have provided an increasingly reliable basis for the representation of existing buildings (Kim & Kim, 2022). In this context, 3D surveys and the most recent advances in scan-to-BIM have made it possible to establish a progressively more robust and valuable foundation for the process of existing building modeling. This process has been widely investigated and consolidated in numerous studies, which have achieved highly reliable results in terms of accuracy and precision, progressing from simple point clouds generated by laser scanning and digital photogrammetry to informative models capable of representing the complexity of existing buildings and large-scale infrastructures (Banfi et al., 2022).

For this reason, the LiDAR point clouds available and downloadable from the GeoSampa portal, as well as the reconstructed point cloud of the Darsena in Ferrara, represent essential input data in this research. Their informational richness allows, in the case of Ferrara, for the representation of roof morphologies, which in the historic center display the complexities typical of Italian urban fabrics. As highlighted in the literature, point clouds are increasingly subjected to segmentation and classification processes, with the aim of enriching them with semantic information, also by exploiting Artificial Intelligence algorithms (Gao et al., 2024; Grilli et al., 2017).

The LiDAR point cloud of São Paulo and the derived point cloud of Ferrara exhibit distinct characteristics, outlined below.

Accessible through the GeoSampa portal, the point cloud of the area surrounding Vila Penteado, in Higienópolis, is subdivided into sections according to a grid system defined by the Municipality. The available point cloud includes both the Digital Surface Model (DSM) and the Digital Terrain Model (DTM). The dataset is pre-classified, as attributes or labels are assigned to distinguish among different types of surfaces or detected objects. Each data class, for example: ground, low vegetation, high vegetation, building, or water, is associated with a false color. In preparing the cloud for CIM modeling, the point clouds corresponding to different portions of the city were merged and subsequently segmented according to the classification stored in the corresponding Scalar Field. For modeling purposes, the segmentation was simplified into three main categories: buildings, vegetation, and terrain. Each class was then assigned a false color, consistent with the visualization scheme adopted in GeoSampa. The result is a point cloud covering the selected urban sector of Higienópolis, organized into layers: one containing the LiDAR RGB point cloud, and three containing the classified and segmented point clouds (Buildings, Vegetation, Terrain), each displayed with its corresponding false color.

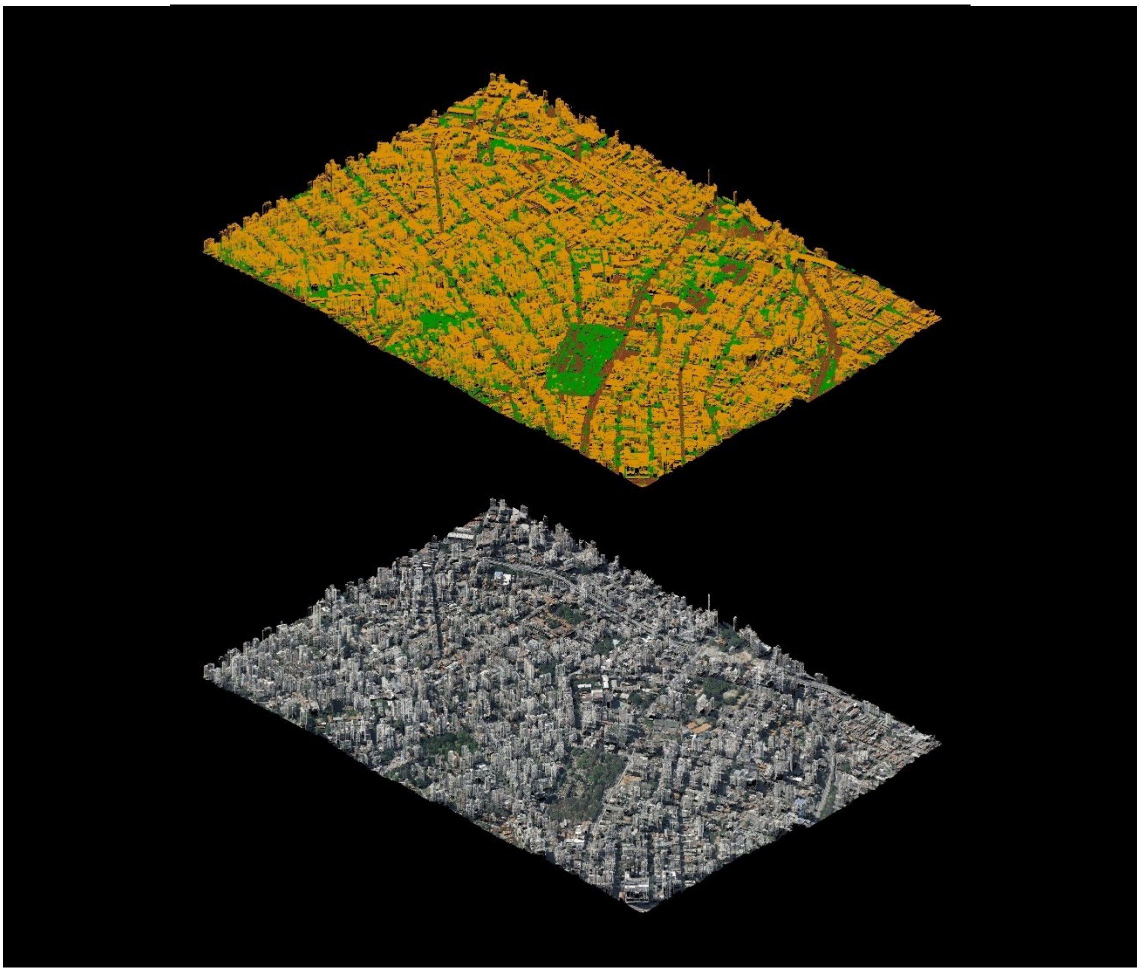

Fig. 4.11 – Classified (top) and RGB (bottom) visualizations of the urban point cloud of Higienópolis (São Paulo), downloaded from GeoSampa and processed in CloudCompare.

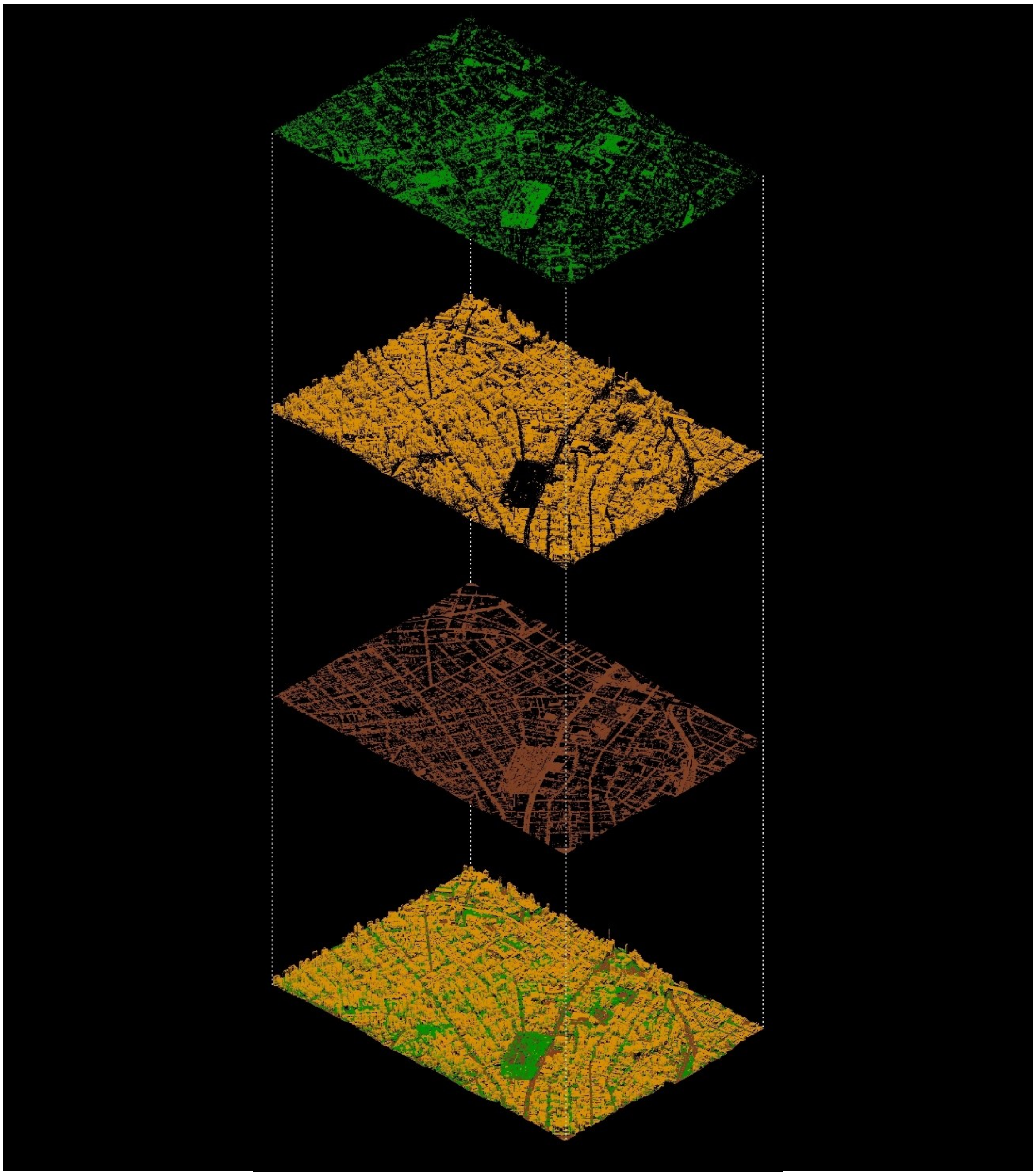

Fig. 4.12 – Layered thematic visualizations of the urban point cloud of Higienópolis (São Paulo), downloaded from GeoSampa and processed in CloudCompare, showing vegetation, buildings, ground/infrastructure classes, and the full classified dataset.

To optimize the modeling approach for the Ferrara case study, segmentation and classification processes were applied to the point cloud reconstructed from Google Earth. The Machine Learning methodology adopted follows the steps described in the literature (Weinmann et al., 2017): class definition, feature extraction, manual labeling of a dataset subset, training, testing, and validation of the selected algorithm (Random Forest), followed by prediction applied to the remainder of the model. Points not correctly classified by the automatic procedure were manually reassigned to the correct classes whenever their extent was significant enough to compromise data reliability. The defined classes were: buildings, roads, low vegetation, high vegetation, river, terrain, street furniture, and vehicles. The latter proved to be the most prone to misclassification, given their small size in relation to the scale of the simulated survey (Planu & Giau, 2024).

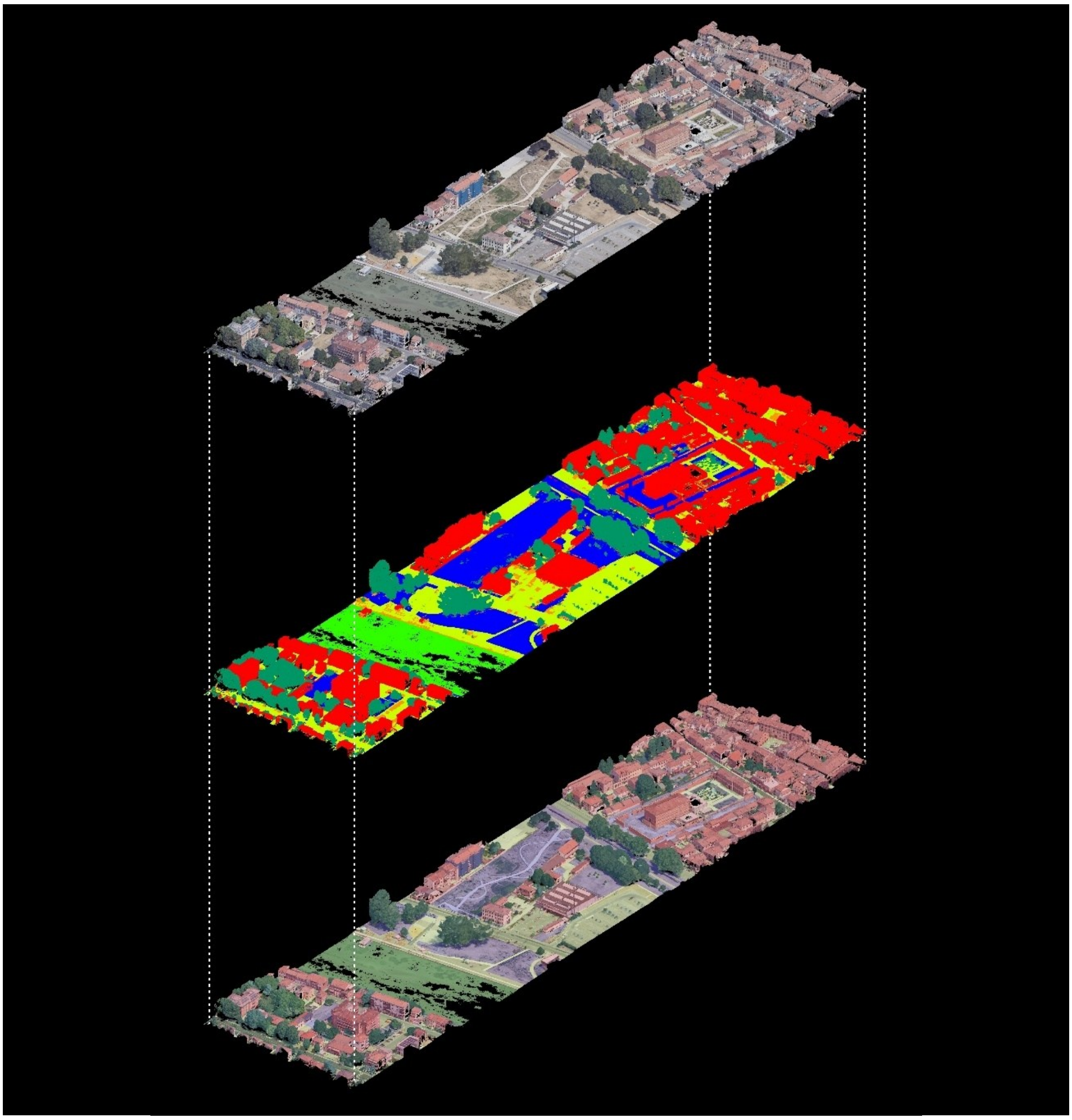

Fig. 4.13 – Point cloud derived from photogrammetric survey simulation and classification: buildings (red), roads (yellow), low vegetation (blue), high vegetation (dark green), rivers (light green), street furniture (orange), and vehicles (light blue).

In both case studies, the support provided by the segmented point cloud significantly accelerated processing for two main reasons. First, by isolating the building class, the source data became immediately functional for simplifying the interpretative phase of the modeling process. Second, the building-only cloud is lighter in computational terms compared to the complete dataset. All data categories were organized into separate layers, thereby enabling both integrated and comparative readings of urban systems, whether in their overall complexity or through the selective analysis of specific classes. Consequently, the management of the model within the authoring software proved more efficient.

4.4.3 *Comparative Assessment of Heterogeneous Data Sources*

By integrating the different data sources with the aim of avoiding duplication and, conversely, maximizing the use of the available datasets, certain overlaps inevitably emerged (Planu & Giau, 2024). Within the framework of this research, particular attention was devoted to the case study of the Darsena in Ferrara.
With regard to buildings, three different sources provide volumetric data that, as expected, exhibit slight variations: GIS datasets, OSM, and the BIM model derived from the Scan-to-BIM process. Consequently, it was necessary to assess which of these could be regarded as the most reliable for this category, in order to determine which should be prioritized. The analytical method involved pairwise comparisons between the extracted volumes and the point cloud generated through the simulated photogrammetric survey. The deviations were then visualized using a chromatic scale. In the specific case of the Darsena, the point cloud was employed as a benchmark, as it was considered the most reliable data source from both a geometric and morphological standpoint. Although the dataset results from an indirect process, Google Earth provides the most up-to-date information. The comparison shows that, in both planimetric and volumetric terms, the BIM-modeled buildings and those included in the GIS dataset of the Municipality of Ferrara display comparable deviations. Furthermore, excluding outliers, the levels of accuracy were deemed acceptable for representation at an urban scale. An additional consideration concerns the buildings generated through the BIM process: this method allows for the geometric modeling of roof structures, a morphological component regarded as essential for the description of the urban fabric that characterizes Italian territory.

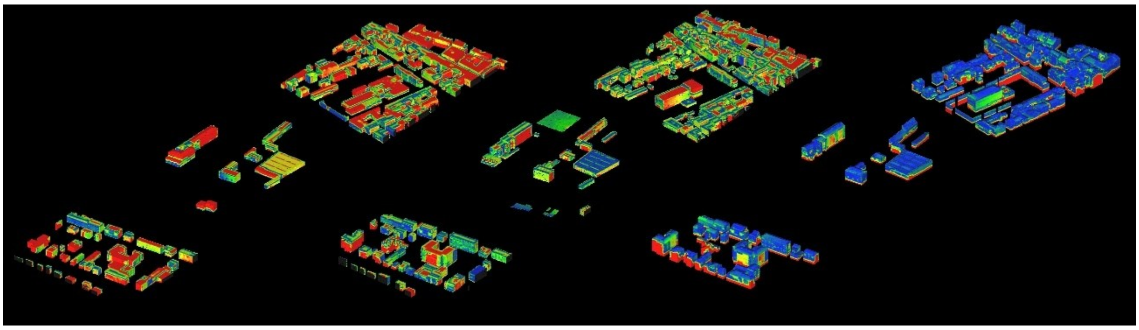

Fig. 4.14 – Comparison between the segmented point cloud of the buildings and the volumes obtained from OSM data (left), GIS data (middle), and BIM model (right). In red are the major distances, in blue the minor ones. The scan-to-bim process model is the most consistent. The model from GIS data shows good overall consistency, but is deficient in describing roofs. The model from OSM data is the least consistent.

4.5 Top-Down and Bottom-Up Modeling Approaches

For the definition and description of the urban context through CIM models, two different modeling approaches can be employed, depending on the type of source data: *top-down* and *bottom-up*. The top-down approach is adopted when managing geodata for the development of primitive geometries that are progressively enriched with incremental levels of detail; the bottom-up approach is employed when survey data are used, applying subsequent reverse modeling for the progressive abstraction of geometries. In fact, in top-down processes, it is assumed that an existing geodata source is available upstream, from which modeling can be initiated by semantically differentiating the generated geometries. By contrast, in the bottom-up approach, the information database is derived downstream, as the geometries obtained from the initial instrumental survey must first be segmented (F. La Russa et al., 2021).

The choice between these approaches depends on the intended applications. For example, in the short term, it may be necessary to obtain a point cloud suitable for visual inspections, which would initiate a bottom-up workflow. It should be emphasized that in the process described in this research, where heterogeneous and pre-existing data sources were used, both approaches were applied.

4.6 3D Modelling of the Urban Envirnoment

The 3D modelling of the built environment involves the creation, manipulation, and use of digital three-dimensional representations of real-world objects, including buildings, terrains, and infrastructure. Over the years, a wide range of such representations has been developed, each modelling objects in a different way and targeting distinct applications. These representations typically combine geometric (i.e., the description of shape), topological (i.e., adjacencies and connectivity), and semantic (i.e., attributes and other properties) information. Although these aspects can, in principle, be combined in arbitrary ways, in practice it is preferable to reduce complexity by modelling only those features required for a given application, and to do so in a manner that is both flexible, so as to apply to the different types of objects being modelled; and consistently structured, to enable automated processing through simple rules (Arroyo Ohori et al., 2022). However, these characteristics often come into conflict with one another; solutions therefore require finding compromises tailored to the specific application case. Since different applications frequently share common elements, it is not necessary to generate an entirely new representation for each of them. Instead, it is possible to reuse certain representational components, combining them as needed to develop an appropriate solution for the case at hand.

Within the framework of City Information Modeling (CIM), in which numerous components are involved, this dissertation aims to propose a process for the creation of an urban 3D model using currently available data sources. The resulting model is conceived as a thematic base, which, through the integration of additional information, may serve as a resource for different stakeholders in the management of the urban context and the cityscape.

The following sections present the various modelling processes employed in the different case studies. It should be emphasized that, given the heterogeneity of the areas under investigation, not only in terms of their geographical location but also of the available input data, different data sources were employed depending on the specific situations and modelling requirements. The output is a parametric, three-dimensional model, suitable for describing the urban context at scales ranging between 1:200 and 1:500.

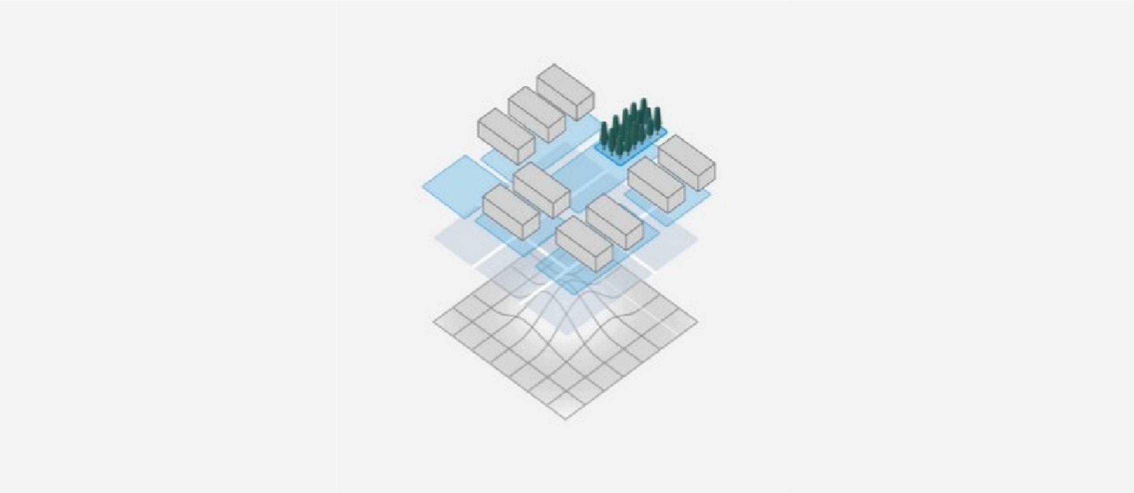

Fig. 4.15 – Concept of City Information Modeling (CIM) for creating integrated digital urban models. (Source: Autodesk).

4.6.1 *Point Clouds in the Modeling Process*

With point clouds, three-dimensional space seemingly reveals all its secrets: regardless of the shape, size, or complexity of the environments, the combined use of one or more surveying instruments enables data acquisition with a high degree of metric reliability and across the entire three-dimensional extent. Manipulating a point cloud in the digital environment is comparable to navigating within a measurable 3D photograph, detached from the acquisition point, as the recognizability of the elements present in the scene is immediate (Scandurra, 2020).

Nevertheless, point clouds in themselves do not generate knowledge, being nothing more than a vast number of points stored in computer memory, entirely independent of one another except for their Cartesian coordinates in digital space. Whether derived from range-based[13] or image-based[14] systems, the point cloud is considered an unintelligent model, as it is unaware of what it reproduces: it merely provides a virtual cast (Remondino, 2011) of the superficial aspects of an architectural artifact, without containing any information regarding the meaning of what has been captured. Moreover, it lacks volumetric consistency, since it reproduces only external surfaces, although it allows for the storage of a vast quantity of dimensional data with a high level of accuracy. In this sense, survey and interpretation operations are merely transposed into the digital environment, as the data must be re-elaborated not only in terms of processing but also, and above all, in terms of semantic understanding. Ultimately, for the study of architecture and the urban scene, models composed of point clouds represent a fundamental reference for dimensional data, yet they cannot provide an exhaustive representation of artifacts: much of the information necessary for proper documentation lies beyond the surface and, in large part, even beyond its physical consistency.

In this process, point cloud classification and segmentation operations have enabled greater efficiency for two main reasons. First, by isolating only the selected class (e.g., buildings, terrain, vegetation, etc.), the source data became more functional for simplifying interpretation-driven modeling. Second, the point cloud corresponding to a single selected domain is lighter in computational terms than the overall dataset. All datasets for the different categories were organized in separate layers, thus supporting an integrated reading of urban systems, either simultaneously in their full complexity or comparatively by selecting only certain categories. Consequently, model management within the authoring software was facilitated.

Within this research, the point cloud was used as input data in the case studies of Higienópolis, São Paulo, and the Darsena of Ferrara. Since the input datasets differ: Higienópolis being a LiDAR point cloud and Ferrara being a derived one, the data processing workflows adopted in this thesis, and described below, were necessarily distinct.

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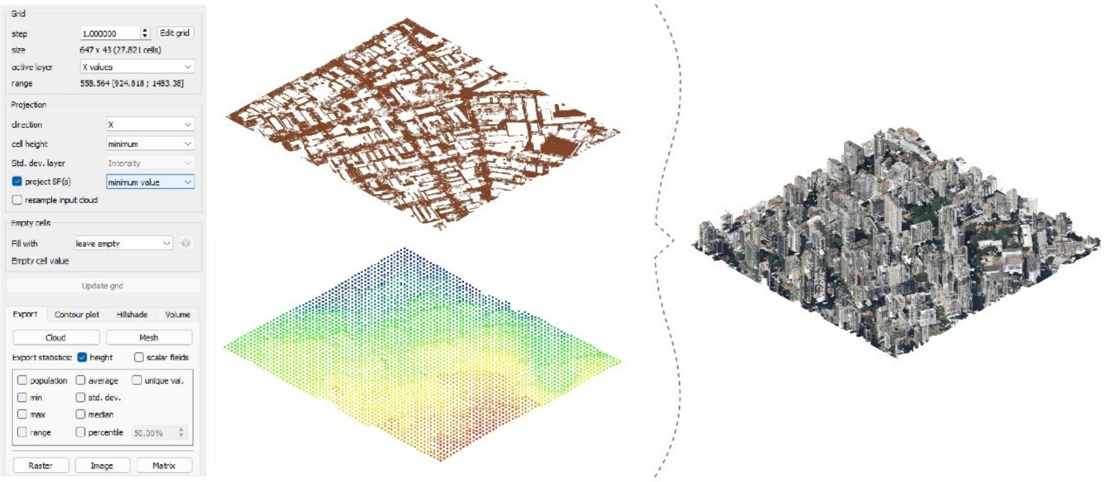
[13] Range-based systems (laser scanners, total stations, radar, etc.), that is, reality-based devices employing active sensors, are equipped with range cameras whose distance acquisition system relies on the projection of suitably encoded light patterns onto the surface to be surveyed, followed by their reception through a sensor capable of recording the response. The most common systems employ laser light, as it allows measurements to be taken over relatively long distances.

[14] This technology is referred to as passive optical sensing, since it does not play an active role in acquiring metric data, and the structuring of the point cloud does not coincide with the moment of acquisition but requires a subsequent processing phase. Among passive acquisition techniques, photomodelling has been widely adopted in recent years. This is a form of digital photogrammetry that makes it possible to generate measurable point clouds from photographic acquisitions. The procedure today is carried out using systems that are almost entirely automated, thanks to numerous protocols that integrate the Structure-from-Motion (SfM) orientation strategy, derived from Computer Vision, with the measurability required by photogrammetry.

The point cloud of Higienópolis, São Paulo, was downloaded from the GeoSampa portal in .las format and was already georeferenced according to the WGS84 reference system, configured as UTM 23S (EPSG:32723). This is a LiDAR point cloud, obtained from an aerial survey using a sensor mounted on a helicopter. The dataset represents a Digital Surface Model (DSM), already classified. To employ it in the modeling process, all point clouds of the study area were downloaded. Using the CloudCompare software[15], they were merged via the "merge" command. The result was an RGB point cloud of the entire study area. Subsequently, the cloud was duplicated and segmented into further layers according to classification, using the associated Scalar Field. To the segmented clouds (terrain surface, buildings, vegetation), false colors were assigned, useful for interpreting the urban context in the subsequent modeling phase.

The terrain model point cloud (DTM), derived from the LiDAR survey, had already been cleaned of non-terrain elements, but still contained "holes" corresponding to building footprints. These gaps were filled using the interpolation algorithm in CloudCompare. This solution enabled the reconstruction of a three-dimensional mesh consistent with the point cloud, as "point-by-point" modeling would have been more complex and less precise (Rossato et al., 2023). The final result consisted of one RGB point cloud and false-color clouds of the classified categories, which were then exported in .e57 format.



Grid
step 1.000000
size 647 x 43 (27.821 cells)
active layer X values
range 558.564 [924.818 ; 1483.38]

Projection
direction X
cell height minimum
Std. dev. layer Intensity
☑ project SF(s) minimum value
☐ resample input cloud

Empty cells
Fill with leave empty
Empty cell value

Export statistics: ☑ height ☐ scalar fields
☐ population ☐ average ☐ unique val.
☐ min ☐ std. dev.
☐ max ☐ median
☐ range ☐ percentile 50.00%

Fig. 4.16 – Process using the interpolation algorithm in CloudCompare to fill gaps in the DTM footprints and to generate the classified terrain model point cloud (DTM) to be integrated into the Higienópolis dataset.

The point cloud of the Darsena of Ferrara, by contrast, is a derived dataset, produced from the simulation of an aerial photogrammetric survey based on Google Earth imagery. The objective was to enhance the morphological coherence of the CIM model by using photographic images to

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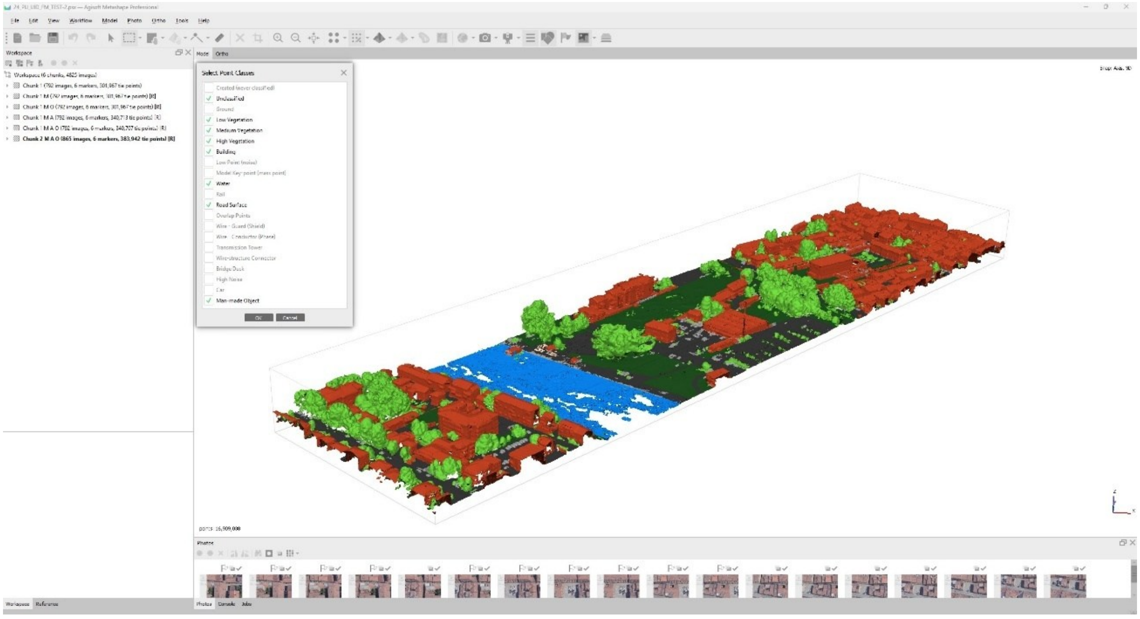
[15] CloudCompare: https://cloudcompare.org/index.html. It is an open-source software for processing 3D point clouds. CloudCompare also integrates several advanced processing algorithms for: registration, distance calculation, statistical calculation, segmentation, visualisation enhancement and optimization.

obtain reliable information on the physical elements of the built environment. Once the photographs were generated, they were processed with Metashape software to create the 3D point cloud. Within Metashape, the cloud was classified using a Machine Learning methodology following the steps described in the literature (Weinmann et al., 2017): definition of classes, feature extraction, manual mapping of a portion of the dataset, training, testing, and validation of the selected algorithm (Random Forest), and prediction over the remainder of the model. Points incorrectly classified by the automatic procedure were manually reassigned to the correct categories whenever their extent risked producing misleading information. The identified classes included: buildings, roads, low vegetation, high vegetation, river, terrain, street furniture, and vehicles. Once exported in .las format, the dataset was processed in CloudCompare, resulting in an RGB point cloud with an associated classification Scalar Field. Through CloudCompare segmentation algorithms, it was possible to generate separate point clouds, structured as layers, according to classification. False colors were then assigned to facilitate their interpretation in the subsequent modeling stage. The final result, consisting of the RGB point cloud and the classified false-color clouds, was exported in .e57 format.



Select Point Classes

- ☐ Created (never classified)
- ☑ Unclassified
- ☐ Ground
- ☑ Low Vegetation
- ☑ Medium Vegetation
- ☑ High Vegetation
- ☑ Building
- ☐ Low Point (noise)
- ☐ Model Key-point (mass point)
- ☑ Water
- ☐ Rail
- ☑ Road Surface
- ☐ Overlap Points
- ☐ Wire - Guard (Shield)
- ☐ Wire - Conductor (Phase)
- ☐ Transmission Tower
- ☐ Wire-structure Connector
- ☐ Bridge Deck
- ☐ High Noise
- ☐ Car
- ☑ Man-made Object

Fig. 4.17 – Classified false-colour point cloud in Agisoft Metashape of the Darsena of Ferrara, showing building, vegetation, water, and ground classes derived from the photogrammetric dataset.

Following this pre-processing workflow, culminating in .e57 exports from CloudCompare, both the São Paulo and Ferrara point clouds were imported into Autodesk ReCap. This software allows the integration of point clouds within the modeling environment, thus enabling the subsequent modeling phase. This workflow, as will be described later, is also indispensable for the integrated visualization of the model alongside the classified clouds.

4.6.2 *Preliminary Modelling in Autodesk Forma*

As part of the CIM modelling process, an investigation was conducted into the software solutions currently available on the market that could support parametric modelling. Among these, *Autodesk Forma* emerged as a promising tool. It is a cloud-based design platform conceived to assist the early stages of architectural and urban planning processes through a data-driven and simulation-oriented approach. Within the scope of this research, its native capability to rapidly generate a BIM model configuration enriched with real contextual data of the selected area was considered particularly valuable.

The preliminary creation of the 3D model in Autodesk Forma was carried out for the case studies of Higienópolis and Verucchio. In these cases, the contextual data employed in the platform were derived from open-source databases natively integrated into the software. For the buildings and the road network, data were obtained from OpenStreetMap. In the case of buildings, estimated heights in metres were automatically calculated at three metres per storey when no height information was available, with the minimum assumption of one storey per building. Streets that were not automatically generated were subsequently modelled directly within Forma. With regard to terrain modelling, the area of Higienópolis in São Paulo was represented using a Digital Elevation Model with an approximate resolution of thirty metres, provided by ASTER GDEM and distributed by NASA, while for Verucchio the elevation data used had a resolution of ten metres, sourced from INGV Italy and hosted by ESRI. It should be noted that Autodesk Forma also enables the import of other types of source data, such as meshes in OBJ or IFC format, two-dimensional vector files in DXF format, and raster images in JPEG or PNG format, with a maximum file size of one hundred megabytes. However, such datasets are not recognised by the platform as native objects. For this reason, within the present research, it was deemed more appropriate to integrate them into Autodesk Revit, which was selected as the working environment. Although Forma also offers the possibility of connecting external data through paid plugins, only its free functionalities were adopted here.

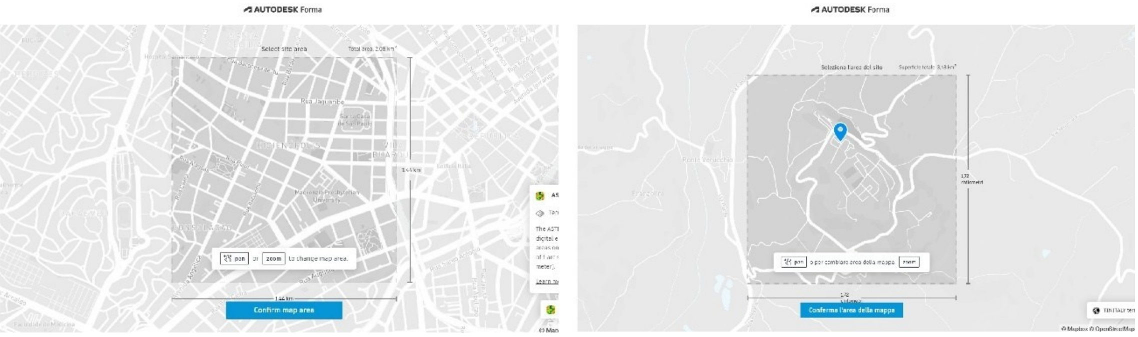


Fig. 4.18 – Site area selection for the creation of the base 3D model in Autodesk Forma: on the left the map of Higienópolis, on the right the map of Verucchio.

The models resulting from this preliminary stage are characterised by terrain morphology consistent with real-world conditions, by buildings correctly positioned in space, and by road layouts that follow the topography of the generated terrain. These models were therefore considered sufficiently reliable as a basis for subsequent modelling phases aimed at increasing the level of geometric detail and at implementing semantic information. Another reason Autodesk Forma was deemed particularly promising for the development of CIM models lies in its interoperability with Autodesk Revit. Through the dedicated plugin "Autodesk Forma Add-In for Revit," it is possible to synchronise data bidirectionally: content produced in Forma can be imported into Revit for further elaboration with well-established tools, while updates made in Revit can be exported back into Forma for additional analyses.

In Autodesk Forma, the coordinate system is based on the Universal Transverse Mercator (UTM) projection with the WGS 84 datum, applied to the UTM zone corresponding to the reference area. This approach allows for the automatic georeferencing of each project within the UTM system, ensuring accurate spatial positioning. During the export of data from Forma to Autodesk Revit via the dedicated plugin, Forma's UTM coordinate system replaces Revit's Shared Coordinates, thereby ensuring rigorous geographic alignment between the Revit modelling environment and the contextual data originating from Forma.

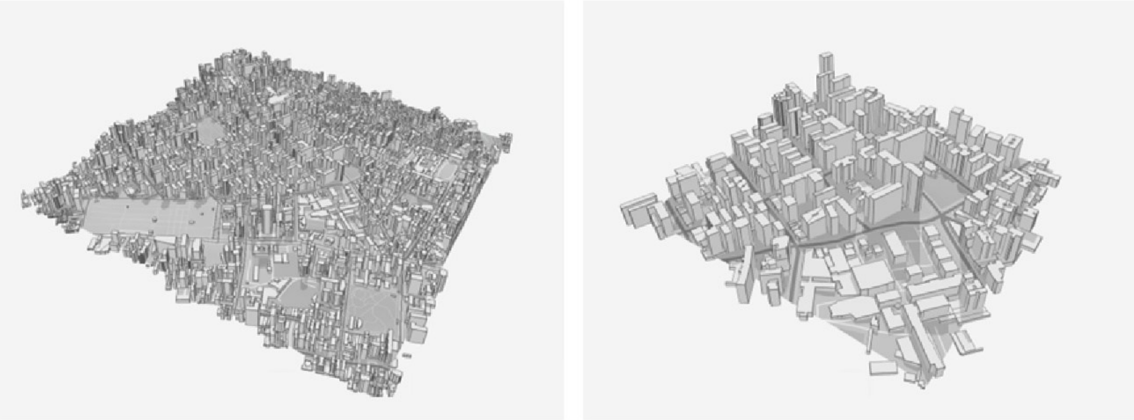


Fig. 4.19 – 3D models made in Autodesk Forma: left shows the Higienópolis area, right the Vila Penteado area within Higienópolis.

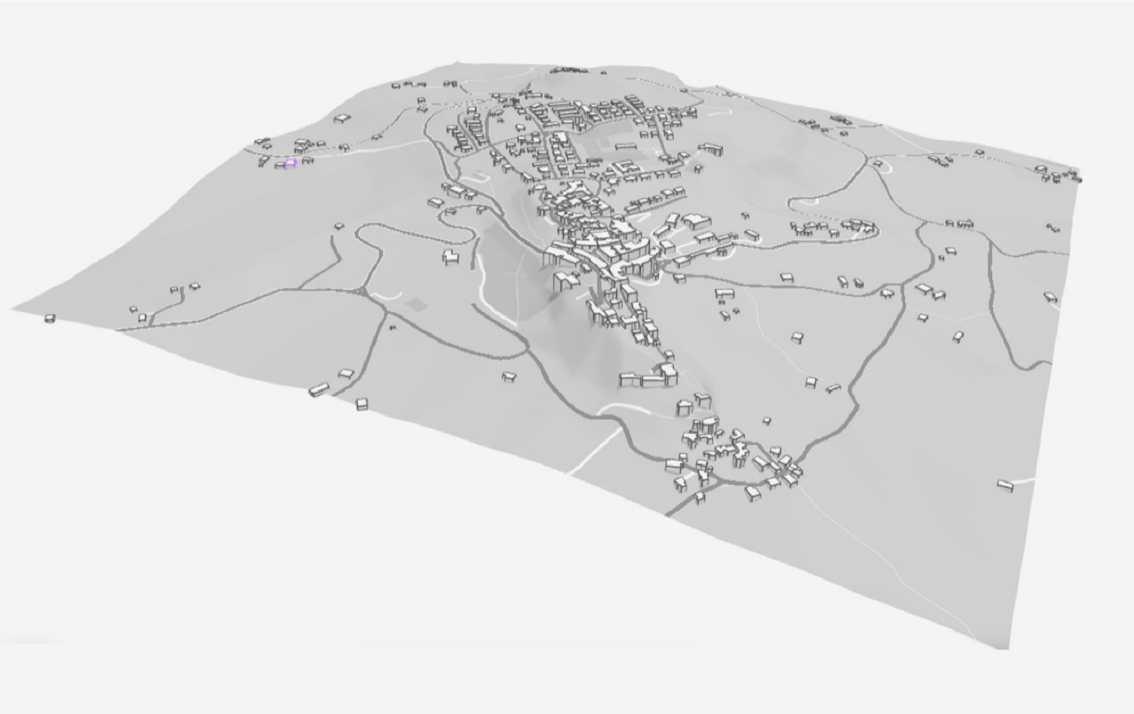


Fig. 4.20 – 3D models made in Autodesk Forma: the historic town of Verucchio.

4.6.3 *Management of 2D Data*

Two-dimensional data in .shp format were downloaded from institutional geoportals. Since these could not be directly implemented within the Autodesk Revit workspace, it was necessary to convert them into .dxf format using QGIS[16] software. This procedure also allowed for verification of the coordinate system (WGS 84 for São Paulo and Verucchio; Roma40/Montemario 1 for Ferrara), so that the linkage could occur “by shared coordinates,” thereby ensuring coordination among all input data and maintaining order and consistency throughout the process. Whenever inconsistencies were detected, the reference system was updated accordingly.

For the Verucchio case study, the municipal technical office provided some CAD data in .dwg format. However, it was necessary to update the coordinate reference system to WGS 84 UTM 33N (EPSG:32633) to ensure correct positioning within the workspace. 2D data are fundamental in the modelling process, as, when read in conjunction with point clouds (where available), they facilitate interpretation and thus optimize modelling operations.

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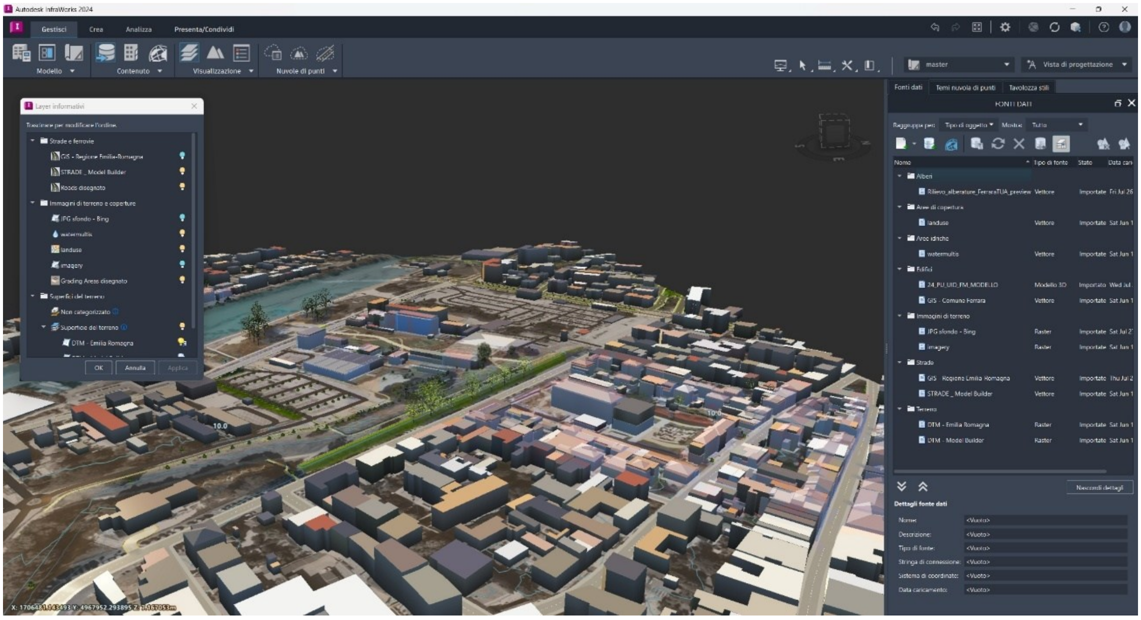
[16] QGIS is an open-source GIS software that provides a wide range of tools for the creation, visualization, and analysis of geographic data.

4.6.4 *Autodesk Infraworks as a Tool for the Visualization and Integration of Urban Systems*

Autodesk Infraworks was selected because it provides advanced tools for the modelling and visualization of urban contexts through the integration of data from heterogeneous sources, thereby enabling the creation of a unified model that represents the required information. It is a software platform designed for urban and infrastructural planning, design, and analysis. Infraworks relies on a georeferenced and spatially indexed database, which makes it possible to construct territorial models from GIS, CAD, and BIM data, while ensuring very high performance despite the large volume of data involved.

In the context of this research, Infraworks was employed exclusively for the case study of Ferrara. In the first step of territorial context modelling, the *Model Builder tool* was used. Applied to a defined area of interest, in this case, the Darsena of Ferrara, this tool enables the creation of a three-dimensional model by collecting different data sets from available open-source databases. Streets, railways, waterways, and buildings were retrieved from OpenStreetMap (OSM). To increase the representational level of detail of the model, a second step involved a search within institutional databases, such as the geoportal of the Emilia-Romagna Region and that of the Municipality of Ferrara. These data, created independently, directly recall one of the aims of this paper: the connection of already available databases for an integrated visualization of urban systems. Accordingly, the following datasets were uploaded and configured in Infraworks: the 5x5 Digital Terrain Model (DTM), derived from altimetric information provided by the Regional Technical Map; and GIS shapefiles containing data on buildings, streets, and tree surveys for the Darsena area.

On the one hand, Infraworks produces a three-dimensional model consisting of a highly complex and heterogeneous database. All datasets from the various categories are organized into separate layers. This facilitates an integrated reading of urban systems, either simultaneously in their full complexity or through the comparison of selected components (for example, buildings and vegetation, or roads and vegetation). Moreover, depending on how the datasets were constructed, it is possible to assign informational parameters both to the entire dataset and to individual objects. The various categories, represented in different forms, are descriptive according to their geometric level of detail and enable the visualization of the urban system of the Darsena in Ferrara. On the other hand, interoperability with Autodesk Revit revealed certain complexities in the export processes from Infraworks and subsequent import into Revit, which were necessary for proceeding with more detailed modelling.



Nome	Tipo di fonte	Stato	Data car
Alberi			
Rilievo_alberature_FerraraTUA_preview	Vettore	Importate	Fri Jul 26
Aree di copertura			
landuse	Vettore	Importate	Sat Jun 1
Aree idriche			
watermultis	Vettore	Importate	Sat Jun 1
Edifici			
24_PU_UID_FM_MODELLO	Modello 3D	Importato	Wed Jul
GIS - Comune Ferrara	Vettore	Importate	Sat Jun 1
Immagini di terreno			
JPG sfondo - Bing	Raster	Importate	Sat Jul 2
imagery	Raster	Importate	Sat Jun 1
Strade			
GIS - Regione Emilia Romagna	Vettore	Importate	Thu Jul 2
STRADE _ Model Builder	Vettore	Importate	Sat Jun 1
Terreno			
DTM - Emilia Romagna	Raster	Importate	Sat Jun 1
DTM - Model Builder	Raster	Importate	Sat Jun 1

Nome: <Vuoto>
Descrizione: <Vuoto>
Tipo di fonte: <Vuoto>
Stringa di connessione: <Vuoto>
Sistema di coordinate: <Vuoto>
Data caricamento: <Vuoto>

Fig. 4.21 – InfraWorks screen showing integration of various data sources.

4.6.5 *CIM Modeling within Autodesk Revit as a Working Environment*

The selection of the working environment for City Information Modeling (CIM) was guided by the need to integrate heterogeneous data sources, while ensuring the preservation of the original information and maintaining compatibility with the native environments from which the data were derived. In particular, it was crucial to adopt a platform capable of combining inputs from GIS systems, Autodesk Forma, Autodesk Infraworks, as well as managing point clouds. A key aspect of this process concerned the definition of the reference system, necessary to coordinate heterogeneous data within a single coherent framework.

For the construction of the CIM model, a Building Information Modeling (BIM) software was identified, one able to support a parametric geometric-informative approach typical of the BIM process. The choice fell on *Autodesk Revit*, which stands out for its ability to handle libraries of parametric objects and diversified input data. This selection is supported by the NBS (National Building Specification) report, which in 2019 identified Revit as the most widely used BIM software worldwide (46%)[17].

The CIM base model was initially created in Autodesk Forma and subsequently transferred to Revit through the Forma add-in for Revit, which allows the import of the three-dimensional model while preserving the WGS84 reference system. This system constitutes the essential prerequisite for the coherent and homogeneous integration of source data (both two-dimensional and three-dimensional), which are managed according to the principle of "shared coordinates."

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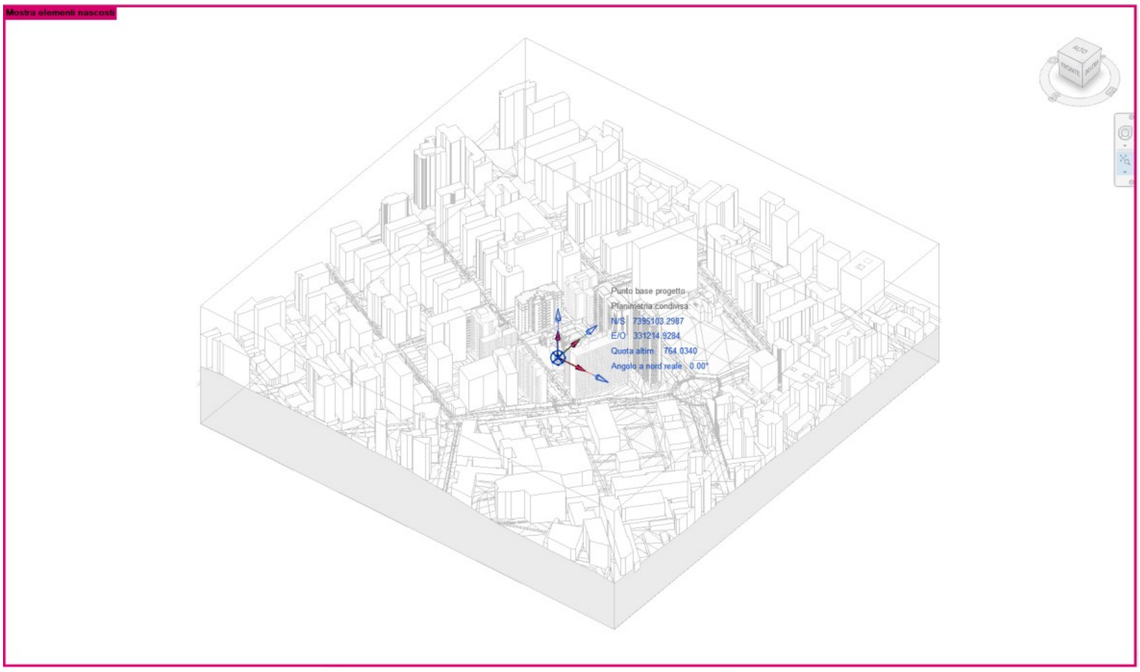
[17] Although more recent reports are not available, practical experience in recent years confirms the persistence of this trend



Punto base progetto
Planimetria condivisa:
N/S 7395103.2987
E/O 331214.9284
Quota altim. 764.0340
Angolo a nord reale 0.00°

Fig. 4.22 – Visualization in Autodesk Revit of the 3D urban model of Higienópolis, imported from Autodesk Forma using the “Autodesk Forma Add-In for Revit” plugin. The image shows the project base point, which displays the georeferencing parameters set for the model using the UTM 23S system, WGS 84 (EPSG 32723).

Producing a CIM model means representing, in a digital environment, real-world elements that assume a dual role: objects of interaction and media through which the interaction itself takes place. Within the BIM framework, the association between the graphic model and the repository of structured information enables each digital object to act as the direct counterpart of the real object, while retaining its semantic annotations (Scandurra, 2020). The elements can be enriched with quantitative properties (geometry, dimensions) as well as qualitative attributes (materials, physical parameters, performance). In Autodesk Revit, the model takes the form of a *relational database*, where the hierarchical structure of elements is defined according to a logic of instances, types, families, and categories. For the CIM modeling developed in this research, the model imported from Autodesk Forma served as the reference base. The terrain was represented as a topographic solid, editable through dedicated tools and aligned with the interpolated point cloud. Roads were imported as elements tangent to the topographic surface, ensuring geometric consistency even in the presence of altimetric variations. Buildings, instead, were initially organized as generic model families and later converted into masses, used as a basis for further architectural developments. The entire geometric modeling process followed a combined top-down and bottom-up approach, depending on the nature of the available input data.

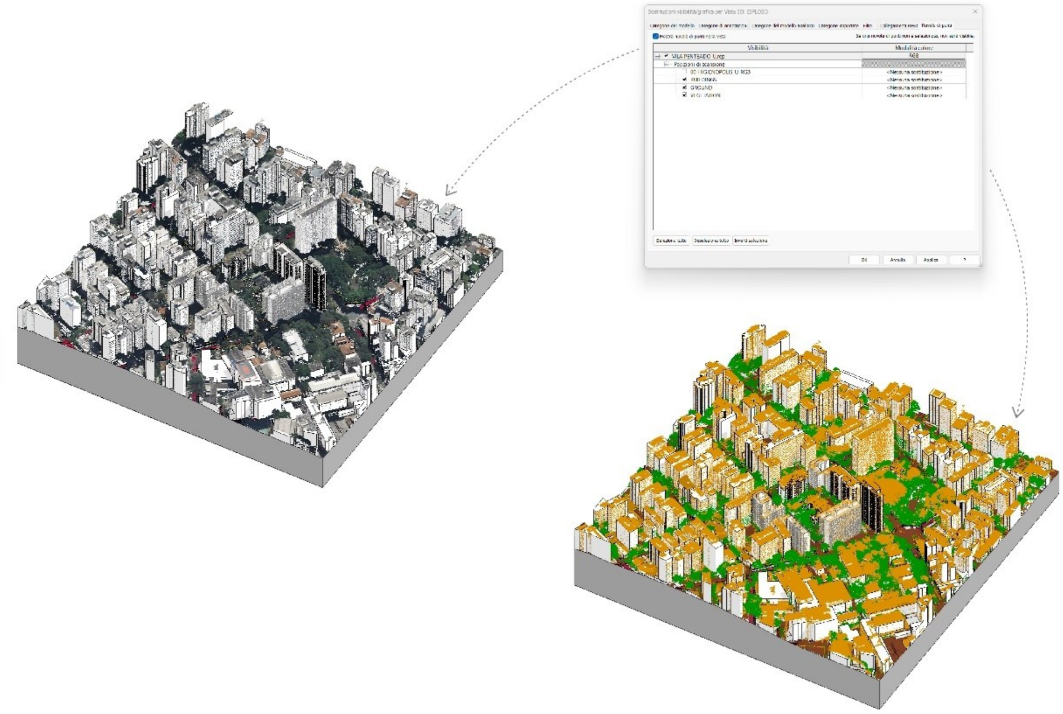
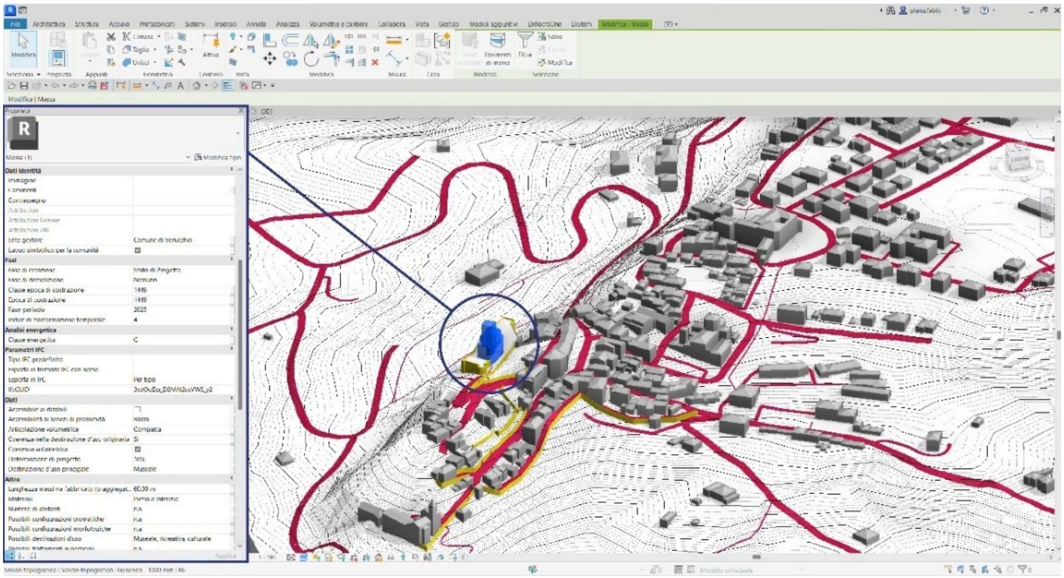


Fig. 4.23 – Visualization of the RCP point cloud - RVT model overlay in Autodesk Revit. On the left the RGB point cloud, on the right the false-colour classified point cloud, segmented into three subsets to support CIM modeling and integrated model analysis.

A central aspect of the process concerns the use of Revit families, which constitute the minimum unit of interaction with the model. Each modeled object belongs to a family and acquires specific geometric and informational properties through parameters. Three main types of families were adopted in the modeling. *System families* comprise the fundamental elements of the built asset, such as walls, roofs, and floors, and are directly managed within the model workspace. *Loadable families*, correspond to objects that can be saved in .rfa format and subsequently imported, modeled through operations such as extrusion, revolution, or joining. Finally, *in-place families* were employed to represent unique elements or those with particular geometric complexity, such as conceptual masses. This articulation made it possible to adapt the modeling to the needs of the urban context, adopting a topological representational approach, and leveraging the flexibility of loadable families and masses to represent complex forms or those subject to future implementations.

The CIM model does not only provide geometric representation, but is enriched with structured informational content in the form of parameters. All model-related information can be defined through parameters, which may be numerical, textual, etc., and serve as the repository for all attributes associated with objects (URLs, descriptions, materials, visibility, etc.). These parameters enable the management and interrogation of the model through schedules, filters, and queries. Two types of informational parameters exist: type parameters and instance parameters.

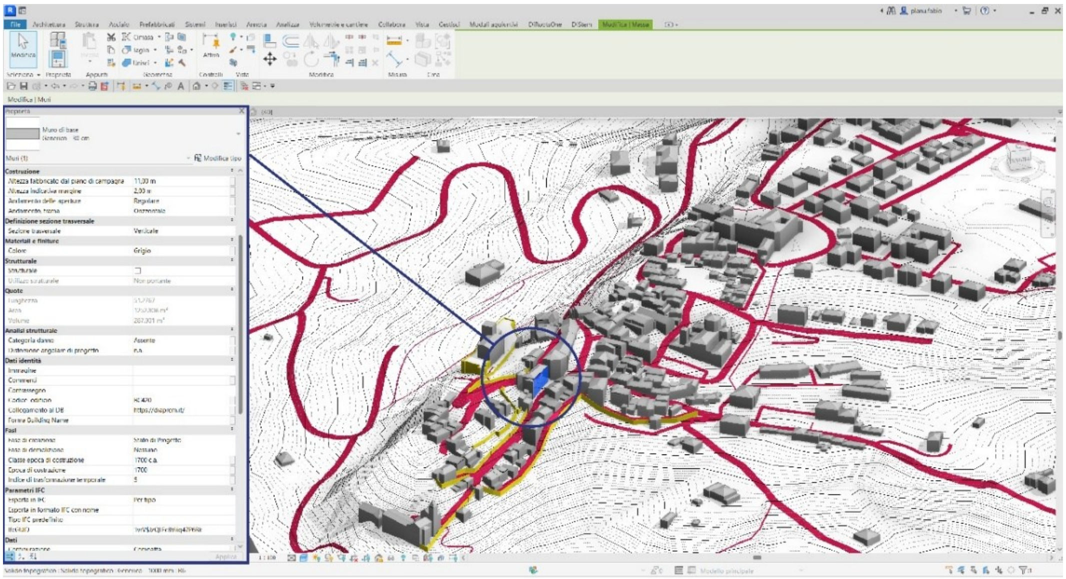
The modification of a type parameter applies to all instances of the same type, whereas the modification of an instance parameter affects only the selected instance. In this work, *instance parameters* were primarily implemented, in order to overcome the rigidity of typological decomposition. Some customized parameters, defined from information sheets, were organized into Property Sets and imported as "shared parameters" via the DiRoots plug-in, which optimizes their management and assignment to categories. Parameters can be selected according to the Level of Information Need (LOIN), including only those necessary to satisfy model requirements and to construct scenarios supporting stakeholders.



Dati identità	
Immagine	
Commenti	
Contrassegno	
Attribution	
Attribution License	
Attribution URI	
Ente gestore	Comune di Verucchio
Luogo simbolico per la comunità	☑
Fasi	
Fase di creazione	Stato di Progetto
Fase di demolizione	Nessuno
Classe epoca di costruzione	1449
Epoca di costruzione	1449
Fase-periodo	2025
Indice di trasformazione temporale	4
Analisi energetica	
Classe energetica	C
Parametri IFC	
Tipo IFC predefinito	
Esporta in formato IFC con nome	
Esporta in IFC	Per tipo
IfcGUID	3xdOuDp_D0VAI2usVWS_y2
Dati	
Accessibile ai disabili	☐
Accessibilità ai servizi di prossimità	Bassa
Articolazione volumetrica	Compatta
Coerenza nella destinazione d'uso originaria	Si
Coerenza volumetrica	☑
Deformazione di progetto	10%
Destinazione d'uso principale	Museale
Altro	
Lunghezza massima fabbricato (o aggregat...	60,00 m
Materiali	Pietra e laterizio
Numero di abitanti	n.a.
Possibili configurazioni cromatiche	n.a
Possibili configurazioni morfologiche	n.a
Possibili destinazioni d'uso	Museale, ricreativa, culturale
Possibili trattamenti superficiali	n.a

Solido topografico : Solido topografico : Generico 1000 mm : 86

Fig. 4.24 – Querying the CIM model in Autodesk Revit by selecting a building within the 3D model of Verucchio. On the left, the instance-parameter panel displays the geometric and informational attributes assigned to the modeled object (building), supporting urban analysis and data-enriched model management.



Costruzione	
Altezza fabbricato dal piano di campagna	11,00 m
Altezza indicativa margine	2,00 m
Andamento delle aperture	Regolare
Andamento trama	Orizzontale
Definizione sezione trasversale	
Sezione trasversale	Verticale
Materiali e finiture	
Colore	Grigio
Strutturale	
Strutturale	☐
Utilizzo strutturale	Non portante
Quote	
Lunghezza	51.2767
Area	[illegible] m²
Volume	207.301 m³
Analisi strutturale	
Categoria danno	Assente
Distorsione angolare di progetto	n.a.
Dati identità	
Immagine	
Commenti	
Contrassegno	
Codice edificio	RC420
Collegamento al DB	https://diaprom.it/
Forma Building Name	
Fasi	
Fase di creazione	Stato di Progetto
Fase di demolizione	Nessuno
Classe epoca di costruzione	1700 c.a.
Epoca di costruzione	1700
Indice di trasformazione temporale	5
Parametri IFC	
Esporta in IFC	Per tipo
Esporta in formato IFC con nome	
Tipo IFC predefinito	
IfcGUID	[illegible]
Dati	
Configurazione	Compatta

Solido topografico : Solido topografico : Generico 1000 mm : 86

Fig. 4.25 – Querying the CIM model in Autodesk Revit by selecting a building within the 3D model of Verucchio. On the left, the instance-parameter panel displays the geometric and informational attributes assigned to the modeled object (building envelope), supporting urban analysis and data-enriched model management.

The CIM modeling of the case studies was developed through a process of progressive detail enrichment. Buildings were initially represented as volumetric masses, useful to define their footprint and overall configuration. Subsequently, these masses were articulated into the Building Envelope, through the modeling of walls and roofs from surfaces, to which loadable families were added to represent specific elements such as openings, loggias, cornices, etc. Roads were imported directly from Autodesk Forma. Additional urban components, such as sidewalks, were modeled as loadable families, following a logic reflecting property conditions. In São Paulo, for example, responsibility for the maintenance of the sidewalk in front of a building, although located in unenclosed space, lies with the property owner[18].

Fig. 4.26 – CIM model in Autodesk Revit of a portion of the Higienópolis district (São Paulo), with the segmented vegetation point cloud overlaid. The Vila Penteado area shows a higher geometric and informational level of detail due to enhanced CIM modeling.

Particular attention was also given to the threshold space, defined by means of system families (walls), with the aim of analyzing the degree of permeability between enclosed and unenclosed spaces. This approach enabled a more accurate description of the spatial and functional relationships characterizing the urban scene under study.

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[18] São Paulo. (2020, August 7). Decreto nº 59.671, de 7 de agosto de 2020 [Decree No. 59,671 of August 7, 2020]. Dispõe sobre a padronização das calçadas no Município de São Paulo. Prefeitura do Município de São Paulo.

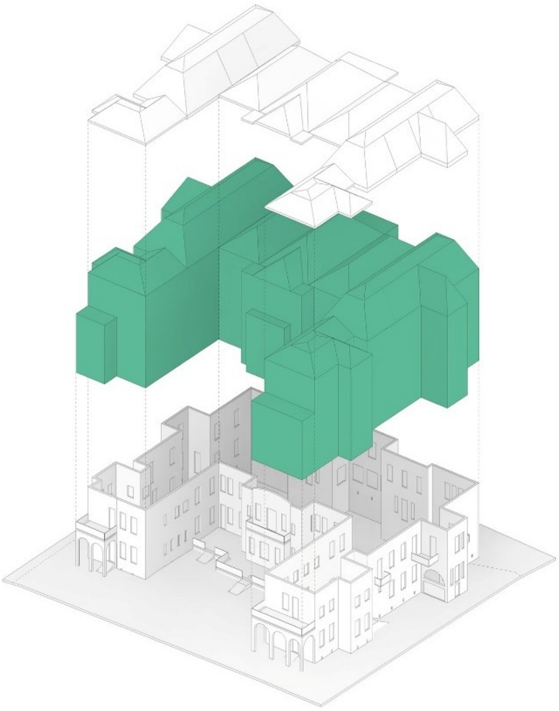

Fig. 4.27 – Vila Penteado in the CIM model.

The modeling of vegetation within a CIM model plays a crucial role, as it consists of objects which, although represented in volumetric and architectural terms, refer to living organisms. These are characterized by seasonality, volumetric changes, forms of growth, crown-to-trunk ratios, and other specific features. Within this research, the modeling of vegetation was not explored in depth, as it would require a dedicated and specific line of investigation[19]. From the perspective of urban management, however, vegetation along road infrastructures is linked to other systems, such as sidewalks, since tree trunks may generate criticalities, for instance in managing the root-to-sidewalk or root-to-street furniture relationship. For this reason, in the CIM models described here, trees along circulation routes were represented through a simplified family reproducing the trunk. This choice made it possible to work with three-dimensional objects to which informative attributes could be associated, useful for linking to records and management parameters. The overall configuration of vegetation, instead, was made visible through the segmented point cloud of vegetation, including both unenclosed areas such as streets and the vegetation pertaining to building properties and public spaces.

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[19] For further details see at: Sandro Parrinello, *Rilevare il verde urbano. Strategie per la rappresentazione e la comprensione dei sistemi di acquisizione e di informazione del verde urbano* (Firenze: Dipartimento di Progettazione dell'Architettura, Università degli Studi di Firenze, 2009).

CIM modeling necessarily entails the *critical interpretation* of data, as modeling and digitization procedures, whether manual or semi-automatic, are numerous, and, to date, no universally recognized operational protocols exist. In a process based on heterogeneous pre-existing data sources, the accuracy and resolution of information have a significant impact on metric and geometric interpretation. It is therefore acknowledged that, in CIM as in any representational process, the work essentially consists of a critical activity of reading and interpreting reality (Scandurra, 2020). CIM implies, indeed, the need to reprocess data not only in terms of computation, but above all in terms of understanding meaning.

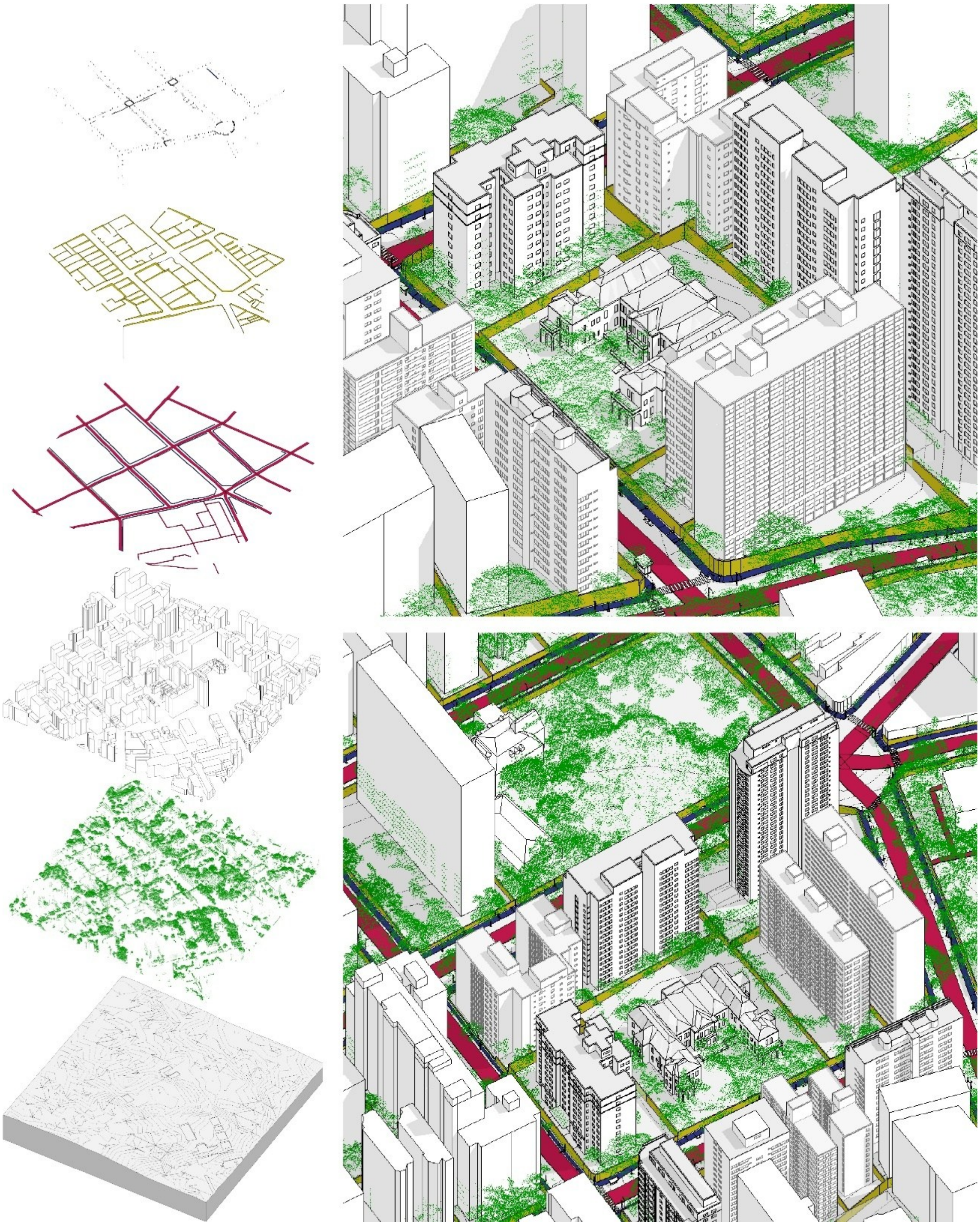

Fig. 4.28 – CIM model in Autodesk Revit. On the left: axonometric exploded view of the CIM model, highlighting the different information layers: Terrain Module, Green System, Buildings System, Infrastructure System, Boundary System, and Other Urban Systems. On the right: integrated CIM visualization of Higienópolis, with a zoomed-in view of the Vila Penteado study area.

4.7 Geometric Variation Delta Analysis[20]

In defining the City Information Modeling (CIM) framework adopted in this thesis, both for validating the accuracy of the source data and for assessing the accuracy of the model, an auto-critical analysis is presented below. This analysis aims to define the variation delta for determining the confidence level, with the objective of making the methodological process explicit. The geometric variation delta represents a "tolerance range" used to assign accuracy classes. The following section describes the process of defining the variation delta in the *Higienópolis case study*, specifically within the *Vila Penteado area*, divided into two phases, since the comparison can only be carried out between pairs. In the first phase, the source data are analyzed, while in the second phase, the delta, translated into its representative form within the CIM model, is examined. The self-validation process of the geometric variation delta was performed using the open-source software "CloudCompare."

First phase: Verification of the variation delta of the source data: Terrestrial SLAM-based LiDAR point cloud (K1) compared with the aerial LiDAR point cloud (GeoSampa).

In the first phase, a methodological process was carried out with the aim of analysing the geometric variation delta of the source data: the aerial LiDAR point cloud available from the official geoportal of the City of São Paulo, GeoSampa. The comparison was performed with a terrestrial LiDAR point cloud acquired using SLAM technology (Lixel Kitty K1)[21], as part of a survey campaign conducted in Vila Penteado in July 2025[22].

Once the area for analysing the geometric variation delta was defined, both point clouds were imported into CloudCompare in .e57 format. For the comparison, the point cloud obtained from the terrestrial survey was set as the reference dataset, as its instrumental accuracy and survey process were well known. The point cloud downloaded from GeoSampa was thus the compared dataset. A maximum distance threshold was imposed, beyond which points were considered

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[20] For further details regarding the measurement of the geometric variation delta, see: Rossato, L., Zaffagnini, T., Giau, G., & Planu, F. (2025). *Evaluating digital tool's integration for the preservation of XX century architectures.* The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVIII-M-9-2025, 1309–1313; and Rossato, L., Giau, G., Planu, F., & Zaffagnini, T. (2025). *The digital narrative of the Eladio Dieste's Church in Atlantida, Uruguay, by tools integrations analyses*. In L. Carlevaris et al. (Eds.), Èkphrasis. Descriptions in the Space of Representation. Proceedings of the 46th UID International Conference (pp. 1865–1874).

[21] The Lixel K1 is XGRIDS' compact handheld scanner, integrating 36 MP panoramic cameras and 360° LiDAR sensors. Its scanning performance parameters are as follows: relative accuracy 1.20 cm; absolute accuracy 3.00 cm; repeat accuracy 2.00 cm; horizontal accuracy 0.015°; working range 0.10 m – 40.00 m @ 10%, 70.00 m @ 80%; scanning speed 200,000 points/s.

[22] Project: "Questões conceituais e de método para a gestão da conservação". FAU-USP, UNIFE.

outliers; in this case, the threshold value was set at 10,00 metres. The CloudCompare algorithm computes the distance of each point from its nearest neighbour and generates a scalar field represented through a false-colour scheme, where the value assigned to each point corresponds to the calculated distance. In this research, the adopted colour scale and associated intervals were as follows: blue [0 – 0,50 m]; green [0,50 – 1,00 m]; yellow [1,00 – 2,00 m]; red [> 2.00 m].

Values greater than 10,00 m [> 10,00 m] are displayed in red but are considered outliers. This is due to the intrinsic differences between the two datasets: when overlapping a terrestrial and an aerial LiDAR point cloud, certain areas such as roofs or streets outside the Vila Penteado plot are not present in the terrestrial K1 dataset. Therefore, the two clouds are not fully superimposable in some zones.
The output is a 3D point cloud visualized in false colours (blue, green, yellow, red), corresponding to the associated scalar field. This representation is particularly useful for directly visualizing the geometric variation delta through the three-dimensional display of the point cloud. Subsequently, the data were extracted into a histogram, where the x-axis represents the distances and the y-axis represents the number of points within each distance interval. The corresponding .csv file generating this histogram was also exported from CloudCompare. By summing the products of each distance interval (classified in 0,10 m increments) and the number of points within that interval, then dividing the result by the total number of points (excluding outliers), the average geometric variation delta between the two point clouds was calculated as 2,08 metres.[23]

From this analysis, it emerges that, despite accounting for outliers, since the two point clouds derive from different acquisition processes, several surfaces (such as roofs and external roadways) are only present in the GeoSampa dataset. Additionally, the aerial cloud contains shadow cones. For these reasons, the analysis of the geometric variation delta was further explored both in plan and in section. The same procedure was repeated by creating both a horizontal slice and a cross-section of the Vila Penteado area. The results indicate that the weighted average geometric variation delta is 0,45 metres in plan and 2,52 metres in section. This significant difference is primarily attributed to the large number of points representing roof surfaces in the GeoSampa dataset, which exert a considerable influence on the computation of the overall average delta value.

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[23] Formula used:

$$Weighted\ average\ \Delta\ variation = \frac{\Sigma\ (value * class\ start)}{\Sigma\ value}$$

Value: number of points in each range
Class star: every 0,10 m.

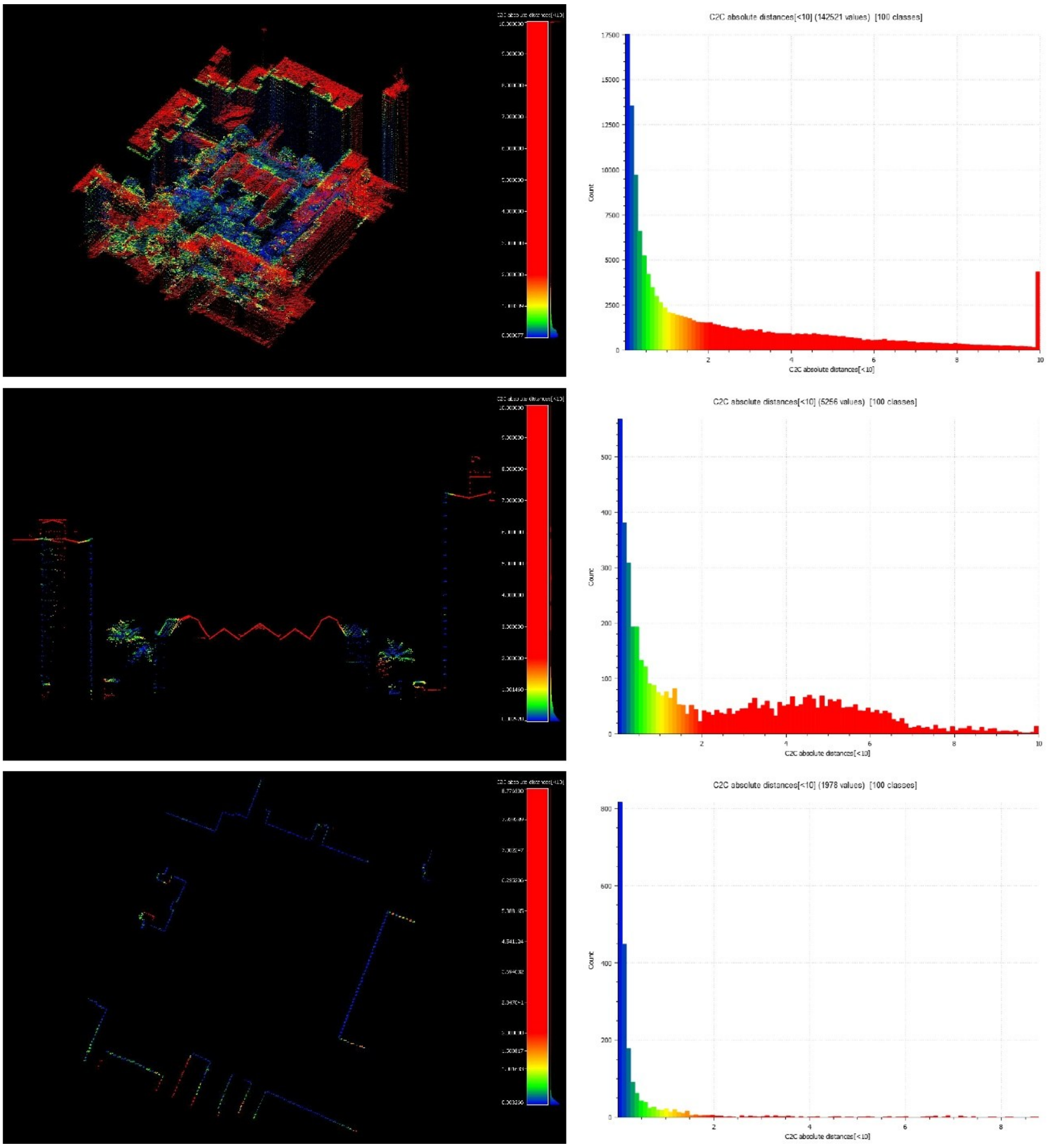

Fig. 4.29 – Process for evaluating the weighted average of the Δ variation. From top to bottom: assessment through the 3D models, the section, and the plan. On the right, the corresponding histograms, where the x-axis represents the distances and the y-axis represents the number of points within each distance interval.

	Weighted average Δ variation (in m)
3D model	2,08
Section	2,52
Plan	0,45

Fig. 4.22 – Process for evaluating

Second Phase: Verification of the variation delta by comparing the airborne LiDAR point cloud (GeoSampa) with the 3D CIM model.

In the second phase, the same process of analysing the geometric variation delta was carried out by comparing the airborne LiDAR point cloud (GeoSampa) with the three-dimensional CIM model developed using Revit. This process aimed to critically examine the modelling procedure applied during the representation phase of the São Paulo context, specifically in Vila Penteado, where data interpretation plays a significant role. The self-verification of the geometric variation delta was performed using the open-source software CloudCompare. Consequently, the 3D model created in Revit was first exported in .obj format. Once the area for the geometric variation analysis had been defined, both the point cloud in .e57 format and the 3D model in .obj format were uploaded to CloudCompare. The selected area is broader than that used in the previous phase, as the comparison involved the CIM 3D model and the point cloud that had been used as the base in the Scan-to-CIM process. It should be noted that, since the trees were not modelled, the vegetation was removed from the classified point cloud in order to reduce outlier values and obtain a more consistent assessment of the geometric variation delta. The methodological workflow subsequently followed was the same as in the previous phase. The results show that the weighted average of the geometric variation delta between the 3D models is 1,18 m. From the analysis of a horizontal slice, the weighted average delta is 1,10 m, while in section it is 0,88 m. Compared with the verification of the variation delta conducted in the previous phase, the data are more consistent, since the model was produced using the same point cloud as its base. The largest variations are attributable to street furniture, roof morphology, and the presence of caixas d'água[24], which were not modelled in the CIM model.

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[24] Water tanks used to store potable water supplied by the public network, ensuring a constant reserve even when water delivery is interrupted or pressure is low

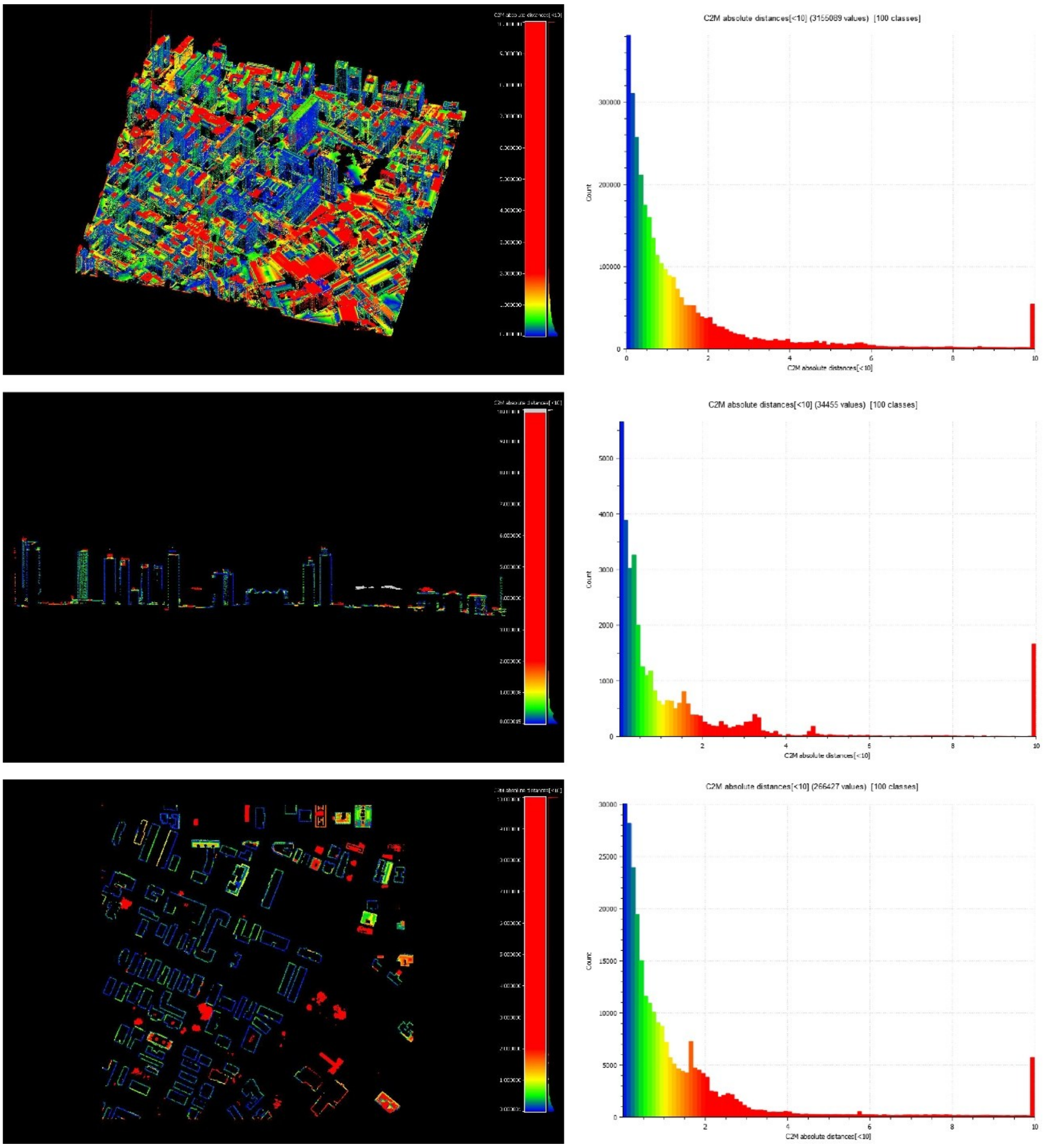

Fig. 4.30 – Process for evaluating the weighted average of the Δ variation. From top to bottom: assessment through the 3D models, the section, and the plan. On the right, the corresponding histograms, where the x-axis represents the distances and the y-axis represents the number of points within each distance interval.

	Weighted average Δ variation (in m)
Modello 3D	1,18
Sezione	0,88
Pianta	1,10

Additional Phase: Verification of the variation delta by comparing the Terrestrial SLAM-based LiDAR point cloud (K1) with the 3D CIM model.

An additional evaluation of the geometric variation delta along the Z-axis was ultimately carried out. Specifically, a detailed comparison was conducted between the Terrestrial SLAM-based

LiDAR point cloud (K1) and the CIM 3D model developed in Revit. For the assessment of the variation delta, two corresponding points were measured in the CloudCompare software, located at the corners of two openings. The measured distance along the Z-axis was 23,30 metres. The same measurement, performed within the CIM model in Revit using the measurement command, yielded a distance of 23,60 metres. The difference is therefore equal to 30 cm.

In this case, the computation of the geometric differential presents certain limitations. Since the point cloud acquired with the K1 Laser Scanner was primarily intended for the survey of Vila Penteado, the effectively overlapping portions between the model and the point cloud in the external areas of the villa, used to assess the variation delta in the height of the surrounding buildings, are limited. Therefore, within the scope of this research, the described process was conducted through distinct phases, with the sole purpose of verifying the geometric consistency between the point clouds and the model, in order to clearly define the geometric variation delta across the datasets employed.

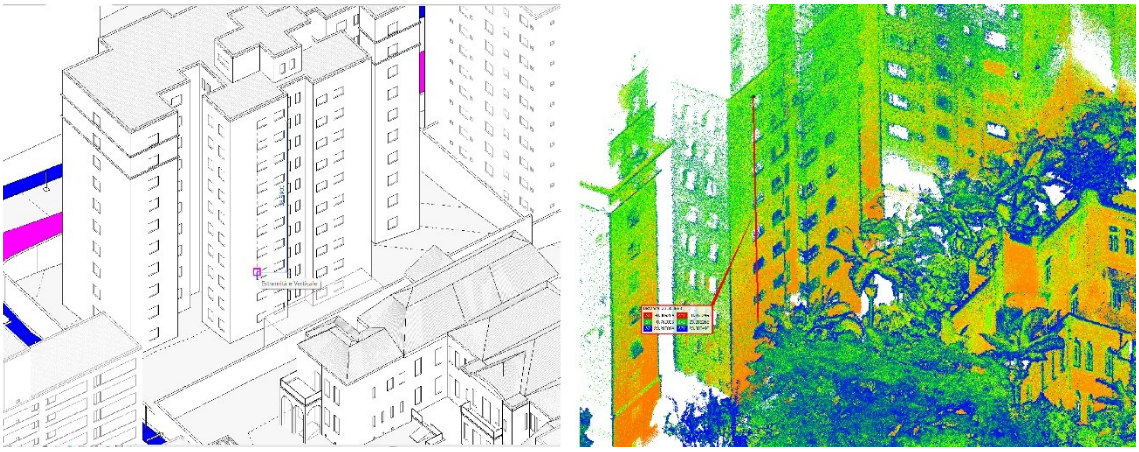

Fig. 4.31 – Assessment of the Δ variation between the model and the SLAM point cloud through the measurement of homologous points in Autodesk Revit and CloudCompare.

	Δ variation (in m)
Z-axis	0,30

4.8 Towards Semantic Interoperability through the Export of CIM Models from Autodesk Revit to IFC

The literature reveals that the digital revolution in the AEC sector is experiencing an increasing acceleration in terms of data interoperability aimed at integrated collaborative projects. The growing use of such data has led to the formulation and dissemination of operational standards, such as IFC (Vernizzi & Mazzi, 2022), which constitute the effective foundation for the development of integrated digital environments. The Industry Foundation Classes (IFC) is an international openBIM standard and format for the exchange of BIM data. It is recognised by ISO

16739-1:2024[25] and provides a highly detailed semantic model for 3D buildings (Eastman et al., 2011). Furthermore, since its level of representation is consistent with the 1:200/1:500 scale, this format has proven to be particularly suitable. Given that this thesis adopts Autodesk Revit as its working environment, the chosen open format is IFC4.

Once exported, the CIM model in IFC format will not only be suitable for future openBIM applications, but will also be viewable and queryable by different stakeholders through the use of free viewers, such as BIM Vision, BIMcollab, and others. The IFC format therefore ensures interoperability, enabling access to models without the mandatory use of proprietary software. In this regard, within the AEC sector and particularly in public procurement, the delivery of IFC format is compulsory.

The structure of the IFC schema is complex and contains numerous abstract layers that are not visible to the end user. Not all of the properties defined in the IFC schema are implemented in Revit[26]. Therefore, in order to perform an export to IFC format free from redundant information, a *Property Set* (Pset) parameter export file was created. This file, in .txt format, acts as a configuration file. For each Pset, which essentially corresponds to a group of parameters, the following properties were defined: Pset Name, Instance/Type, and element list. For each parameter within the group, the Property Name and Data Type were specified. In this way, the properties considered relevant to the CIM models developed in this research were defined; however, in view of future developments, these could be further refined by stakeholders according to their specific requirements. Once created, the file can serve as a standard to be reused across all models produced.

In configuring the IFC format, numerous export properties were imported. After several tests, once the configuration was established, it was saved in a .json file. This operation optimises the export phase and contributes to the definition of a replicable standard for different models.

Before sharing the CIM models in IFC format, a verification phase aimed at ensuring correct export was undertaken, using the free *BIM Vision* viewer. As part of this thesis, several export tests were conducted before identifying the correct configuration. In such cases, if the issue was related to the information layers, the correction had to be applied in the configuration files; if instead it was related to geometries, the modification had to be carried out within the 3D Revit model and the associated families.

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[25] International Organization for Standardization. (2024). *ISO 16739-1:2024* - Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries – Part 1.

[26] For further details see at: Autodesk. (2021). *IFC Standard Manual 2.0 for Revit*. Autodesk. Retrieved from: https://www.autodesk.com/blogs/aec/wp-content/uploads/sites/36/2022/02/09/revit-ifc-open-bim-manual-it.pdf

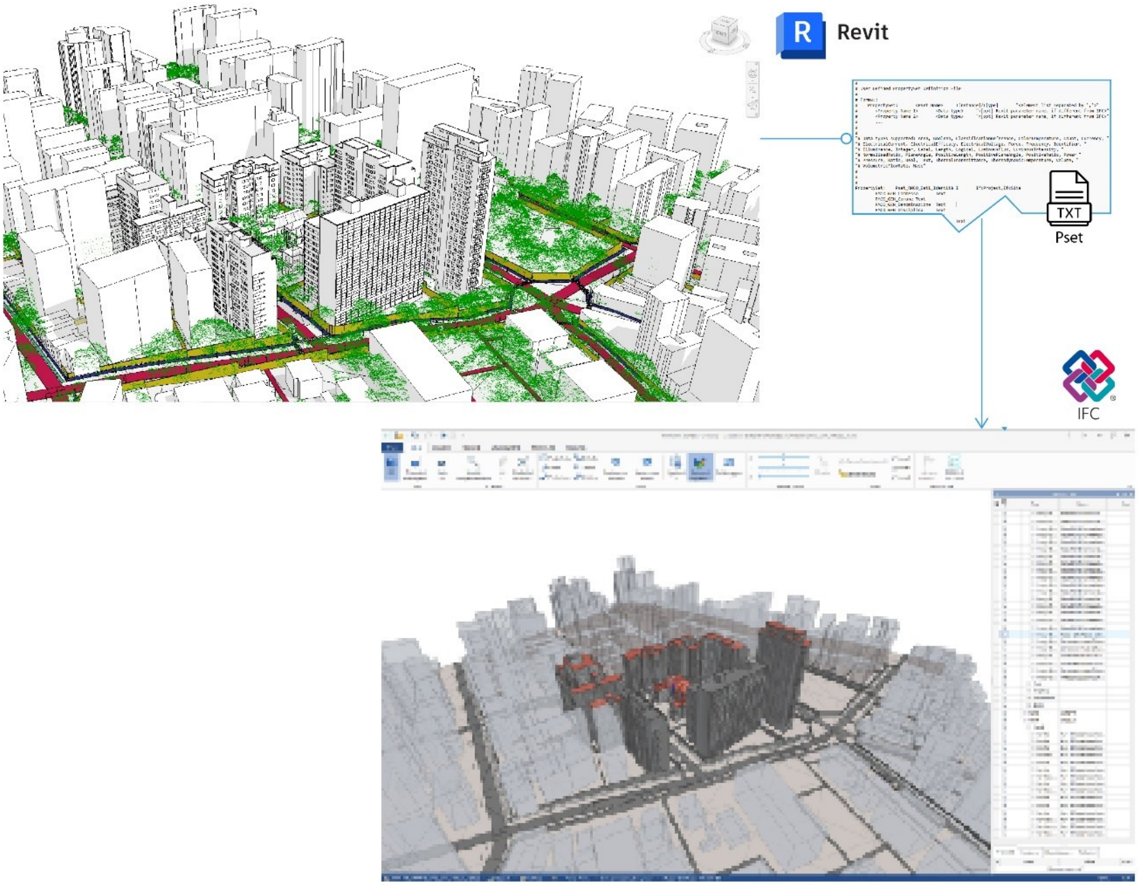

Fig. 4.32 – Export of the CIM model from Autodesk Revit to the open IFC format with its Psets, and visualization of the resulting information model in the BIMvision open viewer.

4.9 City Information Modeling (CIM) and Open BIM

The urban context is a research field that demands the transition toward the application of new approaches where, as expressed by Malinverni, "a structured 3D digital model as part of the process of improving the built environment is today an urgent necessity" (Malinverni et al., 2019). However, with the primary emphasis placed on 3D geometry, the urban scene is characterized by fragmented information and heterogeneous data sources (Balzani & Raco, 2020), which must be interrelated and made available as organized knowledge. Three-dimensional surveys and developments in the field of scan-to-BIM, building upon the established methodology of point-cloud-based 3D modeling, have provided an increasingly reliable foundation for representation processes (Kim & Kim, 2022).

It is widely recognized in the literature that, given the growing availability of enabling technologies for the documentation of the state of buildings, their implementation has now become a fundamental requirement. There is a pressing need to advance toward the development of a unified convergent framework (Banfi et al., 2022) for the visualization and digital representation of models related to the geometric and morphological characteristics of the building or the urban fabric under analysis (Bianchini et al., 2021), by implementing data interoperability protocols that are expected to be fast, reliable, and secure (Raco et al., 2022). A system oriented toward a data-driven approach in the built environment, within a transitional process such as the present one, must be capable of developing an ecosystem of services (Lazarova-Molnar & Mohamed, 2020) that can respond to queries regarding the synchronic state of diachronic scenarios.

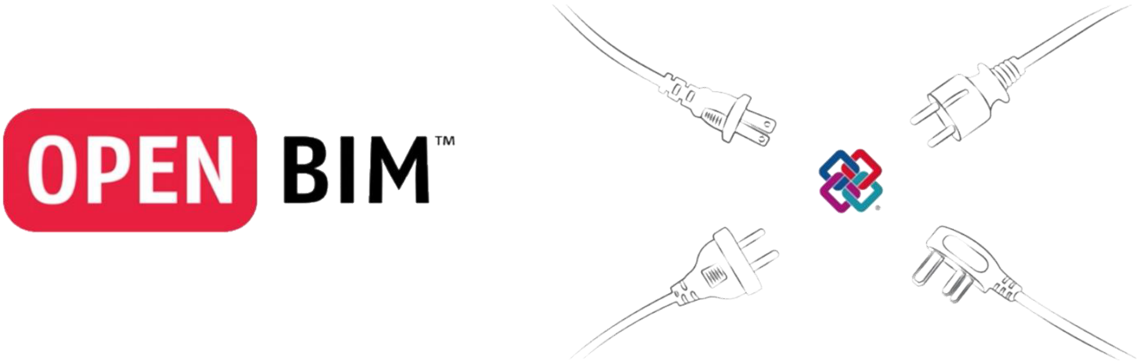

Fig. 4.33 – Open BIM concept. (Source: Artem Boiko, 2021)

The development of City Information Modeling (CIM) requires the exchange of models (i.e., information) among different software applications and tools, which inevitably results in data and feature loss. To enhance stakeholder involvement, interoperability, and interactivity, it is necessary to integrate CIM models with semantic web platforms through an Open BIM approach based on open standards (Iadanza et al., 2019), thereby allowing end users to access information using a standard web browser. Accordingly, open standards are developed with exchange formats to ensure interoperability across different tools (Planu et al., 2023). The CIM models developed in this thesis, exported in IFC format, were subsequently integrated into the Autodesk Tandem platform and into the INCITE platform[27]. In this way, stakeholders can access and explore urban models directly through a standard browser, without the need for dedicated BIM software, thus overcoming the complex expertise required to interrogate models in applications such as Revit or BIM Vision.

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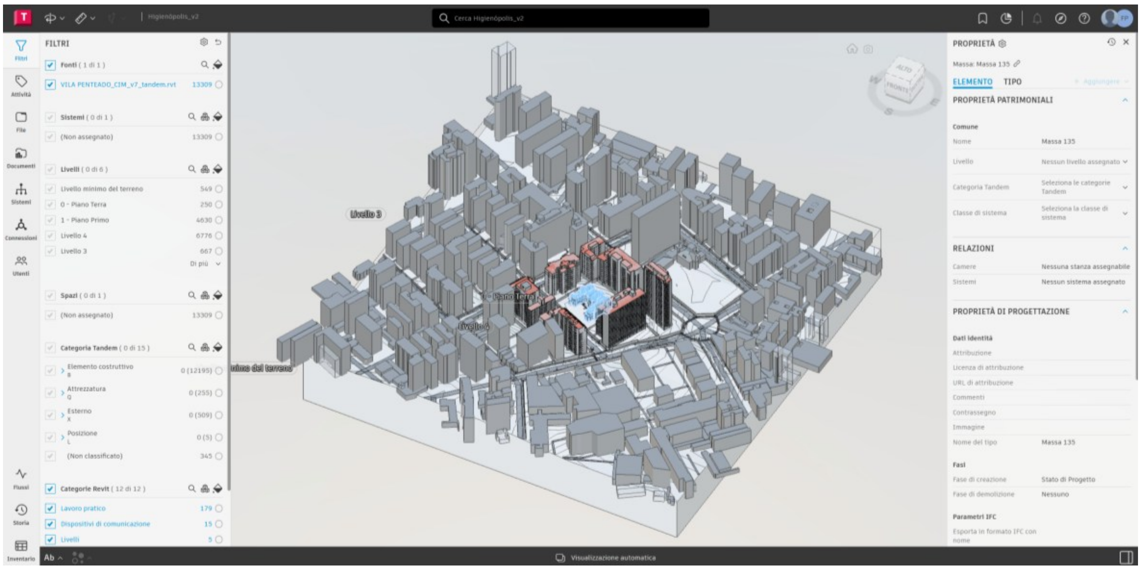
[27] For further details see at: https://www.incite-project.it/home.



Massa: Massa 135

PROPRIETÀ PATRIMONIALI

Comune
Nome: Massa 135
Livello: Nessun livello assegnato
Categoria Tandem: Seleziona le categorie Tandem
Classe di sistema: Seleziona la classe di sistema

RELAZIONI
Camere: Nessuna stanza assegnabile
Sistemi: Nessun sistema assegnato

PROPRIETÀ DI PROGETTAZIONE

Dati identità
Attribuzione
Licenza di attribuzione
URL di attribuzione
Commenti
Contrassegno
Immagine
Nome del tipo: Massa 135

Fasi
Fase di creazione: Stato di Progetto
Fase di demolizione: Nessuno

Parametri IFC
Esporta in formato IFC con nome

Fig. 4.34 – Visualization and query of the Higienópolis CIM model in Autodesk Tandem, a platform accessible through a standard web browser. On the left, the structure of filters and categories; in the center, the 3D view of the model with a focus on Vila Penteado; and on the right, the information properties panel of the selected element.

Fig. 4.35 – Testing the upload of the CIM model to the INCITE platform. (Credits: ACSoftware).

Urban and social regeneration, as highlighted by European policies, represent essential phenomena in the development of strategies for managing and redeveloping the built heritage. The impact of these results thus contributes to reducing costs in maintenance interventions and to enabling more efficient resource management, thereby extending the life cycle of existing assets, improving their accessibility, and, in the long term, promoting a higher quality of life.

The following section illustrates the workflow of the data-driven methodological approach developed within the framework of the present thesis.

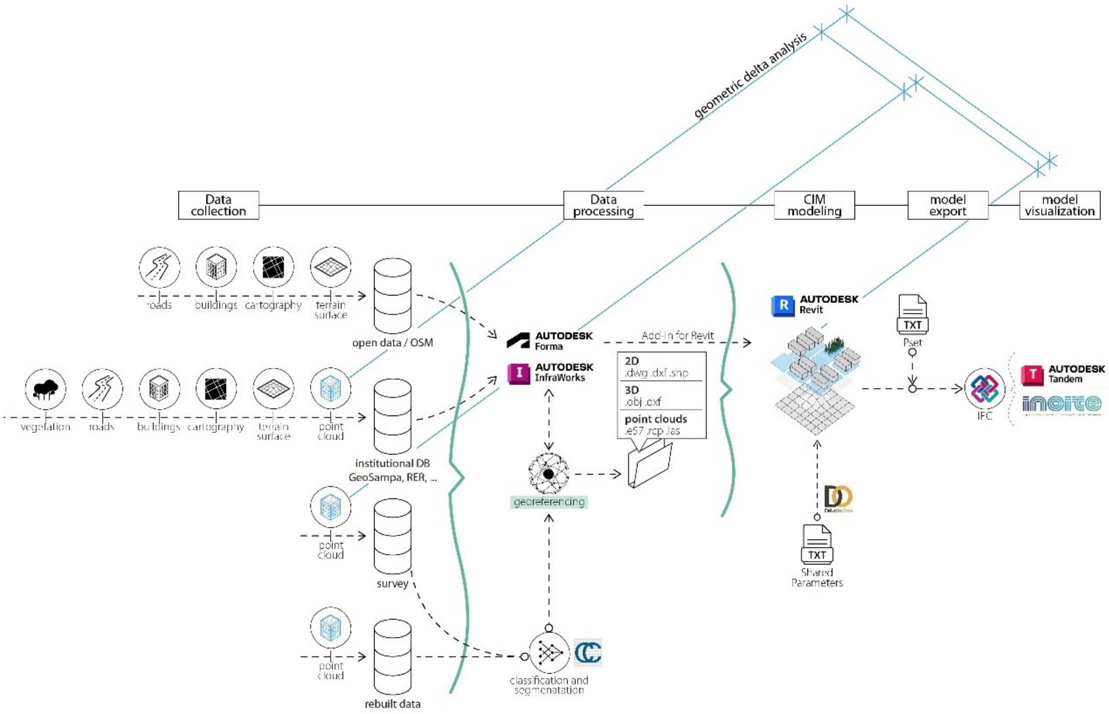


Fig. 4.36 – Methodological Workflow Approach

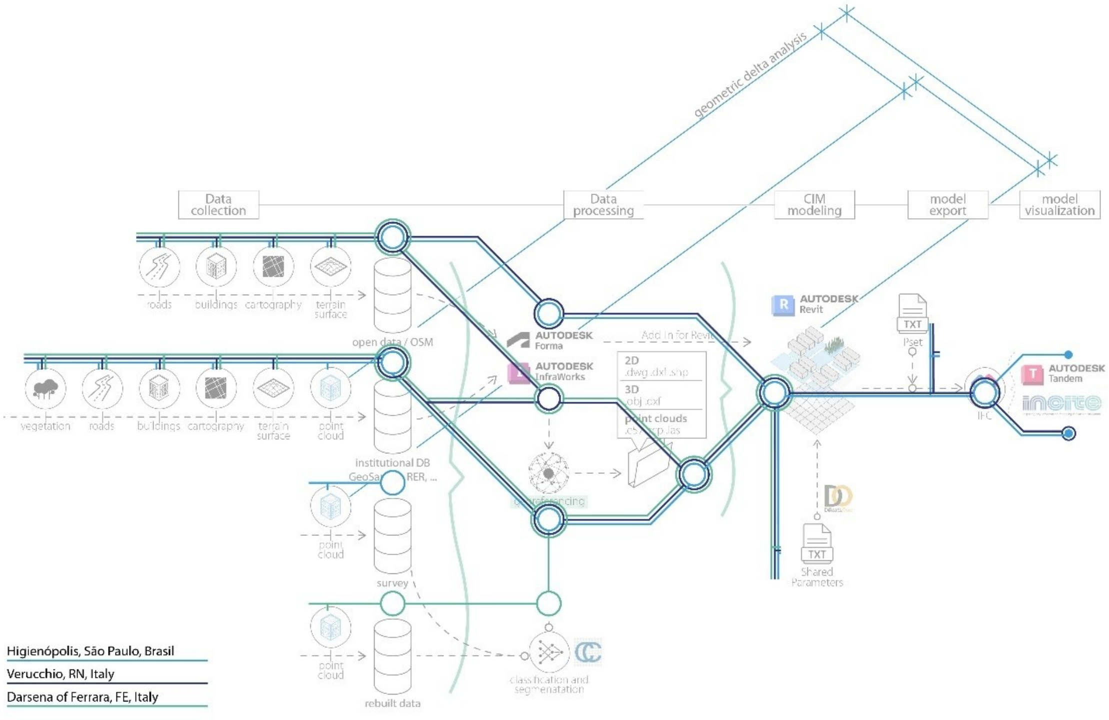


Fig. 4.37 – Methodological Workflow Approach in the Three Case Studies

Chapter 5
CASE STUDIES SELECTION

5.1 Comparative Framework of the Case Studies: Higienópolis, Verucchio, and the Darsena of Ferrara

In the following chapter, the selected case studies examined in this research are presented. In order to understand the specific features related to the development of CIM models, the choice of indicators, and the subsequent simulations conducted on them, a general overview is first provided. This overview serves to outline the broader framework within which the case studies, distinct from one another in multiple respects, are situated. The three contexts analyzed are: the *Higienópolis* district in São Paulo, Brazil; the historic village of *Verucchio*, in the Province of Rimini, Italy; and the *Darsena* area in Ferrara, Italy. The selection of these cases responds to the need to investigate heterogeneous realities, both geographically and socio-urbanistically, in order to assess the applicability and adaptability of the proposed models. In the following sections, each case study will be introduced and analyzed in detail.

Urban growth and morphological transformation
São Paulo, Brasil

Minor historic town, inland area of Emilia-Romagna
Verucchio, RN, Italy

Ongoing urban regeneration context
Darsena of Ferrara, FE, Italy

Fig. 5.1 – Comparative framework of the three case studies: Higienópolis, Verucchio, and the Darsena of Ferrara, shown at the same representative scale to highlight their distinct urban morphologies.

Higienópolis is a district located in the central area of the city of São Paulo, Brazil. It is characterized by a high residential density, the result of an urban transformation process marked by a compact and vertical morphology. Nevertheless, it still retains a distinctive identity, defined by the coexistence of tree-lined streets, isolated historic residences, and an image that evokes, in the collective memory, the aristocratic prestige of its past. This case was selected to simulate temporal accelerators and, within the framework of this research, to analyze the role of the CIM model. The aim is to contribute to the definition of a geometric–informational approach that employs the model as a historical and documentary database supporting intervention proposals.

The village of *Verucchio* was identified as a case study for its dual significance. On the one hand, it is located in a territorial context characterized by a complex orographic relationship, which necessitates a specific reflection on the management of elevation data in the development of the CIM model. On the other hand, it represents a benchmark example of the many historic villages scattered throughout the Apennine area. Therefore, it was considered appropriate to explore the potential for enhancing such urban centers through the implementation of CIM as a management and documentation tool, integrated within networks of municipal unions in a transitional framework.

The selected case study of the *Darsena* focuses on an urban section of the Municipality of Ferrara, located in the Emilia-Romagna region of Italy. This area, situated along the Po di Volano river to the south of the city, was chosen for its distinctive characteristics. It intersects several zones identified in the Municipal Structural Plan (PSC): historical fabric, consolidated fabric, and fabric to be redeveloped. The urban section is distinguished by several key features: the river embankment; residential areas along Via Argine Ducale and Via del Mulinetto; the historic core along Via Piangipane and Via Ripagrande, with the National Museum of Italian Judaism and the Shoah (MEIS); and a section of the historic city walls. Additionally, the area between the walls and the Burana Canal is currently undergoing urban redevelopment, aimed at strengthening its connection with the historic center.

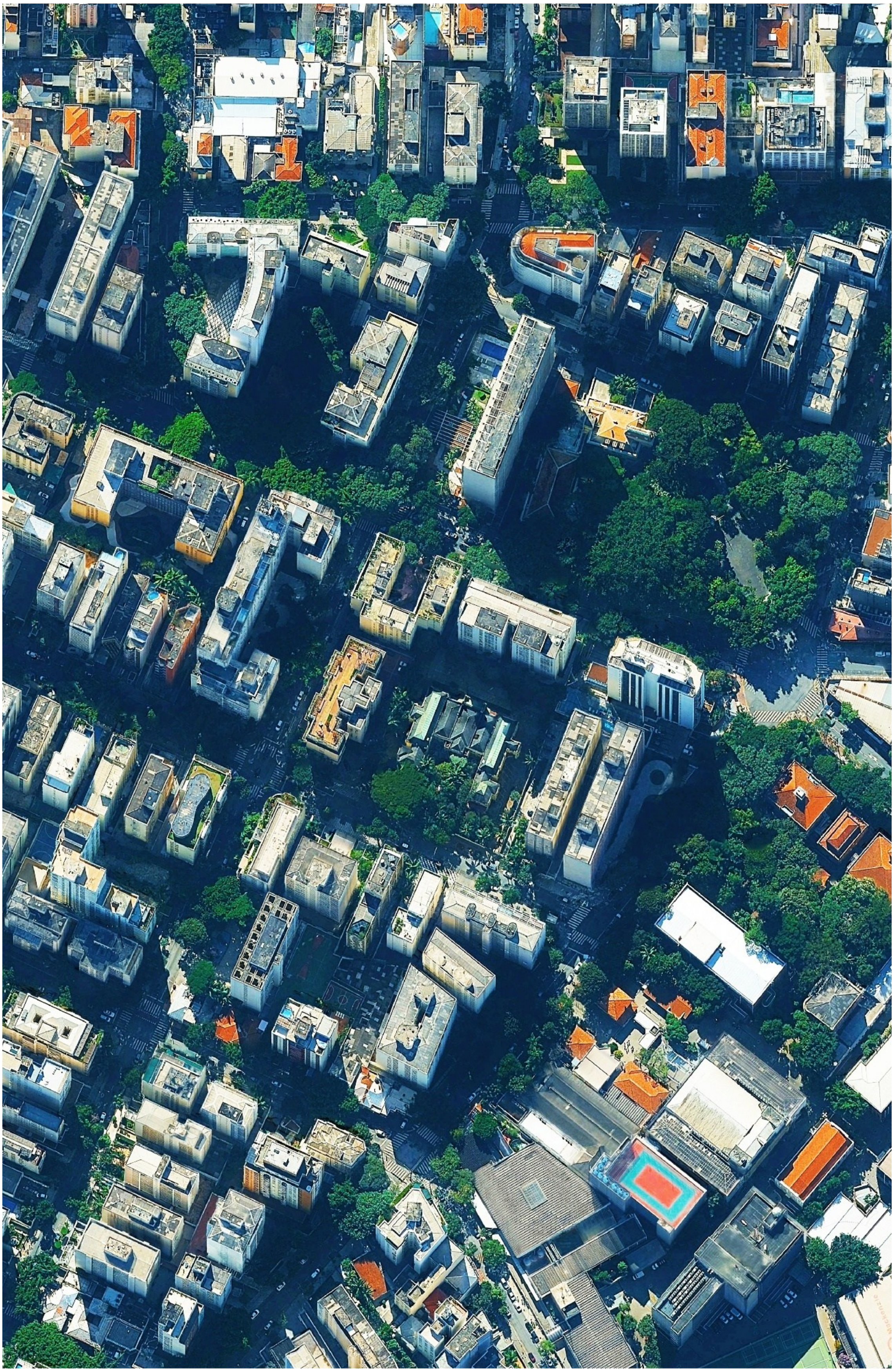


Fig. 5.2 – Higienópolis, São Paulo (Brazil), Vila Penteado Area. (Source: Gogle Earth).

5.2 Higienópolis as a Case Study of Urban Growth and Morphological Transformation in São Paulo

Higienópolis is a neighborhood located in the district of Consolação, in the central area of the city of São Paulo, Brazil. It is characterized by a high residential density, the result of a transformation process marked by a compact and verticalized urban morphology. Despite this, the area still retains a distinctive identity, defined by the coexistence of tree-lined streets, isolated historic residences, and an image that evokes, in the collective memory, the aristocratic prestige of its past.

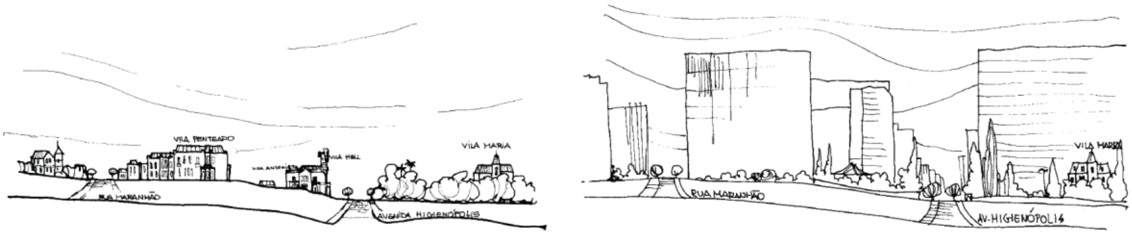


Fig. 5.3 – Urban section with the subdivided land on the left and the Vila Penteado on the right, surrounded by tall buildings. (Drawing: Silvio Soares Macedo, Source: Martins, 2012)

5.2.1 *Selection of the Case Study*

São Paulo is a city marked by an exceptionally rapid urban metabolism; in the 1950s, it was even described with the slogan "a cidade que mais cresce no mundo"[1]. To simulate temporal accelerators and analyze, within the framework of this research, the role of the CIM model, contributing to the definition of a geometric-informative approach aimed at employing the model as a historical and documentary database to support intervention proposals, the context of Higienópolis was selected as a case study. This choice also responds to the aim of including historical categories that are indispensable in transformation processes.

The metropolitan context of São Paulo, with its rapid growth and profound transformations, therefore constitutes the framework within which the case of Higienópolis is situated. The description of this neighborhood, distinguished by its historical and morphological stratifications, provides an exemplary lens through which to interpret the city's urban dynamics. Within this broader scenario, attention ultimately focuses on the lot and the areas facing Vila Penteado, which become the specific object of detailed investigation.

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[1] In english: "the fastest-growing city in the world".

5.2.2 *The Urban Expansion of São Paulo in the Last Quarter of the Nineteenth Century and the Higienópolis District*

In the last quarter of the nineteenth century, the expansion of coffee cultivation in the state of São Paulo initiated the process that would transform the small, still colonial town into the "coffee metropolis" of the early decades of the twentieth century. The activities associated with coffee production placed the Paulista capital in a privileged position: infrastructures such as the railway (which facilitated transport) as well as public lighting, water supply, and sewer systems, together with the influx of immigrants drawn by the so-called "green gold," transformed São Paulo into a large city and endowed it with an unmistakably industrial character. The most radical transformation occurred between the end of the century and the beginning of the new one: the population grew from 28,000 inhabitants in 1875 to 200,000 in 1900. Much of this increase consisted of foreigners (Italians, Spaniards, Germans, English, French, and Slavs), who provided the workforce for both agriculture and the emerging industrial sector. São Paulo rapidly evolved from a modest town into the second most important city in Brazil, after Rio de Janeiro. The city underwent a series of improvements: the planting of trees, the construction of sidewalks, the development of collective transportation (trams and horse-drawn omnibuses), the widening of streets, and the creation of new buildings and neighborhoods, both residential and working-class. Construction techniques changed as well, and new materials became widespread: brick replaced the traditional taipa (rammed earth), accompanied by French roof tiles, imported timber, and iron. Alongside these materials came European architectural styles. São Paulo thus transitioned directly from simple colonial structures to the modern buildings of European eclecticism[2]. It was precisely during this process of urban expansion that the district of Higienópolis came into being. Until then, the small urban nucleus of the city was confined to the historic core, around which extended large *chácaras*[3] with crops and livestock. With demographic growth and new economic activities, however, the city center was transformed into a commercial, administrative, and religious hub. Wealthy families moved westward, to areas such as Higienópolis, while working-class neighborhoods emerged in the lower zones, closer to the railways[4].

Higienópolis was established at the end of the century as a result of real estate speculation promoted by two German entrepreneurs, Martinho Burchard and Victor Nothmann, who purchased and subdivided extensive tracts of land into plots. The neighborhood initially attracted

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[2] In 1900, Alfredo Moreira Pinto described the transformed city as follows: *"São Paulo, who once saw you and who sees you now! Once you wore corduroy trousers, a jacket, and a straw hat. Today you wear a tailcoat, a silk tie, and patent leather boots. You possess opulent buildings, tree-lined squares, streets busy with elegant carriages and traversed by tram lines. Boulevards such as Paulista, charming suburbs such as Campos Elíseos, Santa Cecília, Higienópolis, and Consolação...".*

[3] Self-sufficient agricultural estates

[4] Neighbourhoods including; Brás, Mooca, Ipiranga, Bom Retiro, Barra Funda, Lapa, and Pinheiros

Anglo-German and North American residents, and subsequently the coffee elite: *fazendeiros*[5], merchants, bankers, and early industrialists, forming the *paulista élite*. Higienópolis thus became the city's most elegant residential neighborhood, the setting for the lives of prominent families such as the Prado and Álvares Penteado.

Fig. 5.4 – Comparative series of historical maps, aerial photographs, and satellite imagery of the Higienópolis area (São Paulo, Brazil), used to document the morphological and urban evolution of the district. From top left: territorial framework of the São Paulo metropolitan area (Source: Google Earth); detail of the Topographic Map of the Municipality of São Paulo, produced by the company Sara Brasil, 1930 (Source: GeoSampa); detail of the aerophotogrammetric survey of the Municipality of São Paulo, carried out by Vasp Aerofotogrametria S.A. and Serviços Aerofotogramétrico Cruzeiro do Sul S.A., 1952–1957 (Source: GeoSampa); 1958 aerial photograph (Source: Geoportal/Memoria Paulista); 1973 aerial photograph, Terrafoto (Source: Macedo, 2012); 2020 orthophoto (Source: GeoSampa).

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[5] Large landowners

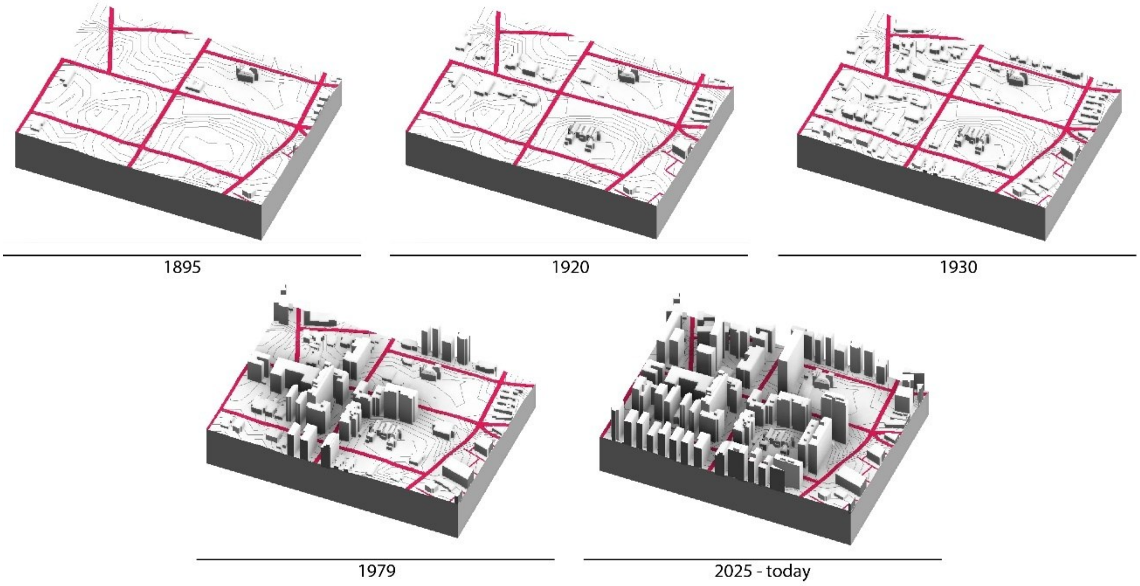
1895
1920
1930
1979
2025 - today

Fig. 5.5 – Evolution of land occupation in the Higienópolis area, including Vila Penteado, from 1895, the beginning of the subdivision into lots, to the present day.

5.2.3 *Origins and Early Historical Background (up to 1870–1880)*

The area, situated on elevated position along the northern slopes of the Avenida Paulista ridge, was originally occupied by large estates belonging to prominent members of São Paulo's elite. However, it also attracted many foreigners, drawn by the healthy, dry, and breezy climate of the highlands. The site was considered one of the most salubrious and pleasant in the region, offering broad vistas and agreeable landscapes. Because of these climatic and environmental characteristics, the area was named *Higienópolis*, literally, "city" or "place of hygiene". The first recorded references to the area date back to 1874. A key moment, however, occurred in 1884, when D. Veridiana da Silva Prado decided to build her palacete, Vila Maria. Constructed with materials and designs imported from Europe, the residence marked the beginning of a new phase in São Paulo's domestic architecture, introducing the first eclectic-style villas set within large gardens, groves, and ornamental ponds. The choice of D. Veridiana, a prominent figure in São Paulo's social and cultural life, conferred prestige upon the area. By the late 1880s, the territory that would become Higienópolis was already characterized by the presence of important chácaras[6] belonging to eminent families such as Prado, Barros, Ramalho, and Jaguaribe, as well as by religious and educational institutions and various initiatives related to health and well-being.

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[6] In Brazilian usage, chácara designates a small rural estate typically located on the outskirts of urban areas. Such properties are often used for small-scale agriculture, livestock raising, or as leisure country residences. The term may be rendered in English as "small farm," "country property," or "rural homestead."

These elements laid the groundwork for the subsequent transformation, when Burchard and Nothmann would launch the large-scale subdivision that officially gave birth to the neighborhood.

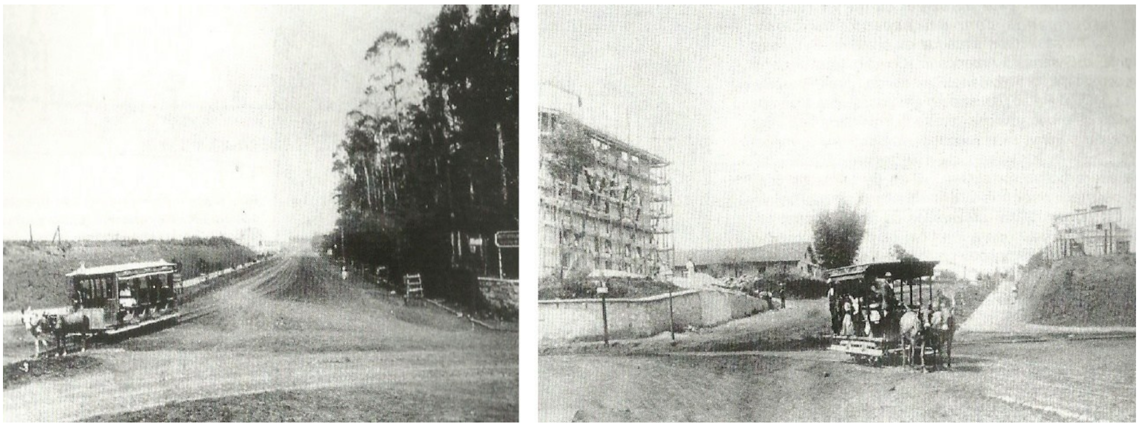

Fig. 5.6 – Historical photographs of Higienópolis. On the left: General view of Avenida Higienópolis in its early years, with the plot on the left where Vila Penteado would later be built, and on the right the dense vegetation of Vila Maria (Source: Macedo, 2021). On the right: On the left, on Rua Itambé, the main building of Mackenzie College is under construction, and on the right the plot where Vila Penteado would be built (Source: Macedo, 2012).

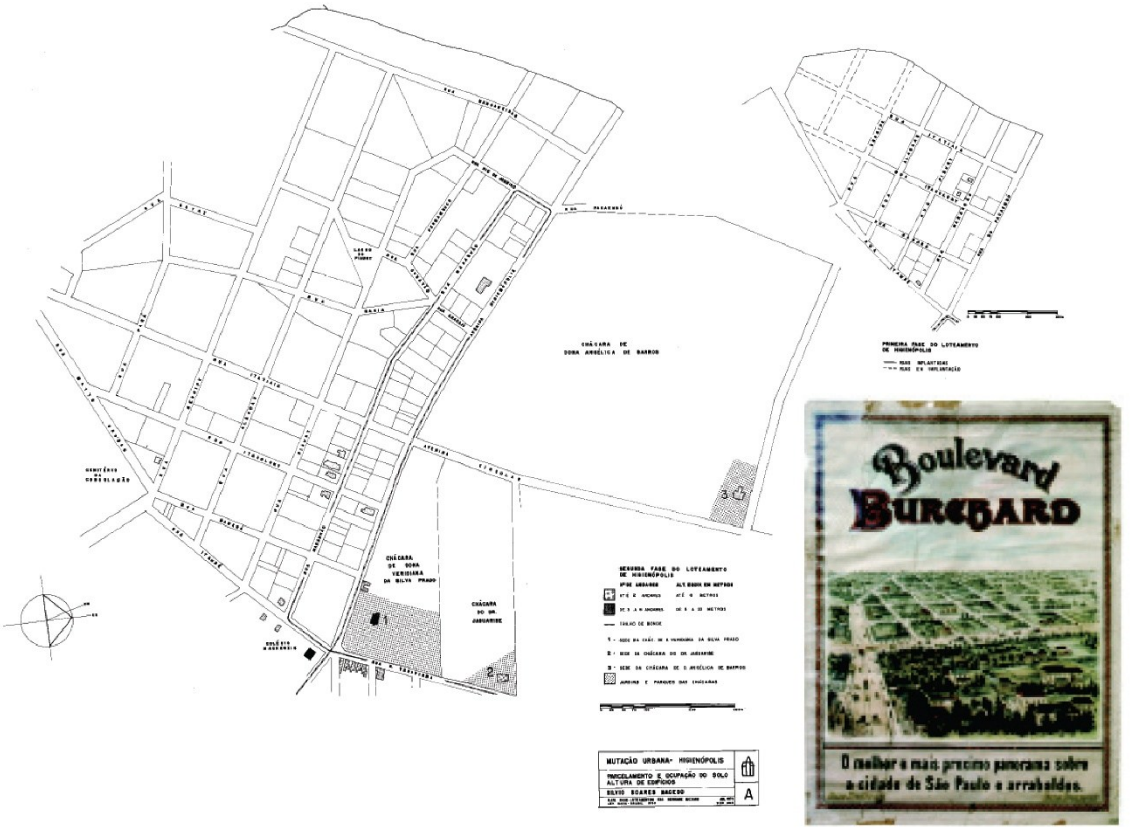

Fig. 5.7 – General plan of the Higienópolis district. In the larger lot, in the left-hand corner, Vila Penteado was built in 1903 by the Penteado family. (Archive: Silvio Soares Macedo). On the right: photograph of the poster for the launch of Higienópolis. In the foreground is Vila Maria, the estate of D. Veridiana Prado, followed by Avenida Higienópolis and, just above it, the tract of land destined for Vila Penteado (Source: Martins, 2012).

5.2.4 *Early Development through the Project of Martinho Burchard and Victor Nothmann (c. 1878–1890)*

The district of *Higienópolis* emerged thanks to the initiative of two German entrepreneurs, Martinho Burchard and Victor Nothmann, who, at the end of the nineteenth century, purchased the lands of Barão de Ramalho and part of the estates belonging to Joaquim Fortano Wanderley. Pursuing their vision of creating a modern urbanization model, they laid out new, wide, and regular streets, equipped with basic infrastructure and intended for the upper-class residents of São Paulo. The new avenues were lined with various species of trees, including plane trees, privets, magnolias, catalpas, and oaks. The neighborhood also benefited from the proximity of schools such as the Mackenzie College and the Brasília Barque Institute, as well as hospitals. The first lot buyers were mostly Anglo-Saxon foreigners and members of the local elite, attracted by the area's healthful environment and refined atmosphere. Higienópolis thus established itself as a high-end residential district, becoming a symbol of the new São Paulo at the turn of the century. In 1894, the Municipal Government officially adopted the name Higienópolis to designate the neighborhood, reviving its original toponym associated with the salubrious qualities of the area. The city further consolidated the district through the implementation of infrastructure and urban improvements, such as the paving of streets with stone blocks, the creation of squares, and the definition of toponyms: developments that transformed it into an elegant, well-served, and desirable location for São Paulo's upper society.

The first lots sold were concentrated along Avenida Higienópolis and the area closest to Consolação. Prices rose rapidly: from 550 réis per square meter in 1890 to over 1,000 réis in the following years. The plots were spacious (on average 35 by 47 meters), allowing for residences with gardens, orchards, and spaces for horses and carriages. The pioneering phase of Higienópolis was marked by an Anglo-Saxon presence, characterized by *European-style chalets and neoclassical influences* that introduced a new aesthetic standard to São Paulo's residential architecture. From 1897 onward, the number of building permits multiplied. With the advent of the twentieth century, the district became the preferred residential area for major coffee barons and São Paulo's emerging industrialists. The relocation of these elites gave the neighborhood its definitive character: the modest chalets of the foreign pioneers were replaced by *monumental palacetes* surrounded by gardens, greenhouses, and stables; residences designed to reflect the wealth and status of their owners. Avenida Higienópolis became home to the Prado and Penteado families, forming an aristocratic axis that united families, capital, and symbols of prestige.

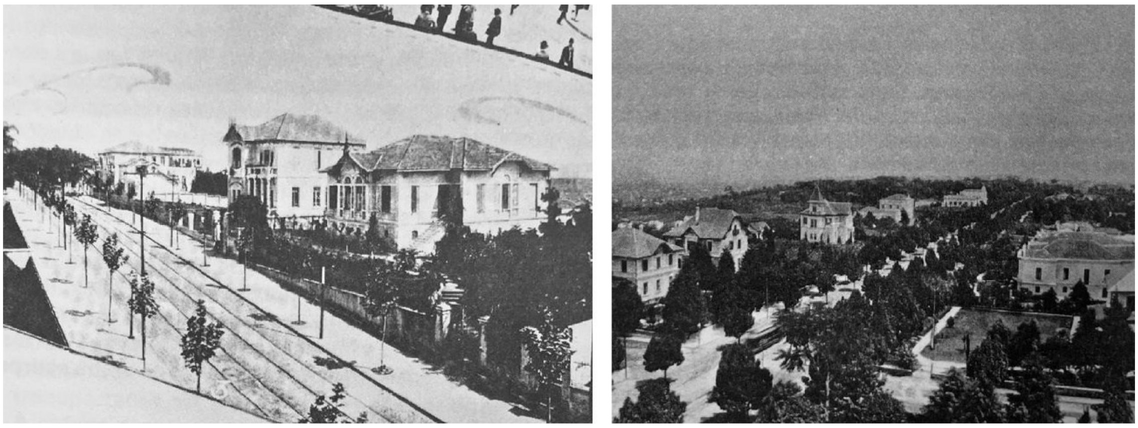

Fig. 5.8 – Historical photographs. On the left: Rua Maranhão in 1905. On the right: Avenida Paulista in 1902. (Source: Prado and Machado, 1976).

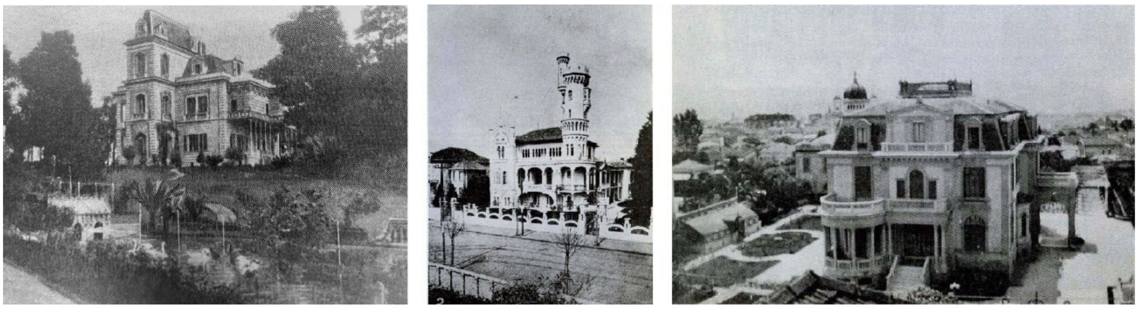

Fig. 5.9 – Historical photographs. From left to right: View of Vila Maria estate (Arquivo: Silvio Soares Machedo. Source: Martins, 2012). House of engineer Maximiliano Hel on Avenida Higienópolis in 1905 (Source: Prado and Machado, 1976). Residence of Dona Stella Penteado as it appeared at the time of its construction in the second decade of the century (Arquivo: Silvio Soares Macedo. Source: Sampaio and Maricato, 2002).

The most notable example is that of Antônio Álvares Leite Penteado, an industrialist and pioneer in the textile sector, who in 1902 commissioned the Swedish architect Carlos Ekman to design the renowned *Vila Penteado*, a symbol of the period during which Higienópolis emerged as the quintessential aristocratic district. Vila Penteado became a model for other prestigious residences, where the floral and decorative language of Art Nouveau reflected the modernity and cosmopolitan spirit of São Paulo's elite.

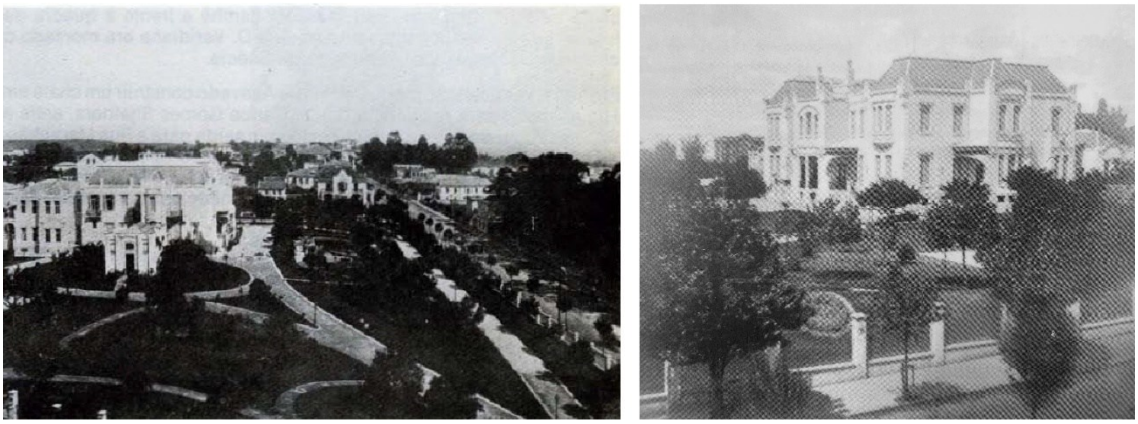

Fig. 5.10 – On the left: Vila Penteado and Avenida Higienópolis, in 1907.On the right: View of Vila Penteado taken from Vila Antonieta, around 1906. (Photograph by Honorio Penteado, in 1975. Source: Martins, 2012).

The matrimonial alliances between the Penteado and Prado families further strengthened their economic and social ties, consolidating the concentration of power and prestige within Higienópolis. The district thus evolved into a compact geography where contiguous family residences along Avenida Higienópolis created a homogeneous, elegant, and exclusive urban landscape.[7]

Fig. 5.11 – Historical map of the main residential nuclei and family properties in the Higienópolis area, up to 1930. (Source: Homen, 1980).

Fig. 5.12 – Historical street elevations of residential buildings in the Higienópolis area, illustrating the architectural character and prominent family properties of the district during the 1930–1940 period. (Drawings: Silvio Soares Macedo. Source: Martins, 2012).

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[7] As Paul Walles wrote, it was the "meeting point of what the city and the state possessed of the richest and most distinguished," notable for "the large number of sumptuous houses, luxurious and comfortable palacetes, although some of them were of questionable, if not even bizarre, taste."

5.2.5 *The Higienópolis Neighborhood during the Paulista Belle Époque (end XX Century – 1930)*

Higienópolis became a place of social, cultural, and architectural prestige, where aristocratic residences and green spaces reflected the luxurious lifestyle of the urban elite through sumptuous mansions and refined gardens, establishing itself as one of the most exclusive and representative neighborhoods of São Paulo. During this period, the majority of the city's elite resided in Higienópolis, which thus became the vibrant heart of the Belle Époque of São Paulo; the space where leading figures sought to bring modernity and cosmopolitanism to the city.

In the 1920s, the traditional bourgeoisie began to show the first signs of decline in social prestige, confronted with the rise of immigrant merchants and industrialists who, through the accumulation of significant personal wealth, contributed to the formation of a new bourgeois class. During these years, industrial development encouraged a diversification of social class: between the opposing classes of employers and workers, a new group of technicians and artisans emerged, joining the ranks of liberal professionals, civil servants, and traders. Consequently, the middle class expanded, driven by consumerism and aspirations of upward mobility, and sought to emulate the lifestyle of the elite. Unlike the aristocracy, however, this new class did not settle in a single neighborhood; rather, it followed both real estate speculation and the pursuit of social status. Favored increasingly by the opportunities offered by industrialization, the middle class gradually moved into Higienópolis, eventually establishing itself there permanently after the Second World War. From this moment onward, along with the major economic transformations initiated by the urbanization processes of the 1920s, the elegant residential character of Higienópolis began to be compromised, laying the groundwork for the neighborhood's extraordinary metamorphosis from the 1950s onward.

5.2.6 *The Contemporary Higienópolis Neighborhood (c. 1930 – Today)*

Between 1930 and 1945, a period marked by the Second World War, São Paulo entered a new phase of progress, characterized by increasingly accelerated growth. During these years, the city retained its cosmopolitan character and continued to be recognized as the "metropolis of coffee," although economic interests had begun to shift toward other crops such as cotton and sugarcane. From an industrial standpoint, São Paulo expanded its productive capacity, although its development still occurred on a relatively modest scale. Within just a decade, the city's population experienced an extraordinary demographic surge, nearly doubling in size. At the beginning of the new decade, São Paulo could already count approximately one million inhabitants. The intensification of demographic growth, resulting from the successive crises in coffee cultivation and from the increasing employment opportunities offered by the consolidation of the industrial sector, generated a strong demand for housing, which in turn stimulated a new phase of urban expansion. Given the enormous demand for dwellings and the absence of fiscal controls, civil construction became one of the most profitable activities, representing, at that time, the true construction industry of São Paulo. Alongside the city's horizontal expansion, the introduction of new construction techniques, innovative materials, and the use of elevators simultaneously encouraged vertical development.

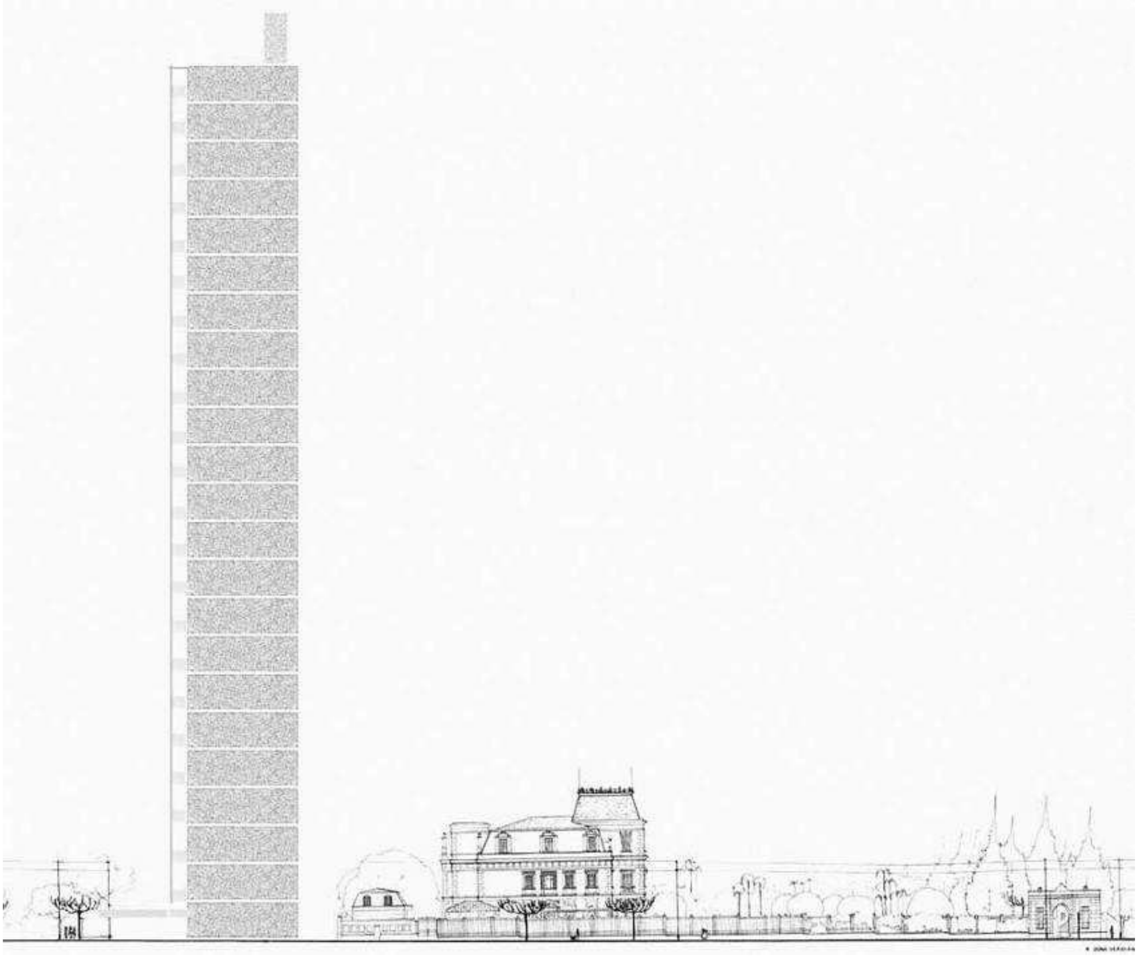

Fig. 5.13 – Contrasts. The Parque Higienópolis and Vila Maria. Montage based on a drawing by Sílvio Macedo. (Source: Kambara and Bortolli JR., 2011)

The district of Higienópolis, due to its proximity to the city center and its long-standing prestige, came under the pressure of the middle class, real-estate speculation, and increasing traffic, factors that ultimately and irreversibly compromised both the quality of life and the original urban landscape. For this reason, after 1930, Higienópolis began to be examined more from sociological and urbanistic perspectives than from a strictly historical one. Within this framework, two main phases of transformation can be identified: the first, between 1930 and 1949, and the second, from 1950 to the present day.

First Phase: 1930–1949

During this phase, defined as the "de-characterization" of Higienópolis, the neighborhood underwent a gradual loss of the morphological, architectural, and socio-cultural traits that had once made it distinctive and emblematic of a particular lifestyle within the urban context. Higienópolis progressively lost its former prestige to Avenida Paulista, Jardim América, and Pacaembu. The first signs of the processes that would intensify after 1950, leading to vertical expansion, began to appear during this period. Consequently, the original urban fabric, once characterized by a perfect balance between built-up areas and green spaces, started to lose its homogeneity. However, changes occurred at a relatively slow pace, as construction activity remained limited. In 1940, Higienópolis still retained a certain prestige among São Paulo's upper-class neighborhoods. At the same time, the social life of the district changed as well, due to the passing of prominent figures, the relocation of wealthy families to more distant areas, and the division of fortunes among heirs. Some mansions, when not left unoccupied for years, were converted into schools, colleges, or even cortiços[8]; others were demolished to make way for the first apartment buildings. Several lots were subdivided and sold separately, paving the way for the entry of the middle class, eager to access spaces that had previously been the exclusive domain of the São Paulo elite. Meanwhile, the city entered the era of reinforced concrete, and Higienópolis, once the "pride of the Paulistas" and a must-see destination for visitors, was among the first neighborhoods to break with São Paulo's characteristic horizontality. In the 1940s, despite having lost part of its prestige, the district still rivaled Pacaembu and Jardim América. The concluding moment of this phase occurred in 1947, when the Álvares Penteado brothers donated the Vila Penteado to the University of São Paulo, on the condition that it would house the newly established Faculty of Architecture and Urbanism (FAU), which moved into the building in 1949.

By the late 1940s, new construction companies, such as Artacho Jurado, initiated the development of the first major luxury condominiums, marking the beginning of a new era. At the same time, more modest buildings, such as Rubayat and Teresópolis, were erected, opening the way for a gradual replacement of aristocratic mansions with apartment towers. This period thus represents the process of Higienópolis's "de-characterization", through the superimposition of new urban and social elements that brought an end to its former state and set the stage for the more radical transformations that would take place after 1950.

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[8] Tenement houses.

Fig. 5.14 – The “Edrucio Ccndorruenc Alaqoes”, the first building in the Higienópolis district, erected in 1933; the “Santo André” and “Augusto Barreto” buildings on Avenida Angélica, the second and third buildings in Higienópolis, completed in 1935 and 1937 respectively; the “Prudência e Capitalização Apartments”, designed by Rino Levi in 1944. (Source: Homem, 1980).

Second Phase: 1950–Nowdays

After the Second World War, Brazil’s industrial sector experienced significant revitalization. By this time, São Paulo had reached a population of three million inhabitants and had acquired the appearance of a modern industrial city, known by the slogan “the fastest-growing city in the world.” The historic monuments of the coffee civilization began to give way to skyscrapers in several districts, including Higienópolis, which entered a phase of urban renewal marked by the arrival of new residents: liberal professionals, technicians, civil servants, affluent Jewish families from Bom Retiro, diplomats, traders, and industrialists. Real estate interest increased steadily, attracted by the area’s large plots, proximity to the city centre, and efficient transport network. However, this new wave of construction compromised the neighbourhood’s urban coherence, high living standards, and residential exclusivity. The proliferation of high-rise buildings and the growth of commercial and service activities transformed Higienópolis from a noble district into a densely populated, upper-middle-class neighbourhood. Within this process of verticalization, real estate companies capitalized on the district’s former aristocratic image, employing it as a rhetorical and promotional device: living in a modern building located in a “noble” area was presented as a mark of social prestige, even when the apartments were relatively small.

At the same time, private vegetation diminished, although the network of tree-lined streets continued to distinguish Higienópolis from the rest of the city. Public transport expanded with the introduction of trolleybuses in the 1950s and the replacement of trams with buses in 1966. Avenues such as Higienópolis and Angélica became major traffic corridors and hubs of diversified commercial activity, hosting supermarkets, restaurants, cafés, pharmacies, boutiques, newsstands, workshops, and small service providers. Over time, Higienópolis became an overcrowded district, with multiple buildings occupying single plots and few open spaces remaining. It was only in the 1970s, with the enactment of urban planning laws (in 1972 and 1977), that attempts were made to regulate land use. The neighbourhood was divided into three mixed-use zones (residential and commercial). Despite its saturation, Higienópolis remained one of the most desirable residential areas due to its location, amenities, and green spaces. The population became more diverse, marked by a strong Jewish presence, with synagogues and cultural centres contributing to the neighbourhood's identity. In subsequent decades, the demolition of historic buildings intensified in the name of "progress," leading to the loss of significant Art Nouveau, Art Déco, and eclectic structures. Meanwhile, real estate speculation persisted: modern condominiums replaced old mansions, and even peripheral plots were marketed under the name "Nova Higienópolis," a testament to the enduring symbolic appeal of the district's name.

Fig. 5.15 – Rua Maranhão, Higienópolis, today, 2025.

Today, only a few original residences remain, generally small and of limited architectural value. The Vila Maria and Vila Penteado survive as historical landmarks, although now surrounded by high-rises. The Vila Penteado, declared a historic monument by the São Paulo State Council for the Protection of Historical Heritage (CONDEPHAAT) in 1978, still preserves part of its original structure, despite the loss of its gardens.

Fig. 5.16 – 3D aerial view of the Higienópolis district today, highlighting the main axis of Avenida Higienópolis. (Source: Google Earth).

5.2.7 *The Vila Penteado Area*

Vila Penteado (1902), one of the most significant works by Carlos Ekman (1866–1940)[9], was commissioned as a private residence by Antônio Álvares Leite Penteado, an industrialist and pioneer in the textile sector, who had acquired the land from Martinho Burchard. Vila Penteado remains today the symbol of the period that defined Higienópolis as the quintessential aristocratic neighbourhood: a building that embodies the union between agricultural wealth, industrial ambition, and international openness. It consecrated Higienópolis as one of the most prestigious residential areas in belle époque São Paulo, as well as one of the largest buildings erected in the city at the beginning of the century. For this reason, given its importance, this research includes an in-depth bibliographical and CIM-modelling analysis focused on the Vila Penteado plot, today considered one of the most important symbols for São Paulo’s architects, not only for its architectural value but also for its urban and landscape significance. Indeed, besides being one of the few remaining examples of art nouveau and a model residence for major coffee plantation owners or those connected to the rise of industrialisation between the late nineteenth and early twentieth centuries, the villa was also a landmark within the Higienópolis landscape and a key heritage site in the cultural life of the city. Donated to the University of São Paulo (USP) in 1947 by heirs Sílvio and Armando Álvares Penteado to support the launch of higher education in architecture, Vila Penteado today is listed as a Cultural Heritage site of the State of São Paulo and

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[9] For further details: Sampaio & Maricato, *Vila Penteado: 100 anos*, 2002

hosts the postgraduate programmes of the Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo (FAU-USP).

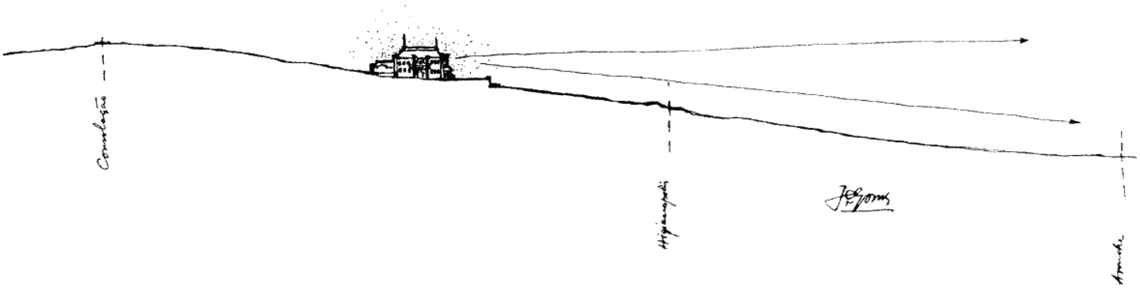

Fig. 5.17 – Vila Penteado. (Drawings: José Clàudio Gomes. Source: Martins, 2012)

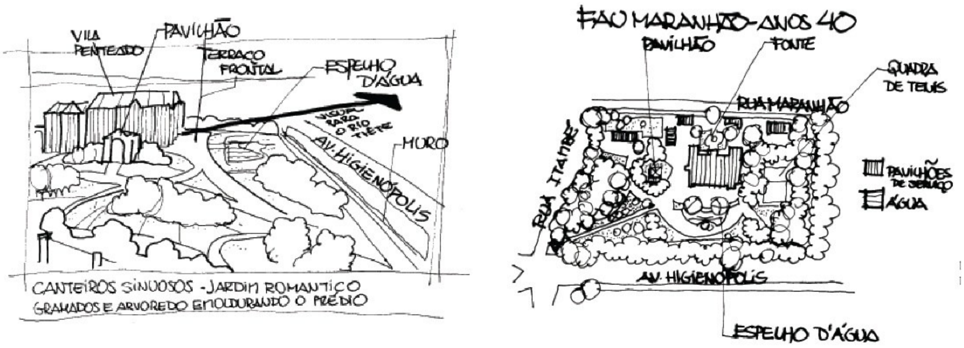

Fig. 5.18 – On the left: Sinous garden beds and a Romantic-style garden, with lawns and groves of trees framing the building. On the right: FAU–Maranhão, 1940s. (Drawings: Silvio Soares Macedo. Source: Martins, 2012).

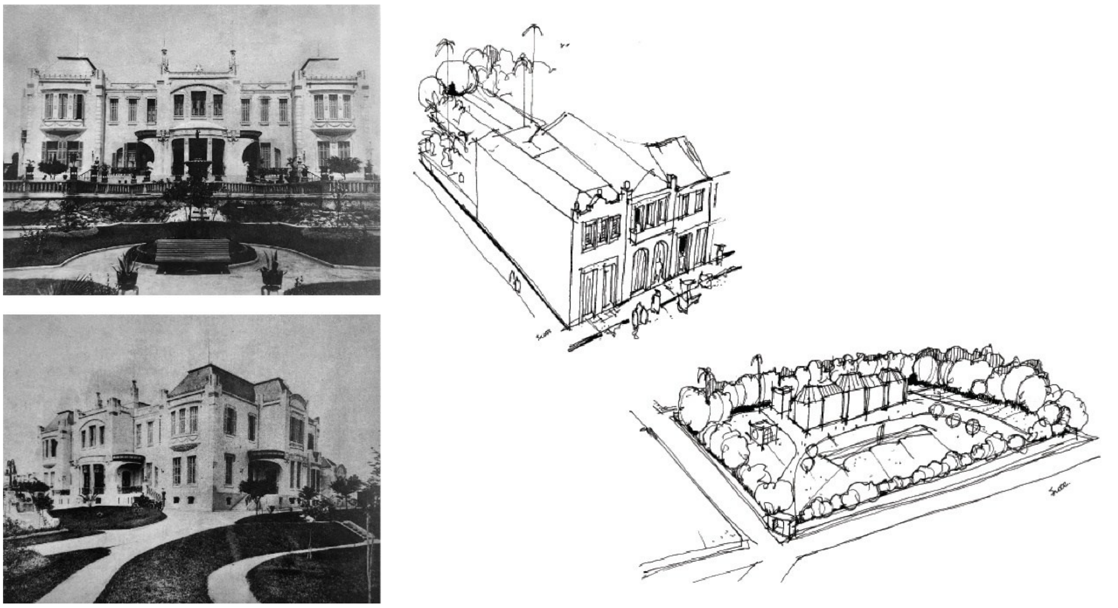

Fig. 5.19 – On the left: historical photographs. At the top, the main façade of “Vila Penteado,” facing Avenida Higienópolis; below, the coexistence within Vila Penteado of two eras at the beginning of the century, the carriage and the automobile. (Source: Martins, 2012). On the side: drawings of Vila Penteado and of the block. (Drawings: Silvio Soares Macedo. Source: Martins, 2012).

The late XIX century was marked by significant transformations in the urban models of São Paulo, which consequently reshaped its landscapes. A new residential typology emerged, comprising a detached house set within a private plot. This model became consolidated at the beginning of the XX century as a benchmark of modernity, associated with the aspirations of the upper classes to live in residential districts inspired by French boulevards, complete with tree-lined streets, sidewalks, and public lighting. Along these wide avenues, eclectic-style buildings arose, typical of the so-called Belle Époque. Vila Penteado was built within this urban context, between the end of the nineteenth and the beginning of the twentieth century, along the main axis of the Higienópolis district. The size of the property, together with its architectural style and gardens, made it an urban landmark upon its inauguration in 1903. The villa was not merely an architectural masterpiece but also a symbol of social representation: ornamental gardens, greenhouses, and specialised service areas formed a unified whole, where the floral and decorative language of Art Nouveau reflected the modernity and international outlook of São Paulo's elite, a language that Penteado himself had discovered at the 1900 Paris Universal Exposition. This example opend the way for other notable residences; indeed, Vila Penteado became one of the models for new buildings in the Higienópolis neighbourhood, which was being developed specifically to meet the privileged needs of São Paulo high society[10].

Fig. 5.20 – Comparative view of the urban transformation of Vila Penteado (Higienópolis, São Paulo): on the left, the residence set within its original romantic garden; in the center, the FAU-Maranhão building in the 1940s, surrounded by the early stages of vertical development; on the right, a contemporary aerial view highlighting the district's densification and the urban pressure on Vila Penteado. (Sources: Sampaio and Maricato, 2002; Prado and Machado, 1976; Google Earth).

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[10] For further details: Naclério Homem Prado & Gomes Machado, *Exposição Vila Penteado*, 1976.

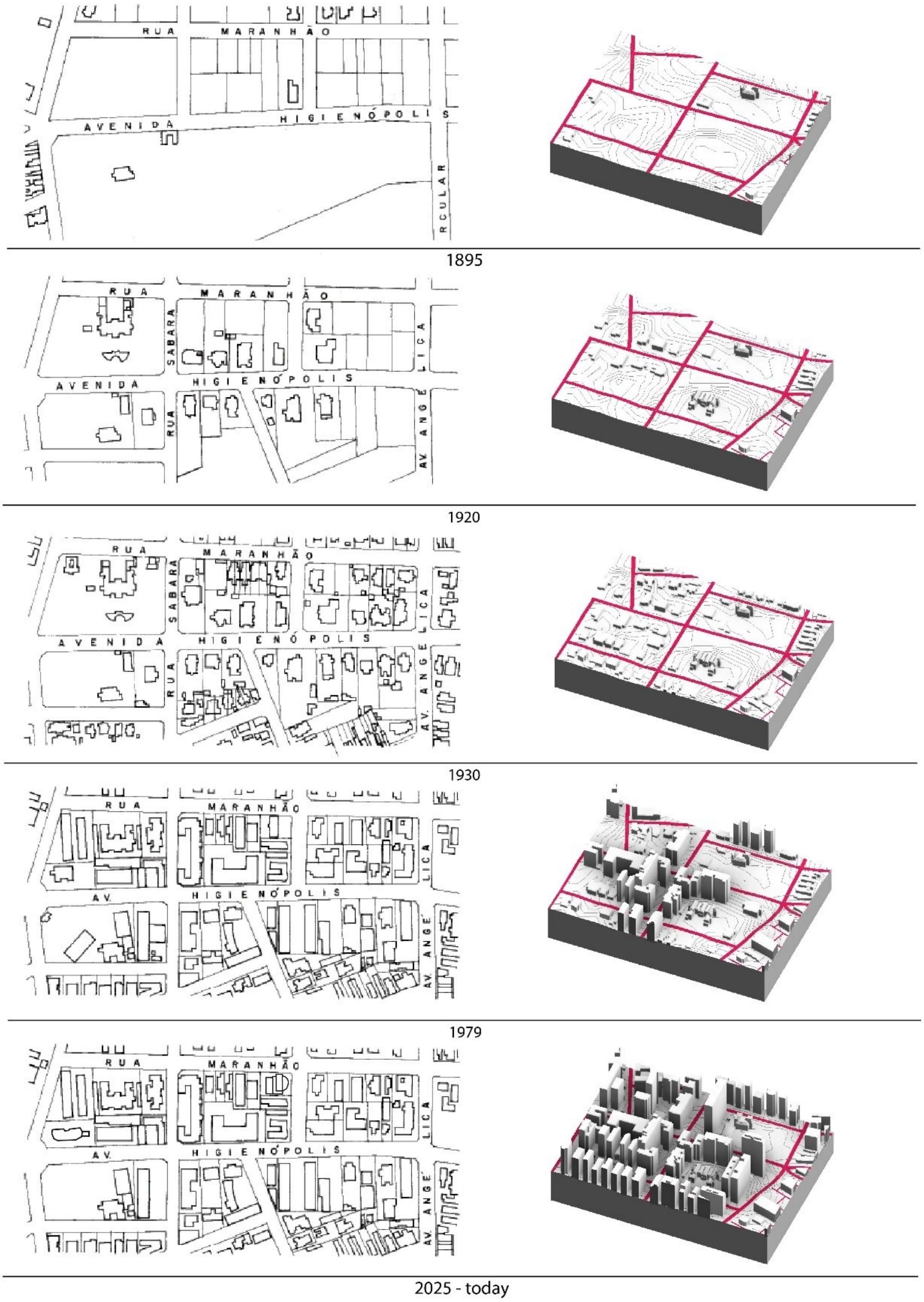

Fig. 5.21 – Evolution of land occupation in the Higienópolis area, including Vila Penteado, from 1895, the beginning of the subdivision into lots, to the present day. On the left, the planimetric drawing (Source: Sampaio and Maricato, 2002); on the right, the three-dimensional model illustrating the altimetric evolution phases.

The building was erected at the centre of its lot, facing Avenida Higienópolis, where its main entrance was located. Surrounded by a sumptuous garden and situated at the highest point of the block, it accentuated the elevation marking the beginning of the avenue, framing the vista of the boulevard. The complete transformation of the complex began when the family decided to donate the main building to the Faculdade de Arquitetura e Urbanismo da Universidade de São Paulo in the late 1940s, subdividing the rest of the estate, including the plots facing the avenue. The former rear façade then became the building's new front, opening onto Rua Maranhão, originally the service entrance of the villa, and the environmental quality of both the building and its open spaces was diminished due to the surrounding apartment buildings, which now hinder natural light and ventilation. Nevertheless, Vila Penteado remains a historical reference for the city's architecture, recognised by generations of architects and urban planners.

Fig. 5.22 – Zenithal view of Vila Penteado, captured with a drone during a flight in July 2025, showing the historic central garden and the high-density residential buildings surrounding the block. (Credits: Diogenes Miranda, Emilio Leocadio e Jonas Sossai: Equipe Foto Vídeo FAUUSP - Seção Técnica de Audiovisual, 2025).

Fig. 5.23 – Entrance from Rua Maranhão and historic garden of Vila Penteado, with a view toward the building's main façade (today).

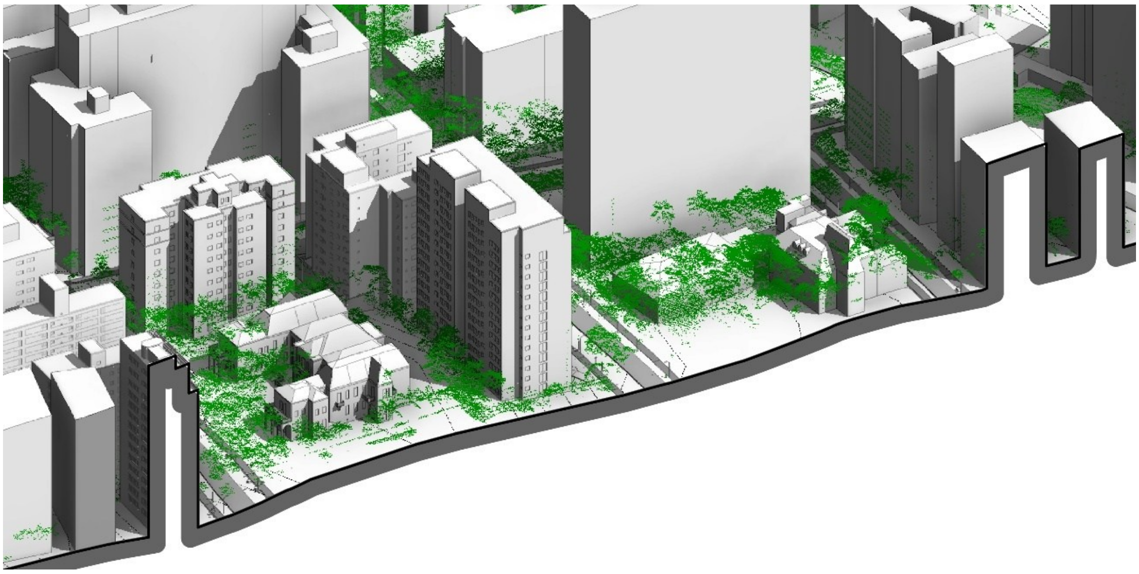

Fig. 5.24 – Axonometric section of the Higienópolis CIM model, showing the integration of the segmented vegetation point cloud and highlighting the Vila Penteado area and the relationship between the historic complex and the surrounding high-density urban fabric.

Fig. 5.25 – Verucchio, RN, Emilia-Romagna (Italy). (Source: Google Earth).

5.3 The Historic Town of Verucchio, Rimini, Italy

Another case study examined in this research is the small town of Verucchio, a minor settlement in the Province of Rimini, Italy, located between the sea and the hills, characterized by a complex historical stratification. Its periods of greatest prosperity date back to the Etruscan era and to the lordly age under the dominion of the Malatesta family.

5.3.1 *Selection of the Case Study*

The village of Verucchio was selected as a case study due to its dual significance. On the one hand, it is situated within a territorial context defined by a complex orographic relationship, which necessitates a specific reflection on the management of elevation differences in the development of the CIM model. On the other hand, it represents an exemplary instance of the numerous historic villages scattered throughout the Apennine area; therefore, it was considered appropriate to explore the potential for enhancing such urban centres through the implementation of the CIM as a tool for management and documentation, integrated within networks of municipal unions in a transitional framework. Moreover, Verucchio exhibits a dual stratification: historical and altimetric; dimensions of fundamental importance that were addressed during the research process, as they constitute the intrinsic peculiarities of the case study.

Fig. 5.26 – View of the town of Verucchio from the Rocca Malatestiana. (Source: Rossato, 2023)

5.3.2 *Historical context*

The archaeological campaigns carried out between 1893 and 1894, and later resumed in 2005, attest to the presence of a flourishing Etruscan civilization of the Villanovan phase, active on the site between the tenth and seventh centuries B.C. The numerous archaeological finds are now preserved in the Civic Archaeological Museum of Verucchio, where rich funerary assemblages from the nearby necropolis are on display (Von Eles, 1998). Due to its proximity to Rimini, the Etruscan society was soon influenced by the Roman one, and the town of Verucchio was gradually moved to the foot of the spur upon which the village still stands today. Later, also because of the barbarian invasions, the settlement returned to its original position on the top of the hill, where it developed into a true castrum and remained so until the advent of the Malatesta family, around 1114 A.D. (Mascanzoni, 2003). The village of Verucchio appears to have a double stratification, both historical and altimetric, factors of fundamental importance that we have considered during the research process, as they are intrinsic characteristics of the case study. Despite successive demolitions and reconstructions, the village still retains its medieval urban structure. The small town stands on two rocky peaks, on which once rose two separate fortifications, overlooking the ancient road that led from Rimini to Tuscany (Berardi et al., 1970). When Sigismondo Malatesta arrived in Verucchio, one of his first interventions concerned these fortifications, which were joined by a defensive wall, traces of which can still be seen on some of the houses. The Malatesta Fortress of Verucchio was enlarged by Sigismondo in the same year as the construction of the aforementioned defensive walls, in 1449 (Bernardi, 2004). The fortress is located on the towering summit of the rocky spur dominating the Marecchia Valley and extends over several levels, adapting to the orography of the terrain. During the same period, Sigismondo also strengthened and renewed the fortifications of Montefiore and Santarcangelo, but focused particularly on those of Verucchio (Berardi et al., 1970), owing to its strategic position. A polygonal bastion, known as Porta del Sasso or Porta di Sant'Andrea, provides access to the Rocca del Sasso (Fortress of the Stone), which is still well preserved thanks to successive restorations, the most important of which took place between 1959 and 1960 (Berardi et al., 1970). A symbol of Malatesta power, the fortress became an important strategic and defensive center thanks to its commanding view over the Adriatic Sea and the Apennines, standing almost three hundred meters above sea level. For centuries, it remained the main seat of Malatesta power along the coast and in the territory of the Marche (Larner, 1972). In 1462, a siege, ended through deception by Federico da Montefeltro, marked the fall of Malatesta domination over the fortress, after which Verucchio passed under papal rule. Architecturally, the Rocca also underwent changes, although the exact period is not known. Indeed, "some historians have attributed to Sigismondo Malatesta the construction of the two twin towers of SS. Trinità and S. Andrea, close to the city walls to the northwest; however, based on the current state of research, the study of the vents in the lower part of the towers and the comparison of construction techniques suggest that these two towers were leaning against each other at opposite corners in the period immediately following Sigismondo" (Giuccioli, 1996, p. 24). During the 1500s, the territory of Verucchio was governed by several important families: in 1500 it passed from the Montefeltro to Cesare Borgia, by concession of Alexander VI, and then came under Venetian rule three years later, before passing to the Holy See in 1509. Seven years later, Verucchio was granted as a fief to Giovanni Maria de' Medici, and finally passed to the Pio family of Carpi (Berardi et al., 1970). Later, under papal rule, Verucchio was designated a city for its economic importance (Giuccioli, 1996).

Fig. 5.27 – Historical hand-drawn map of Verucchio (Emilia-Romagna, Italy), depicting the urban structure of the historic hilltop village, its built fabric, and public spaces, likely dating around the eighteenth century.(Source: Archeological Museum of Verucchio)

Today, the Fortress of Verucchio remains one of the best-preserved Malatesta fortresses, with exceptional historical and cultural significance (Pasini, 2013). Verucchio has retained its character as a fortified historic centre, integrating its archaeological heritage with its medieval and Renaissance architectural legacy. At the same time, as in other towns located in the Apennine areas of Emilia-Romagna, the village has undergone processes of urban and landscape transformation that have involved both functional adaptations to residential and productive needs and renovation and expansion works between the nineteenth and twentieth centuries. In the second half of the twentieth century, these transformations culminated in preservation and enhancement initiatives aimed at reconciling the conservation of the town's historical identity with its integration into the surrounding hilly landscape.

Fig. 5.28 – Left: Aerial view of the Malatesta Fortress and the historic center of Verucchio (Credits: Guido Galvani); right: corresponding representation of the area in the CIM model.

Fig. 5.29 – Darsena Area in Ferrara, FE, Emilia-Romagna (Italy). (Source: Google Earth).

5.4 An Ongoing Urban Regeneration Context Case Study. The Darsena Area in Ferrara, Italy

Another case study in this research concerns an urban section of the Municipality of Ferrara, located in the Emilia-Romagna region of Italy. This area, situated along the Po di Volano River to the south of the city, was selected for its distinctive features, taking into consideration the various zones defined in the Municipal Strategic Plan (PSC). This section includes the Darsena of Ferrara, an area currently undergoing regeneration, where recreational, landscape, and cultural functions converge.

5.4.1 *Selection of the Case Study*

The selected case study focuses on an urban section of the Municipality of Ferrara, located in the Emilia-Romagna region of Italy. This area, situated along the Po di Volano river to the south of the city, was chosen for its unique characteristics. It intersects various zones as defined in the Municipal Strategic Plan (PSC): historical fabric, consolidated fabric, and to be redeveloped fabric. The urban section is distinguished by several key features: the river embankment; residential areas along Via Argine Ducale and Via del Mulinetto; the historic center along Via Piangipane and Via Ripagrande, which houses the Italian National Museum of Judaism and the Shoah (MEIS); and a section of the historic city walls. Additionally, the area between the walls and the Burana Canal is currently undergoing urban redevelopment, aimed at enhancing its connection to the historic center.

5.4.2 *Historical context*

In Ferrara, the river has always played a fundamental role in the city’s history, serving as a key element since its foundation and throughout the centuries of economic prosperity, from the Este period to the subsequent papal and French dominations (Bassi, 1981). In the Late Antiquity and Early Middle Ages, the main course of the River Po flowed near the present-day Via Carlo Mayr, considerably further north than its current channel. The river, with its considerable water volume, formed two islands along its course (the Island of Belvedere and the Island of Sant’Antonio), before bifurcating southward (Po di Primaro) and eastward (Po di Volano) (Bocchi, 1987).

Within this context, in the VII century, the first urban nucleus was established, which would later give rise to the city of Ferrara. Between the IX and X centuries, the original settlement began expanding westward, becoming a strategic military outpost that, thanks to its advantageous position near the Po River, gradually shifted its vocation towards a growing commercial hub (Cesari et al., 1976; Cesari, 1985). By the end of the tenth century, Ferrara was taking shape as a port system structured between two poles and organized along road networks parallel to the river. However, with the relocation of the cathedral in the course of the twelfth century, Ferrara entered a new phase of urban evolution that led it to lose its parafluvial character, favouring instead an expansion north of the original urban core (Cervellati, 1985). The diversion of the Po's course to the north through the "rotta di Ficarolo" in 1152 not only altered the waterborne trade system that had developed over time but also transformed the geomorphology of the entire area. This event caused a narrowing of the riverbed near Ferrara and the consequent shifting of the ancient river channel away from the city, toward the south.

Fig. 5.30 – Left: Ferrara, sixteenth-century view. Right: Relationship between the sedimentary substrate, surface geometry, regional routes, and the evolutionary phases of urban growth. (Source: Dalla Negra and Ippoliti, 2014)

Ferrara: From the Duchy to Papacy Governemnt

Ferrara, the capital of the Este duchy, was the seat of one of the most illustrious courts in Italy. The city's position along a major river, located at a natural geographic junction between the Adriatic Sea and the Po Valley, and between Romagna and the northern regions, endowed it with considerable strategic and commercial significance, making it the object of continual disputes between the Empire and the Papacy (Di Francesco & Borella, 1988). For over a century, Este hegemony was unsettled by internal conflicts and tensions with the Papal States. However, by the late fourteenth century, the construction of the castle commissioned by Nicolò II (1385) and the establishment of the university seat granted by Pope Boniface IX to Alberto V (1391) attested to a lasting consolidation that brought vitality and renown to the city of Ferrara.

As the river gradually shifted away from the urban center, extensive tracts of land were left available and successively occupied by new urban settlements known as "addizioni"[11]. Among these were the first addition of 1386, designed by the military architect Bartolino da Novara; the

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[11] In english: "additions".

second, commissioned in 1451 by Marquis Borso; and the renowned “Addizione Erculea”, conceived by the court architect Biagio Rossetti, which marked a decisive turning point in the architectural and urban development of Ferrara (Zevi, 1971). Through this project, Ercole I d’Este (1471–1505) aimed to create a city that was large, well-defended, and densely populated. Subsequently, Alfonso I, Ercole II, and Alfonso II ruled the duchy with less success, ultimately losing it in 1598 due to the absence of a legitimate heir. This event led to the devolution of Ferrara to the Papal States at the end of the XVI century (Farinelli & Scafuri, 1991).

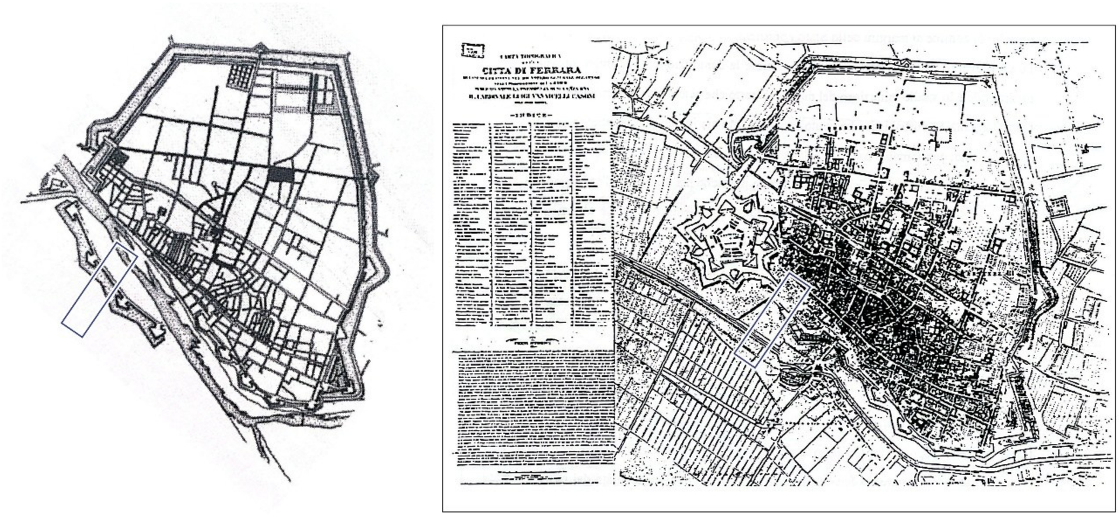

Fig. 5.31 – Left: Plan of Ferrara with the “Addizione Erculea” (Source: Dalla Negra and Ippoliti, 2014). Right: Plan of the city of Ferrara: Topographic Map of the Pontifical Cadastre of 1850. (Source: Zironi, 1997).

The Fortress and its Partial Demolition

The construction plan of the Fortress (1598) caused a profound rupture in the urban geography, becoming the ultimate symbol of the oppressive and despotic logic of the Papal government, which downgraded Ferrara to a provincial town and border stronghold at the margins of the Papal States. It represented a significant act of urban planning, as it required the demolition of an entire medieval quarter and a meticulous study of the new spatial conditions that were being created. This urban operation held both ideological and strategic significance and was, from the outset, strongly opposed by the local Ferrarese community. When the political circumstances changed in 1859, with Ferrara’s annexation to the Kingdom of Italy, the Fortress was almost entirely demolished, and the remaining sections were incorporated into the system of urban bastions. The Fortress had revealed its strategic limitations, and the defensive structure had by then lost all military relevance. The partial demolition of the Fortress freed a large urban area, providing an opportunity for city-scale interventions, while still remaining within the perimeter of the city walls.

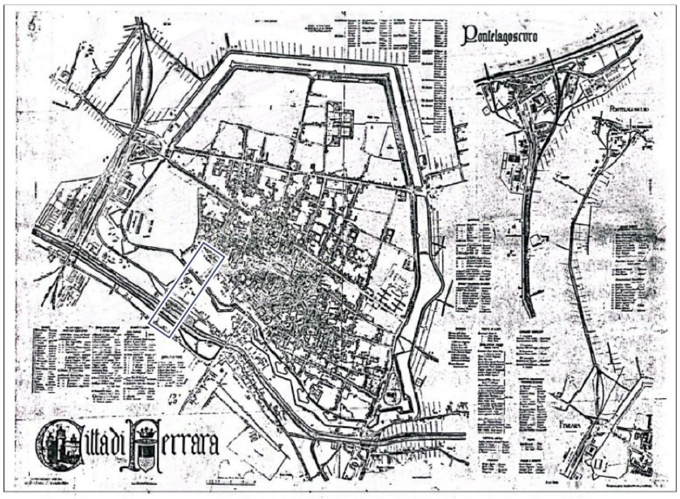

Fig. 5.32 – Plan of the city of Ferrara by Prof. Enrico Scanavini (1912): disappearance of the Fortress and beginning of the city's expansion beyond the walls. (Source: Zironi, 1997).

Origins and Development of the Industrial Area around the Darsena

The city was rooted in a highly fertile agricultural territory, and its planning process was structured around the creation of infrastructures: the railway (1862), Viale Cavour lined with emerging bourgeois villas, the new road axes that extended beyond the former city walls (partly demolished), the zones designated for industrial settlements, and the construction of navigable canals. The railway station became a pivotal element of the new urban framework, and in its proximity arose both small and large industrial buildings, warehouses, and production sheds. The spatial organization of Ferrara, however, was particularly significant for its productive sector, as the city became a service centre for the entire area of the major "bonifiche ferraresi"[12] (Lanzoni & Venturini, 1984). As can be observed in late XIX century maps, this period marked the beginning of the industrial occupation of the western part of the city, alongside the strengthening of the north–south axis towards Padua and Bologna, which remained the dominant infrastructural direction shaping the organization of both the city and its surrounding territory.

Between Italian unification and the Fascist period, the population of Ferrara grew considerably, partly due to immigration from other Italian regions, encouraged by the employment opportunities generated by the reclamation works carried out between 1880 and 1910. During these years, the Genio Civile undertook the expansion of the Darsena along the Volano River to enhance its traffic capacity and equip it with an efficient infrastructural network.

In 1907, the Municipal Administration strengthened the staff of the Technical Office, and in 1911 engineer Ciro Contini became Head of the Technical Office for the City Plan, tasked with drafting

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[12] In english: reclamation works.

the "Piano Regolatore e d'Ampliamento della città di Ferrara e sobborghi" ("Master Plan and Expansion of the City of Ferrara and Its Suburbs"). The plan's definition followed a complex process, culminating in its final adoption in 1926. Although never formally approved, it proved decisive for the urban structure of Ferrara until the post-war period. The Contini Plan represented Ferrara's first modern urban planning tool, aimed at a comprehensive reorganization of the city. It was articulated through general guiding principles and implemented via a series of detailed interventions. These actions reveal Contini's urban culture as anything but provincial, emphasizing goals such as preserving the city walls and promoting expansion within the existing perimeter, rather than through indiscriminate growth beyond the historic centre. After World War II, Ferrara faced a situation in which 40% of its buildings were destroyed or uninhabitable. The industrial area had suffered extensive damage, particularly the zones closest to the Darsena and the historic centre, which subsequently experienced gradual decay leading to their eventual abandonment.

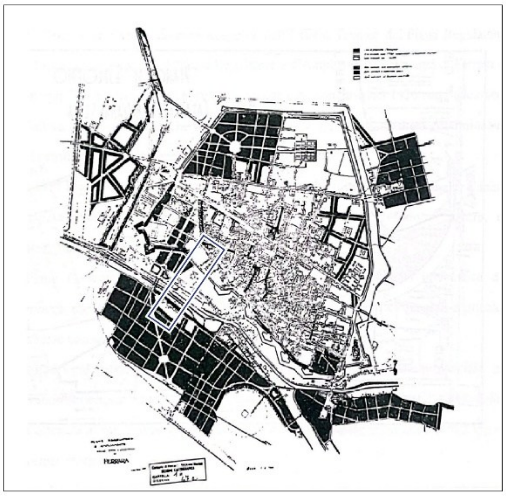

Fig. 5.33 – Plan of the "Piano Regolatore e d'Ampliamento della città di Ferrara e sobborghi" by Ciro Contini, 1926. (Source: Zironi, 1997).

The Post-War Period and Urban Masterplans

In the aftermath of the war, given the extensive damage suffered by the city, Ferrara faced the urgent need to equip itself with a new and efficient urban planning instrument. Preparatory studies for the Piano Regolatore Generale[13] (PRG) began in 1945; the plan was adopted in 1957 and subsequently approved in 1960. The drafting of the Masterplan was carried out simultaneously with that of the Reconstruction Plan. In 1950, the key planning guidelines were defined: Ferrara's PRG was conceived with the idea of the city as an urban centre endowed with considerable

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[13] Literary translation: General Master Plan.

potential for development, particularly in the industrial and commercial sectors, and as an intermediary between the Adriatic Sea and the Po Valley hinterland. The plan sought to encourage industrial growth while preserving the city's pre-existing urban form. At that time, the industrial area was still regarded as an integral part of the city, within a consciously planned framework. The Master Plan therefore aimed to guide future urban expansion around the historic walls, utilizing the available areas contiguous with the ancient nucleus. Its objective was to provide general guidelines capable of directing the city's long-term development.

Around 1970, the Municipality of Ferrara requested ministerial authorization to draft an amendment to the PRG, in order to comply with new legislative provisions and to address the development of urban services, university facilities, and the reorganization of the road and traffic system. In 1982, the Municipality submitted a request for a Second General Amendment to the PRG, which was subsequently approved by the Regional Council in the same year. This process led to the preliminary design of Ferrara's new Master Plan, presented in 1989 and formally adopted in 1993. Within this framework, the city's former industrial zone, by then largely decommissioned and abandoned, was identified as a major opportunity for urban regeneration, through the reconversion and reuse of disused areas.

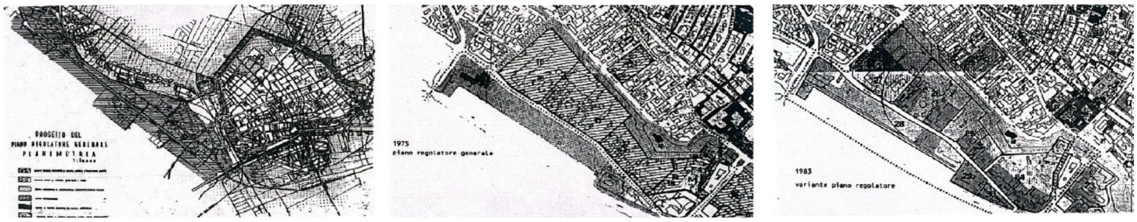

Fig. 5.34 – From left to right: Piano Regolatore Generale, 1957; Piano Regolatore Generale, 1975; Piano Regolatore Generale, 1983-85. (Source: comune.ferrara.it)

The Darsena: the San Paolo Section

The area examined in this thesis encompasses the urban section once occupied by the former Papal Fortress. In 1886, during the works for the regulation of the Volano Canal, the ancient bed of the Po River of Ferrara, the nowdays Darsena was constructed along the Burana Canal. In the years immediately following its construction, the Darsena basin served only local traffic; it became a more efficient transport route, as well as a genuine inland navigation channel, only in the 1920s, with the opening of the Boicelli Canal and the Pontelagoscuro double lock. At the same time, the Darsena basin was expanded, and in the 1930s, anticipating urban growth towards the south-west, the stretch of city walls adjacent to the Fortress was demolished. Today, this section is historically the least recognizable part of the entire city wall system. The 1985 Masterplan

(PRG/85) classified the entire "sottomura"[14] area as a system of redevelopment zones intended to contribute to the restoration of both the walls and the Volano Canal, through the introduction of urban-territorial facilities and public green spaces. Indeed, as the river's infrastructural role gradually declined, due to the increasing predominance of land transport, productive activities were slowly relocated to other parts of the city. The Darsena of San Paolo was redesigned and redeveloped by the Municipality in the 1980s as a "fluvial tourist port", featuring mooring spaces, a Nautical Club, various sports facilities, and a maintenance shipyard.

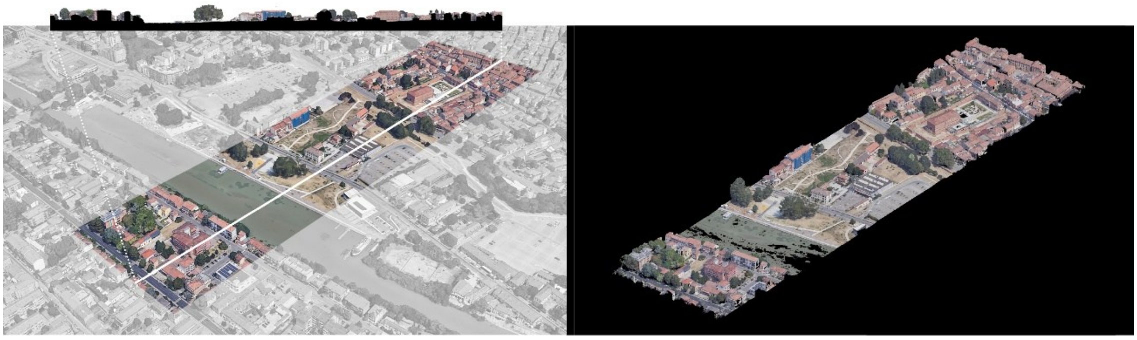

Fig. 5.35 – Left: Identification of the case study area and urban section. Right: Point cloud derived from photogrammetric survey simulation. (Source: Planu and Giau, 2024).

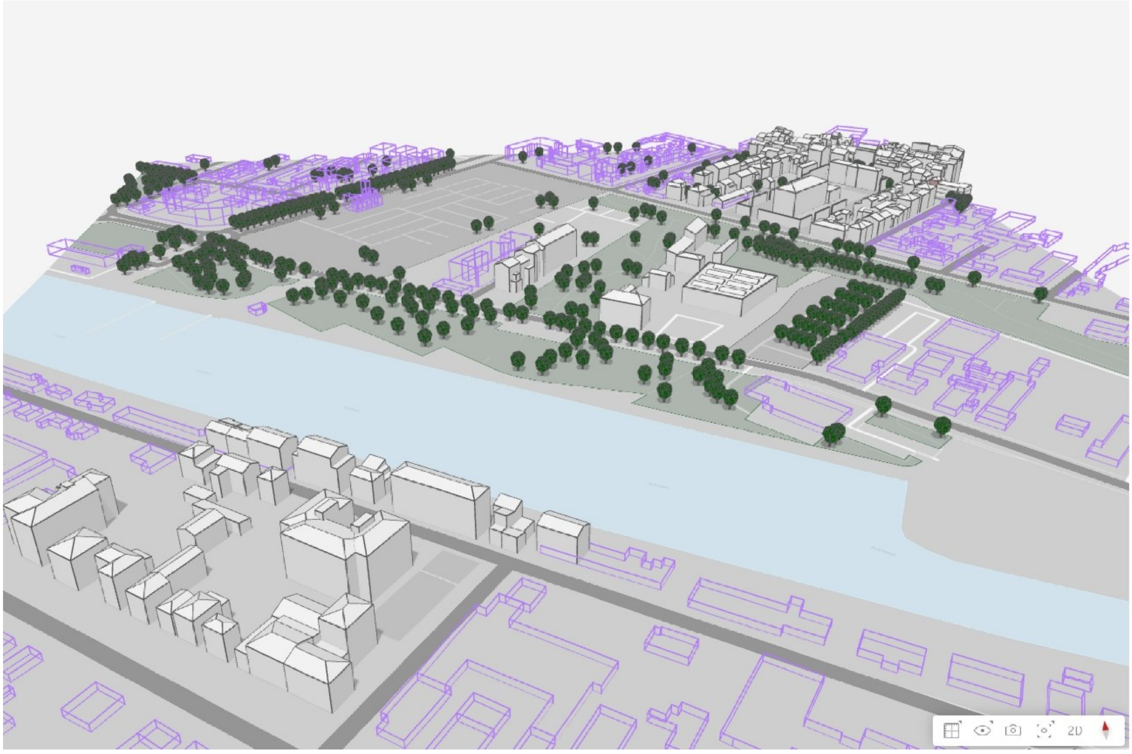

Fig. 5.36 – View of the model of the Darsena of Ferrara into a unified digital representation of the urban context, made in Autodesk Forma.

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[14] Area below the city walls.

5.4.3 *The Darsena of Ferrara Nowdays*

In 2020, the Darsena area of Ferrara appeared as a degraded and underused urban space. Under the new Municipal Strategic Plan (PSC), the area, falling within the Historical Centre and specifically in the sub-area known as “Darsena”, was designated for a comprehensive regeneration initiative. The plan includes the completion of the restoration of the city walls and moat, the creation of openings to enhance their visibility, the rationalization of Via Darsena and the existing public parking system, and the integration of the Darsena and its leisure facilities into the wider urban fabric. Furthermore, it envisages the establishment of residential, administrative, hospitality, commercial, and recreational functions. In this context, the redevelopment of the Darsena Park in Ferrara, designed by the architectural firm INOUT architettura (Mario Benedetto Assisi and Valentina Milani), represents a significant urban regeneration project aimed at restoring the river’s central role in the life of the city, reconnecting the urban core with the riverbank. The project, winner of the competition promoted by the Municipality of Ferrara in 2019, was financed within the framework of the national program for the regeneration of urban peripheries[15].

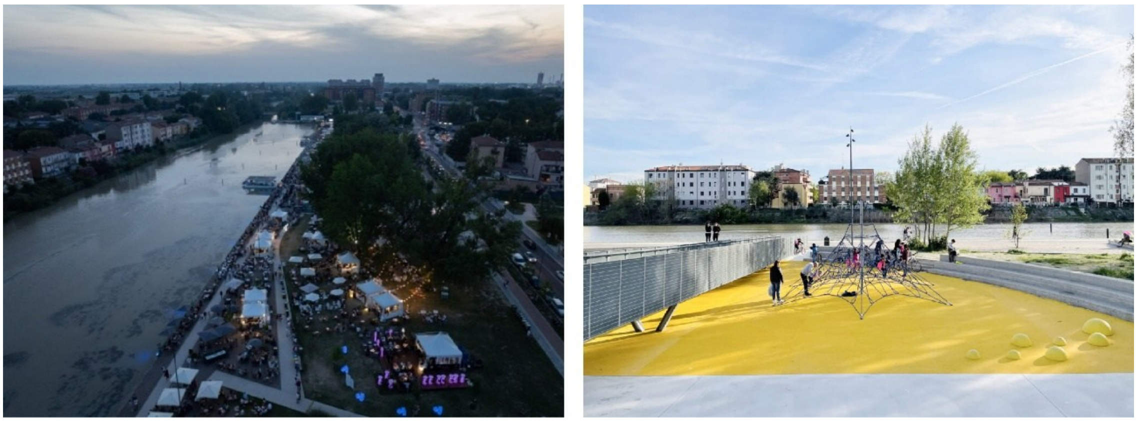

Fig. 5.37 – Left: evening event and temporary activities along the riverside, illustrating the area’s function as a public space for cultural and social gatherings (Credits: Pierluigi Benini). Right: the new linear park, redesigned as part of the recent urban regeneration project (Source: inoutarchitettura.com).

Today, the Darsena of Ferrara stands as a regenerated public space where recreational, landscape, and cultural functions converge. The redevelopment, has redefined the area with a dense network of urban relationships. Functionally, the Darsena now serves as a venue for cultural events and community activities. It is conceived as an urban river park, a cultural stage and collective space that seeks to reintegrate the water’s edge into the daily life of the city. Although still in a phase of full consolidation, the project stands as a contemporary model of urban regeneration, attentive to the balance between naturalness, livability, and social participation.

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[15] For further details see at: https://inoutarchitettura.com/it/parcodelladarsena/

Chapter 6
ASSESMENT OF THE INDICATORS THROUGH THE CASE STUDIES: TESTING THE CIM-BASED FRAMEWORK

6.1 Towards Knowledge and Representation

The following section describes the process followed in the research, with the objective of verifying the possibility of graphically representing, within a single integrated system, the set of selected indicators, translating analytical data into a dynamic visualization connected to the CIM model. The proposed indicators are as follows: Urban Pressure, Hybridization, Accessibility, Traffic Congestion, Comfort, Meaning, Perception, Transformation, Conservation, Energy Behaviour, Structural Behaviour, and Post-Disaster Damage Behaviour. Each indicator was assigned a score ranging from 1 to 5 in order to construct a coherent profile of the urban context under investigation. A low score indicates a negative condition, with the exception of Urban Pressure and Traffic Congestion, for which a high value, although consistent in terms of interpretation and value attribution, actually corresponds to a negative condition. The indicators thus serve as the necessary tools for creating a technically defined and unique code for the reading and interpretation of the different components of the territorial and environmental system under study (Garzino et al., 2021). It is important to underline that this proposed articulation makes no claim to completeness. The knowledge factor represents the degree of depth and completeness of the available informational data: it may gradually increase through the contribution of professionals and specialists with specific expertise in the parameters underlying each indicator. At this stage, the assessment of the indicators was conducted through observations and simulations, with the aim of testing the proposed process via the CIM model. At times, the output of accessibility tools may be purely numerical and listed in tables, matrices, or data sheets, without providing any type of visual result; in other cases, it requires accessibility tools and generates a two or three dimensional visual product (Garzino et al., 2021).

To achieve this level of data representation, two aspects were taken into consideration: first, the spatial definition level of the indicator, which must be adequate and appropriate to the scale of representation at which the various analyses are developed; and second, the variation gradient of the indicator, which must allow for the correct visualization of the magnitude of variations.

The following section represents a fundamental step in constructing a system of cross-cutting references. The definition of these indicators is intended to capture the whole, describing the urban scene through the construction of a spatio-temporal framework in which the landscape is mechanically encompassed, yet where the observer is typically not considered. The aim is to provide, through these investigative criteria, a framework capable of supporting the monitoring and simulation of decisions related to urban regeneration (Balzani, 1995). The abacus thus becomes a tool for consultation and orientation, aimed at supporting the documentation and management of the territorial and urban context, responding in a targeted manner to specific needs through its application in a defined location. From this perspective, the graphic representation constitutes the first necessary step in establishing the relationship between the indicators and the analyzed urban context. The organization of potentially disaggregated data into an abacus of codified actions provides a way to systematize the conducted surveys, making their mutual interactions assessable and thereby offering an opportunity for further investigation and understanding.

The chapter is organized as follows: for each case study, a summary of the case is first presented. Subsequently, each case study is assigned a value for the selected indicator, which is briefly described in general terms, followed by a specific description of how the indicator applies to the case study. Finally, the assigned values are summarized and visually represented in a chart included in the concluding paragraph of the chapter.

6.2 Higienópolis, São Paulo, Brazil: Indicators Assessment

Higienópolis is characterized by a high residential density, the result of a transformation process that has produced a compact and verticalized urban morphology. Despite these changes, the area still preserves a distinctive identity, defined by the coexistence of tree-lined streets, isolated historic residences, and an urban image that evokes, in the collective memory, the aristocratic prestige of its past. For the purposes of this research, the context of Higienópolis was selected as a case study to simulate temporal accelerators and to analyze the role of the CIM model. This approach contributes to the definition of a geometric–informative methodology that employs the model as a historical and documentary database to support intervention proposals.

6.2.1 *Indicators Assesment*

Urban Pressure | Score attribution: 5

The Urban Pressure indicator measures the impact generated by the expansion and density of the urban fabric. It also includes factors of spatial constraint, which produce a set of introspective relationships between building façades and smaller-scale structures in adjacent areas. These factors also give rise to specific conditions related to shading and microclimatic constraints.

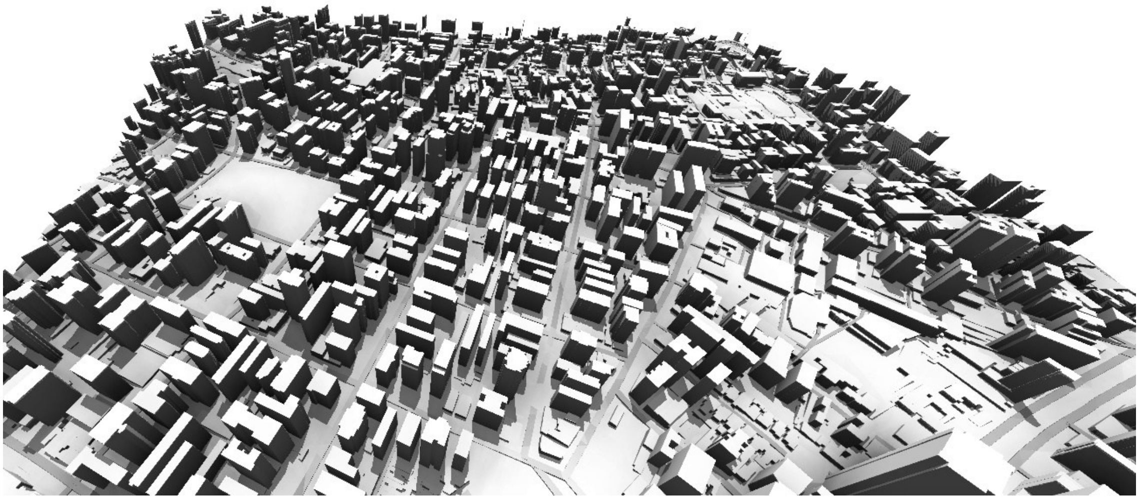

Fig. 6.1 - View of the Higienópolis CIM model.

In Higienópolis, unprecedented transformations have taken place, driven by socioeconomic growth. The district was selected for its rapid metabolism, which has profoundly reshaped its urban space from the late XIX century to the present day. Within this context, the area of Vila Penteado was chosen to investigate the Urban Pressure indicator in greater depth.

With the aim of simulating the development and use of City Information Modeling (CIM) systems across historical successions, Higienópolis, characterized by a dynamic and rapidly evolving urban metabolism, proved to be a suitable case for performing such analyses and data visualizations over a temporal series. Based on historical documentation, including archival maps and scientific publications[1], a specific CIM model was developed in Autodesk Revit, focusing on the Vila Penteado area. Within this model, a dedicated view was created for each historical phase. The selected timeframes, deemed representative of Higienópolis's urban development, are: 1895, 1920, 1930, 1979, and today. This approach allows for coherent simulation of the neighborhood's transformations while also testing how the CIM model can support future urban transitions that will shape cities and territories in the coming decades. The models corresponding to the different

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[1] For further details see at: 5.2 Higienópolis as a Case Study of Urban Growth and Morphological Transformation in São Paulo, p.128

historical phases were exported in the *Industry Foundation Classes (IFC)* open format and subsequently uploaded to *Autodesk Forma*[2]. During the analysis of the state of the art and the definition of workflows, Autodesk Forma was identified as a valuable tool for conducting intuitive and comprehensive assessments of environmental impacts, aimed at evaluating both habitability and sustainability. For the analysis of the factors that, once recomposed, contribute to interpreting the Urban Pressure indicator, the following integrated analytical tools were employed: Sunlight Hours and Daylight Potential Analysis (EnergyPlus Weather Data), Wind Analysis (Global Wind Atlas 3.0), and Microclimate Analysis (Copernicus ERA5)[3]. Having developed models representing different historical periods, it was possible, and indeed particularly significant, to replicate the same analyses across all models, thereby simulating a phase-based historical process. This type of simulation was feasible in São Paulo thanks to the city's rapid urban metabolism over the past century, which provides a valuable framework for understanding how the CIM models developed in this research may evolve in the coming years, offering potential methodological and operational solutions of this kind. For the analysis of solar exposure and shadowing, 21 March (the equinox) was selected as the representative date. Commonly used in urban-scale analyses, this date provides an "average" representation of annual solar radiation and is thus employed as a standard reference.

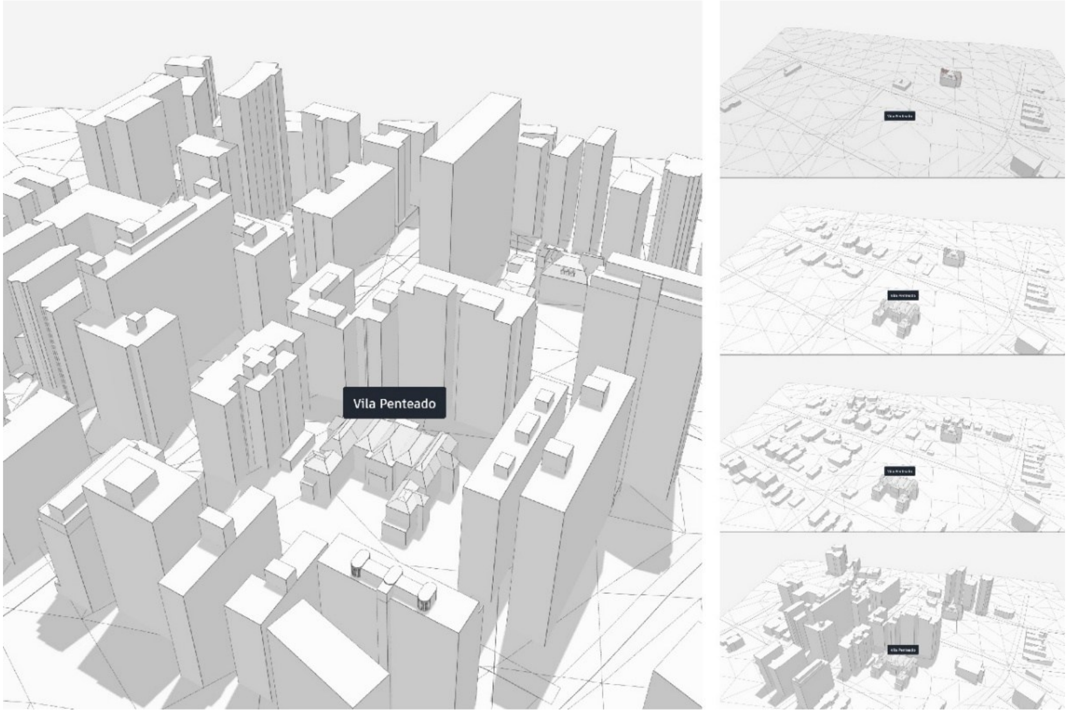

Fig. 6.2 – Shadow study for the Vila Penteado area (center) in Higienópolis, conducted through the CIM model over the years.

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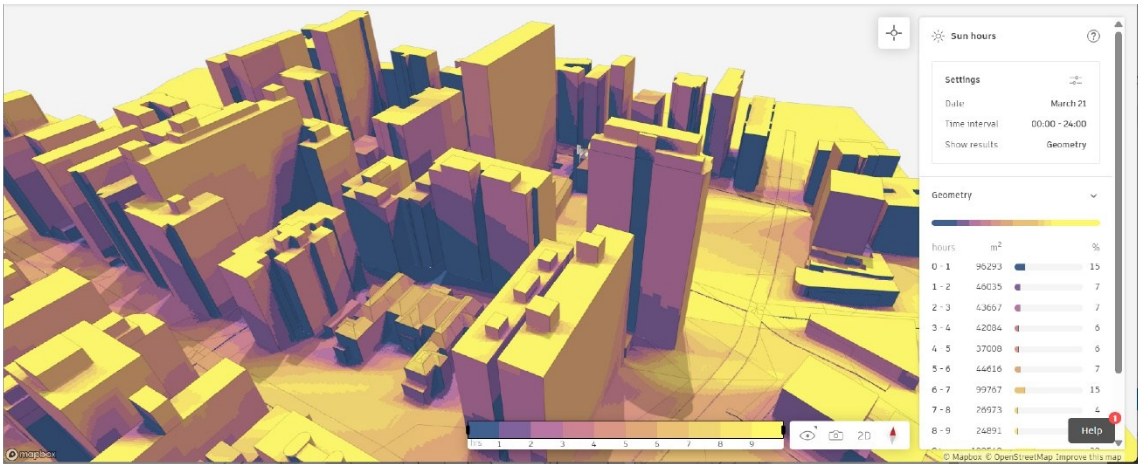
[2] Thanks to the Education License, the software could be used to its full potential at no cost
[3] The data sources used by the software to perform the analyses are indicated in parentheses

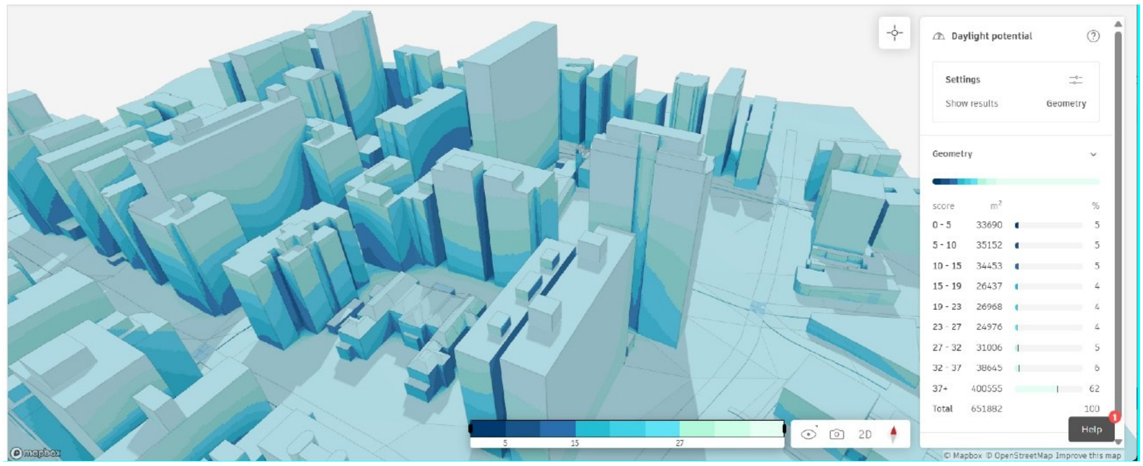
The Daylight Potential Analysis measures the amount of natural light reaching façades from the sky, identifying areas where daylight access is suboptimal. The Overcast Sky Model, which simulates a typically overcast day in September, is commonly employed in daylight simulation studies.



Settings
Date: March 21
Time interval: 00:00 - 24:00
Show results: Geometry

hours	m²	%
0 - 1	96293	15
1 - 2	46035	7
2 - 3	43667	7
3 - 4	42084	6
4 - 5	37008	6
5 - 6	44616	7
6 - 7	99767	15
7 - 8	26973	4
8 - 9	24891	4

Fig. 6.3 – Analysis of sun exposure within the CIM model.



Settings
Show results: Geometry

score	m²	%
0 - 5	33690	5
5 - 10	35152	5
10 - 15	34453	5
15 - 19	26437	4
19 - 23	26968	4
23 - 27	24976	4
27 - 32	31006	5
32 - 37	38645	6
37+	400555	62
Total	651882	100

Fig. 6.4 – Daylight potential analysis within the CIM model.

Wind conditions were analyzed to assess the impacts produced by the construction of high-rise buildings in the Vila Penteado area. The prevailing wind from the southeast (135°), with a frequency of 26%, was used as the reference for the microclimatic analysis, as it represents the principal direction of natural ventilation for the site.

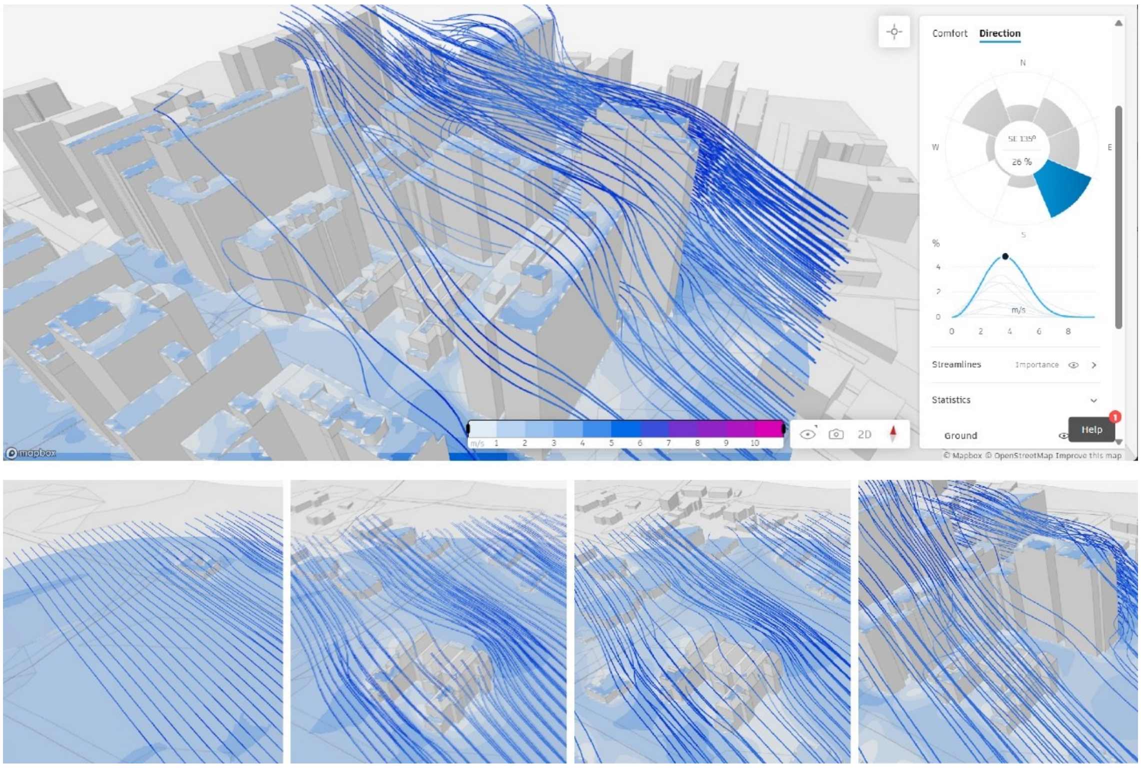


Fig. 6.5 – Wind analysis within the CIM model over the years, throughout the transformation process of Higienópolis.

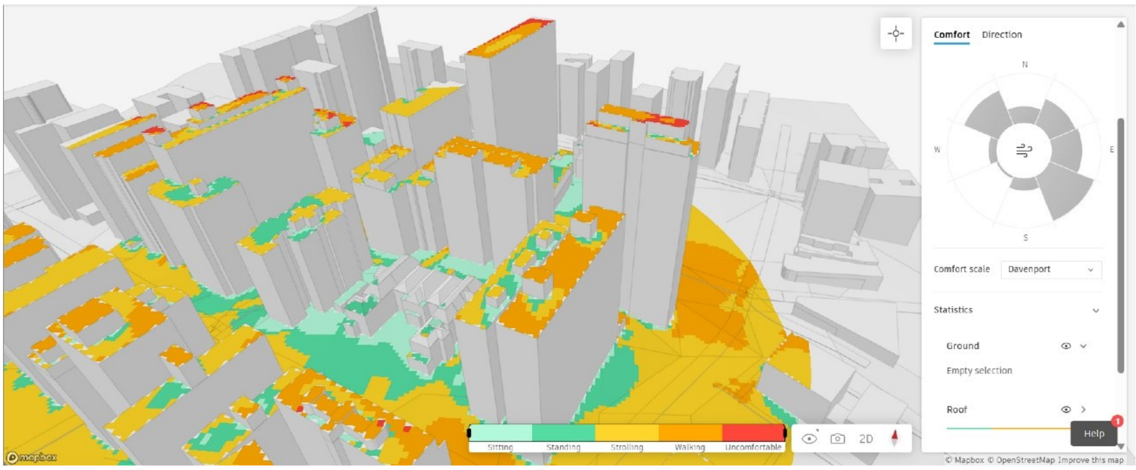


Fig. 6.6 – Wind comfort analysis within the CIM model.

In the analyzed urban context, urban pressure manifests through a high volumetric concentration and an extremely dense building fabric, generating a complex and interdependent spatial system. Such configuration intensifies the spatial constraints among façades and smaller-scale structures, resulting in specific microclimatic conditions related to shading, reduced ventilation, and limited visual and environmental permeability of the built tissue.

Hybridization | Score attribution: 4

The Hybridization indicator expresses the degree of integration among different functions, forms, and uses within the urban space, representing the city's ability to adapt to contemporary transformations while maintaining coherence and quality. It reflects the dynamic and composite nature of the urban context, understood as a continuously evolving social product in which diverse elements interact, generating new spatial and relational configurations. Monitoring this indicator makes it possible to interpret the complexity and sustainability of urban transformation processes, contributing to an understanding of the ways in which the city evolves and regenerates itself.

In the Higienópolis neighborhood of São Paulo, a high level of urban hybridization can be observed, understood as the capacity of the context to integrate diverse forms, functions, and uses while preserving spatial coherence and quality. The coexistence of buildings from different periods and architectural languages, the residential density combined with a rich supply of cultural, educational, and commercial services, as well as the variety of public space uses, together delineate a complex and dynamic urban fabric. This configuration reflects the evolutionary nature of the contemporary city, where interactions among heterogeneous elements generate new spatial and social configurations. The application of the hybridization indicator to this context yields a medium-to-high value, indicating the neighborhood's strong adaptive capacity to urban transformation processes, while also highlighting certain criticalities linked to the gradual socioeconomic homogenization of the area.

Accessibility | Score attribution: 4

The Accessibility indicator assesses the morphological conditions and usage patterns of the urban space, taking into account dimensional factors, safety, and the expenditure of psycho-physical energy. It assumes a dual role: on the one hand, it represents a condition for social inclusion, measuring the autonomous and safe usability of the urban environment, including for people with motor or sensory limitations; on the other hand, it relates to the temporal dimension of mobility, referring to the concept of urban proximity. This indicator aims to provide information for evaluating the degree of self-sufficiency of a neighbourhood, contributing to the development of sustainable and liveable urban models. Its relational nature highlights how the malfunction of a single element can compromise the overall effectiveness of the urban system.

In the context of Higienópolis, the Accessibility indicator reveals a generally favourable condition, where the urban structure and the regular street network facilitate pedestrian movement and connections with the main urban axes. The widespread presence of proximity services (cultural, educational, and commercial), together with the proximity of public transport networks (metro and bus), helps reinforce the temporal dimension of accessibility, also towards other metropolitan areas. However, the altimetric conformation of the neighbourhood represents a critical issue for the usability of soft mobility. There is also notable attention to the continuity of pedestrian routes, through ramps, crossings, and systems designed for people with reduced sensory abilities, which enhance accessibility to the neighbourhood in terms of social inclusiveness.

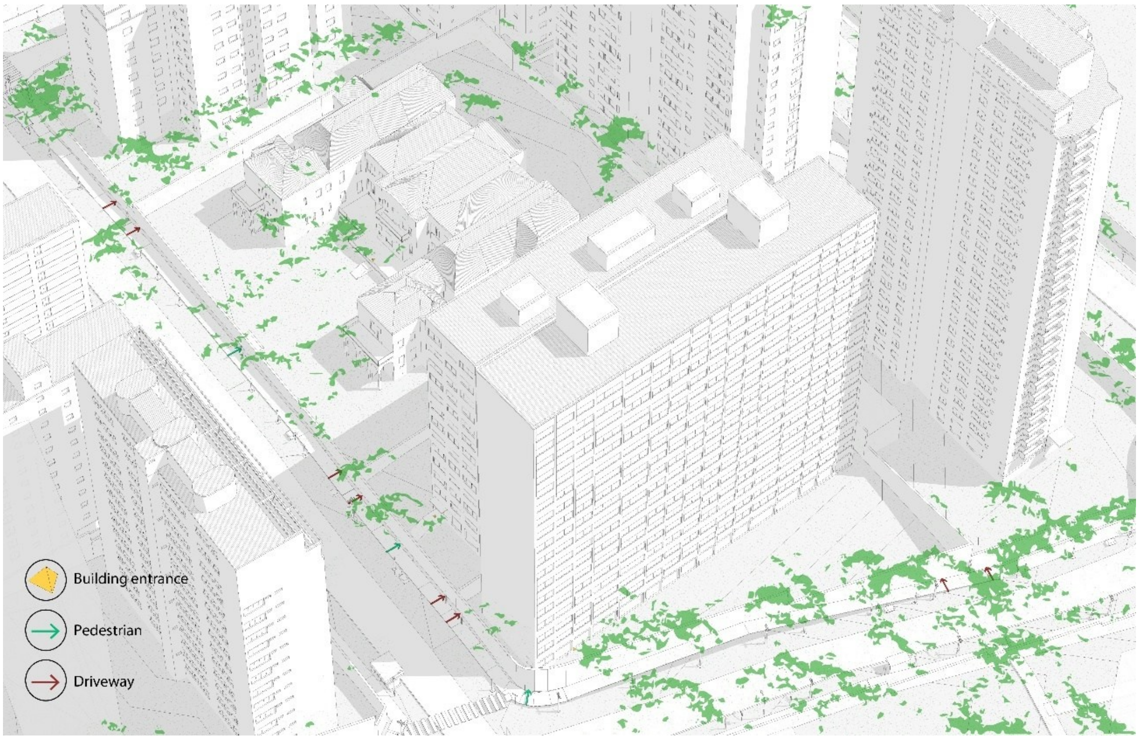


Fig. 6.7 – CIM model visualization of the Vila Penteado area (Higienópolis, São Paulo), showing the main building entrances, pedestrian pathways, and driveways.

Traffic Congestion | Score attribution: 3

The measurement of the Traffic Congestion indicator makes it possible to correlate the pressure exerted on the road network with the resulting acoustic and environmental effects, as it represents one of the main critical issues in urban mobility systems. It negatively affects both travel times and the overall efficiency of transport flows. Moreover, it influences the general sensory quality of the urban environment, as it constitutes a source of external noise that impacts the perception of comfort and the dynamics of social interaction.

The Traffic Congestion indicator reveals significant pressure on the road network of Higienópolis, particularly along the main axes of Avenida Angélica and Avenida Higienópolis. This is an exclusive district of São Paulo, traditionally characterized by the presence of high-quality schools, which generates a dual mobility dynamic: on the one hand, the daily influx of non-resident populations with high economic means, who predominantly use private cars to accompany their children; on the other, the residents themselves, who tend to favor private transportation over public transit. Nevertheless, in terms of noise and air quality, no major criticalities emerge. The abundant presence of vegetation and green spaces contributes to mitigating the acoustic and environmental effects generated by congestion, filtering part of the pollution and enhancing the overall sensory quality of the neighborhood.

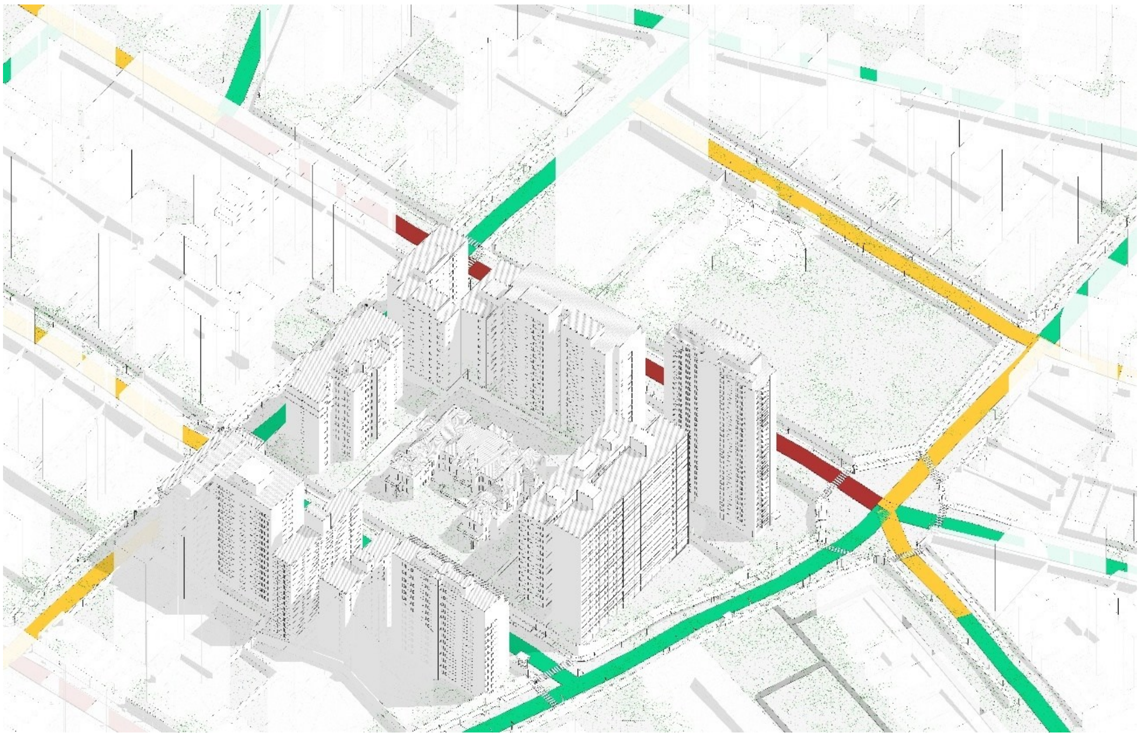


Fig. 6.8 – Simulation-based analysis of traffic congestion within the CIM model.

Comfort | Score attribution: 5

The measurement of the Comfort indicator represents well-being in relation to the quality of living, taking into account the main requirements of safety, wayfinding, urban diversity, and the availability of green areas, all essential elements for the proper functioning of the various types of urban activities: necessary, voluntary, and social.

In Higienópolis, the comfort indicator reveals generally favorable conditions, attributable to the spatial and environmental quality of the neighborhood, which has been recognized since its foundation by São Paulo’s upper class. Despite its proximity to the city center, the perceived sense of safety remains high, contributing to an overall feeling of well-being. Moreover, the widespread presence of green spaces and the abundant tree canopy create a healthy environment consistent with contemporary standards of residential quality. The clarity of the urban morphology and the legibility of the street network facilitate orientation and wayfinding, supporting everyday usability of public spaces. Overall, the urban comfort of Higienópolis emerges as an integrated expression of liveability and vitality, where the physical and perceptual quality of the built environment interacts with social dynamics, contributing to the overall comfort of urban life.

Meaning | Score attribution: 5

The Meaning indicator aims to measure the emotional and affective dimension that the urban scene causes in citizens. In this way, it seeks to highlight the affective value of places, spaces with which citizens identify, and which they are therefore encouraged to care and protect.

In the case of Higienópolis, the affection indicator reveals a deep relationship between the resident community and the neighborhood, grounded in the symbolic role that this urban area has assumed throughout the development of São Paulo. Higienópolis represents an environment where the urban image is clearly organized and distinctly legible, enabling a strong sense of collective recognition. The coherent ensemble of tree-lined avenues, historic buildings, and high-quality public spaces contributes to shaping an urban landscape endowed with shared meaning, one that evokes belonging, memory, and a sense of civic pride. Affection for this place is further reinforced by the historical and cultural value the neighborhood has acquired over time: a prestigious area that also serves as a symbolic reference point in São Paulo's civic life, where architectural and social stratification become integral to the environmental image and to the sense of community that defines it.

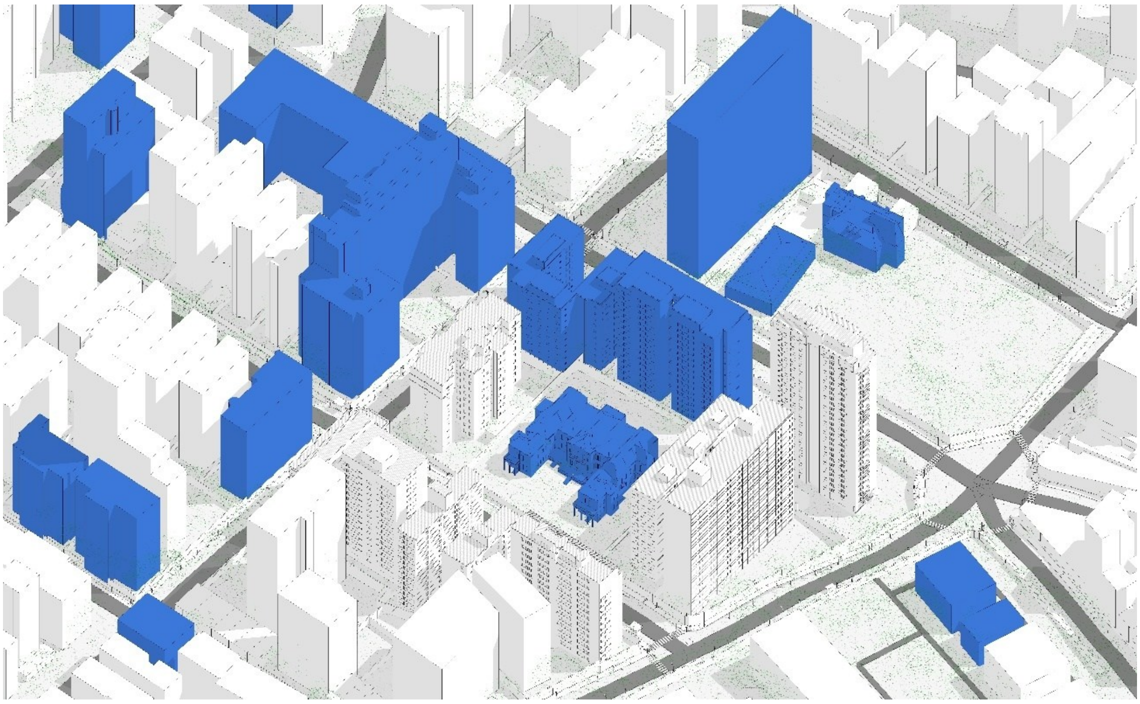


Fig. 6.9 - Higienópolis CIM model with historically significant buildings highlighted in blue, identified from the Guia Arquitetônico de São Paulo and the Guia de Arquitetura de Higienópolis. (Source: Silva, 2018 and Kambara, 2011).

Perception | Score attribution: 4

Perceptual processes identify the visual relationships that guide the formation of cognitive habits in relation to the urban environment, which is often perceived distractedly by citizens absorbed in their own thoughts and practical intentions. In such conditions, undelimited space, devoid of recognizable reference points, acts subtly and unconsciously, orienting behaviour without full awareness. The perception indicator, primarily governed by sight, therefore emphasizes the sensory apprehension of the urban scene and landscape, with the aim of representing their qualities (that is, their differences and underlying reasons) without preconceptions or hierarchical value judgments.

When analysing this indicator in the context of Higienópolis, it emerges that the urban scene exerts a kind of visual pressure on the observer. This is an area of the city where the verticalization of São Paulo has manifested particularly intensely: the urban landscape is dominated by high-rise residential buildings that define a marked vertical dimension. As a prestigious district, the boundaries between public and private space are clearly articulated and differentiated, sometimes materialized as railings or low walls, in other cases as continuous fences or screens of vegetation, depending on the specific characteristics of each property. Within this dense and enclosed urban scene, perception is activated selectively when, among the skyscrapers, historic belle époque buildings such as Vila Penteado or Vila Maria emerge, alongside significant examples of modernist architecture that reflect the cultural character of the neighbourhood. These elements function as visual landmarks which, even amid the distracted attitude typical of those who move through the city, guide the gaze and contribute to the construction of mental maps that facilitate orientation and spatial recognition. Thus, the perception of Higienópolis takes shape as a layered experience, in which the coexistence of contemporary verticality and historical memory produces a unified yet complex urban image, one capable of constructing perceptual relationships that define the district's visual identity. Interestingly, despite being located within a metropolitan context, the observer, when engaging with this urban scene, does not feel disoriented but is instead able to establish reference points through the perceptual relationship forged with the urban environment.

Fig. 6.10 - Simulation-based analysis of urban scene perception, examining the possible material groups for a building façade within the CIM model.

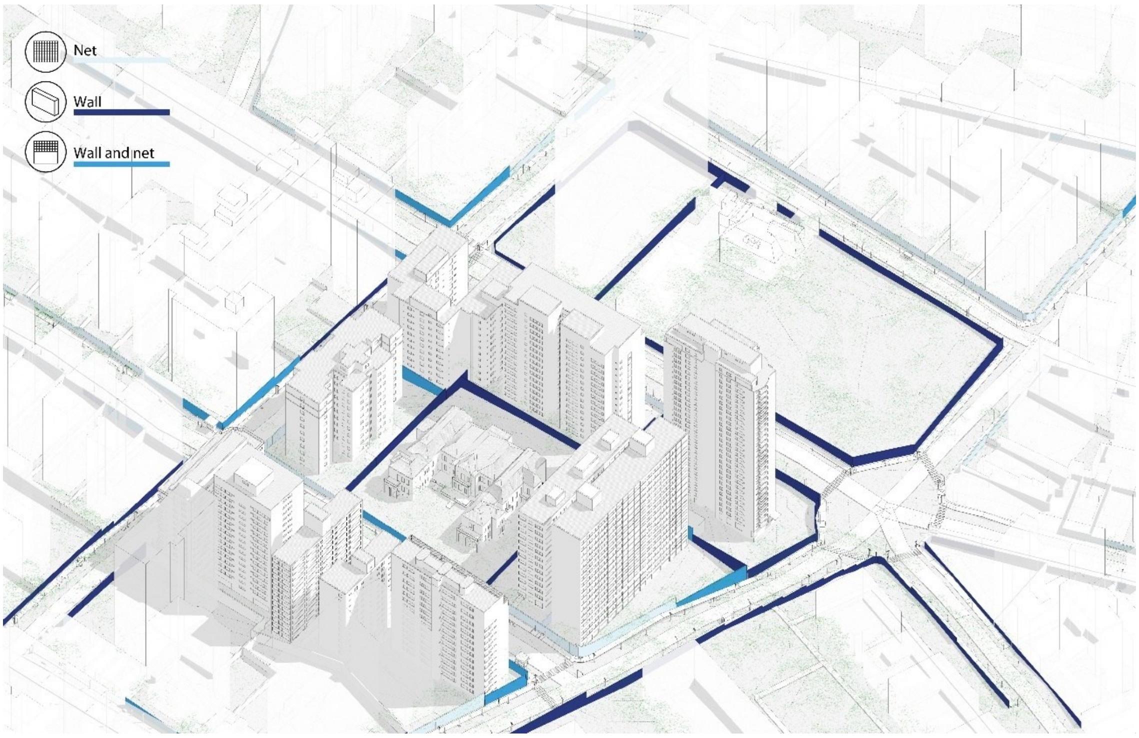
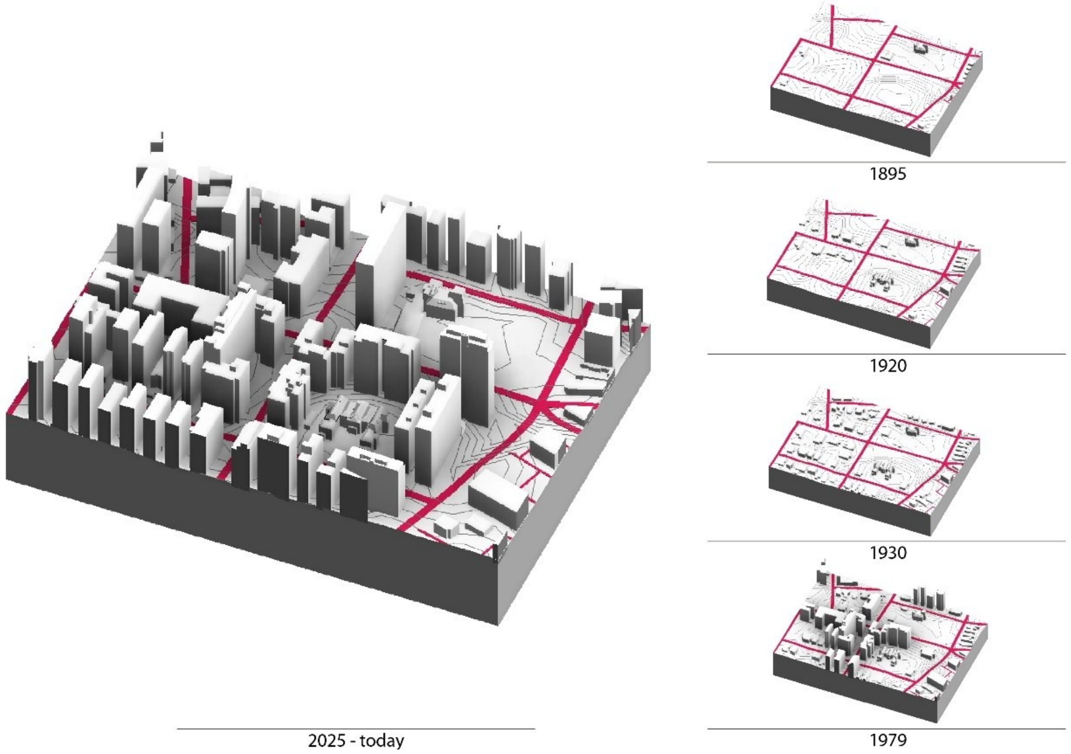


Fig. 6.11 - Simulation-based analysis of urban scene perception, focusing on the threshold space within the CIM model.

Transformation | Score attribution: 1

The Urban Transformation indicator is proposed as an analytical tool to support the monitoring of morphological and functional changes within the urban fabric. By integrating the temporal dimension, this indicator makes it possible to document transformation processes from a twofold perspective: a retrospective one, aimed at analysing modifications that have already occurred, and a prospective one, intended to estimate the intrinsic propensity for change of a plot, a block, or an entire neighbourhood.

The reading of the Transformation indicator in Higienópolis entails a dual reflection that relates the historical dimension of the neighbourhood to its contemporary condition. From a retrospective standpoint, the area has undergone numerous transformations associated with processes of densification and progressive verticalisation. Through these dynamics, the original single-family residences and belle époque buildings have been progressively replaced or complemented by new constructions, altering both the morphological profile and the overall urban image of the district. From a prospective perspective, the indicator highlights that, despite the strong real estate pressure historically affecting Higienópolis, the neighbourhood currently displays a low propensity for transformation, due to the heritage protection measures introduced to safeguard its symbolic and identity value. The district therefore appears oriented towards selective, small-scale transformations, limited to specific and carefully targeted interventions.



1895

1920

1930

2025 - today

1979

Fig. 6.12 - Evolution of the Higienópolis area, including Vila Penteado, from 1895 to the present day, with the CIM model illustrating the phases of altimetric development.

Conservation | Score attribution: 3

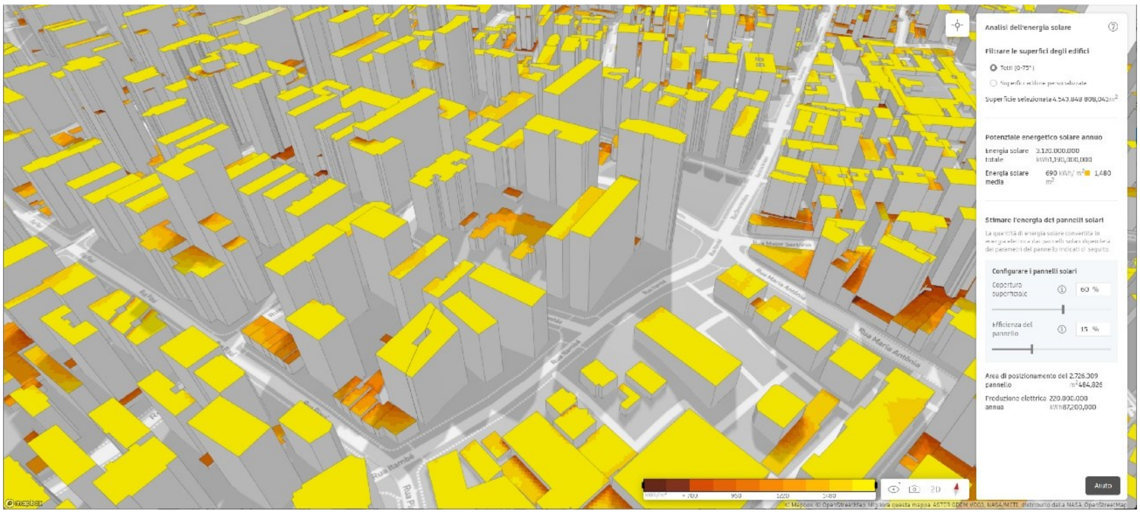
The Conservation indicator aims to identify and make visible the presence of a shared orientation toward the safeguarding of the urban scene. Conservation introduces an additional dimension, one based on a conscious choice, an intentional act that entails deciding which elements to preserve and which to exclude. In this sense, conservation becomes a useful parameter for understanding the relationship between memory, tradition, and the future, highlighting how the distinction between having and not having, preserving or letting go, is decisive in shaping collective meaning. In Higienópolis, following real estate speculation and the intensification of demolitions of historic buildings in the name of "progress," numerous significant examples of Art Nouveau, Art Déco, and eclectic architecture have been lost. The Vila Penteado, declared a historic monument by the Conselho de Defesa do Patrimônio Histórico, Arqueológico, Artístico e Turístico (CONDEPHAAT) in 1978, represents one of the few preserved examples, although it has lost part of its original gardens. This decision reflects a growing awareness of the need to protect the urban and architectural heritage of one of the most symbolic districts of São Paulo's tradition. Such awareness is manifested in the conservation of historic residences and belle époque buildings, which serve as identity and symbolic references for the community. Through the Conservation indicator, however, the objective is to recognize the overall value of the urban scene and the systems that compose it: the relationship between vegetation and pathways, the edges between enclosed and unenclosed spaces, urban furnishings, morphologies, colors, and textures that define the image and memory of the neighborhood. In this perspective, to conserve means to acknowledge and transmit the value of what endures as part of a dynamic process of continuity over time, one capable of guiding the future of Higienópolis without severing its bond with history.

Fig. 6.13 - Visualization of the Higienópolis CIM model, integrating a sidewalk texture library to support material characterization.

Energy Behaviour | Score attribution: 1

The Energy Behaviour indicator aims to begin a cognitive process designed to provide preliminary estimates of building energy performance through an expedited assessment approach. Its main purpose is to support decision-makers in developing informed strategies for energy retrofit planning.

In the context of Higienópolis, the analysis of energy behaviour enables the correlation between the typological and morphological variety of the built fabric and its energy and environmental behavior, thus offering an interpretative framework useful for planning urban-scale efficiency strategies. The climatic conditions of São Paulo have historically encouraged architectural design practices in which bioclimatic and energy aspects were not always taken into account; however, only in recent years has there been a paradigm shift and growing awareness of issues related to building energy performance and sustainable efficiency systems. Through a rapid assessment approach that relates the formal characteristics of buildings to indicators of thermal, lighting, and ventilation performance, it becomes possible to outline an initial energy map of the district, distinguishing building types with higher energy demand from those that are more efficient. This typological diversity constitutes a valuable source of knowledge for defining urban energy classification models based on representative parameters. Overall, the energy behavior of the built environment in Higienópolis appears heterogeneous yet evolving, reflecting an increasing trend toward the adoption of sustainable technologies.



Analisi dell'energia solare

Filtrare le superfici degli edifici

● Tetti (0-75°)

○ Superfici edilizie personalizzate

Superficie selezionata 4.543.848 808,043m²

Potenziale energetico solare annuo

Energia solare totale 3.120.000.000 kWh1,190,000,000

Energia solare media 690 kWh/ m² 1,480 m²

Stimare l'energia dei pannelli solari

La quantità di energia solare convertita in energia elettrica dai pannelli solari dipenderà dai parametri del pannello indicati di seguito.

Configurare i pannelli solari

Copertura superficiale 60 %

Efficienza del pannello 15 %

Area di posizionamento del pannello 2.726.309 m²484,826

Produzione elettrica annua 220.000.000 kWh87,200,000

Fig. 6.14 – Solar energy analysis within the CIM model.

Structural Behaviour | Score attribution: 4

The Structural Behaviour indicator, aims to synthesise the analysis of the classification of building typologies on an urban scale, with the goal of beginning an exploratory process that can later be refined through more detailed methods and measurement-based tools. This measure proves particularly useful for supporting the planning of extraordinary maintenance interventions and, more generally, for guiding strategies for risk management and urban regeneration.

From a typological standpoint, Higienópolis displays a composite building structure: historical masonry constructions coexist within the same urban fabric with reinforced concrete structures from the modernist and postmodern periods. This structural diversity allows the district to be classified according to distinct structural types, each with different levels of resistance and behaviour under stress. Compact masonry buildings exhibit good vertical stability but are more vulnerable to soil deformation or vibrations, whereas reinforced concrete structures from later decades ensure greater ductility. The correlation between structural typology and geotechnical conditions is a crucial aspect in assessing expected damage. Higienópolis, located on a topographically stable area with predominantly cohesive soils, does not show significant phenomena of subsidence or ground movement, a condition that reduces structural risk linked to soil displacement. Nevertheless, the high building density and proximity of deep foundations can generate localised structural interactions, particularly in cases of replacement works or excavations for underground car parks, which require careful management of differential settlement risks. Overall, Higienópolis can be characterised as an urban context with good overall structural stability, yet one that requires continuous monitoring of the conservation state of both historic and modernist buildings, in order to ensure the safety, durability, and functional continuity of the built heritage over time.

Post-Disaster Damage Behaviour | Score attribution: 4

The indicator of Post-Disaster Damage Behaviour is thus conceived as a dynamic measure, one that does not merely describe the pre-existing condition of fragility, but rather the sequence of processes activated in the post-event phase. It seeks to overcome the traditional static conception of vulnerability by highlighting the processual and transformative dimension of resilience. Among the dimensions feeding into the indicator are: recovery time, recovery quality, and the relative level of functionality achieved (total, partial, or transformative restoration); as well as adaptive capacity, understood as the ability to introduce structural and innovative changes in order to reduce vulnerability to future critical events.

In the context of Higienópolis, the post-disaster damage behavior indicator enables an interpretation of the neighborhood's urban resilience in relation to potential natural or anthropogenic events. The main risks to which Higienópolis is exposed include fire and hydrogeological hazards. Consistent with the complex systems approach, the analysis does not merely consider the degree of exposure to risk but focuses on the capacity of the urban system to react, reorganize, and recover following a catastrophic event. Regarding fire risk, Higienópolis benefits from well-developed urban infrastructure and an efficient emergency response network. Most medium- and high-end residential buildings are equipped with fire prevention systems, evacuation routes, and condominium safety protocols, which are mandatory under the municipal building regulations of São Paulo. However, certain historic residences or modernist buildings may exhibit greater structural vulnerabilities due to the original construction materials or the absence of comprehensive infrastructural upgrades. With respect to hydrogeological risk, the neighborhood’s elevated topographical position protects it from direct flooding. Nevertheless, the high degree of soil impermeabilization and the considerable urban density can lead to localized surface water accumulation during intense rainfall events. For this reason, the sewage and drainage system requires continuous maintenance to ensure its efficiency and to manage temporary overloads during extreme weather conditions.

6.3 Verucchio, Rimini, Italy: Indicators Assessment

The small town of Verucchio, a minor settlement in the Province of Rimini, Italy, located between the sea and the hills, characterized by a complex historical stratification. Its periods of greatest prosperity date back to the Etruscan era and to the lordly age under the dominion of the Malatesta family. It was selected due to its dual significance. On the one hand, it is situated within a territorial context defined by a complex orographic relationship, which necessitates a specific reflection on the management of elevation differences in the development of the CIM model. On the other hand, it represents an exemplary instance of the numerous historic villages scattered throughout the Apennine area; therefore, it was considered appropriate to explore the potential for enhancing such urban centres through the implementation of the CIM as a tool for management and documentation, integrated within networks of municipal unions in a transitional framework.

6.3.1 *Indicators Assesment*

Urban Pressure | Score attribution: 1

The Urban Pressure indicator measures the impact generated by the expansion and density of the urban fabric. It also includes factors of spatial constraint, which produce a set of introspective relationships between building façades and smaller-scale structures in adjacent areas. These factors also give rise to specific conditions related to shading and microclimatic constraints.

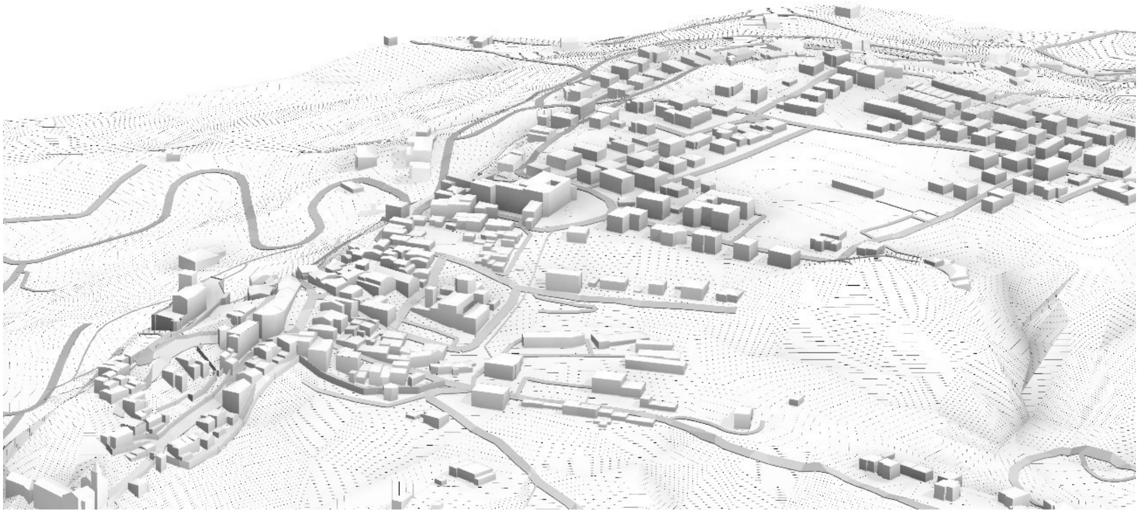


Fig. 6.15 - View of the Verucchio CIM Model.

In the context of the Municipality of Verucchio, simulations were carried out using the CIM model developed within the framework of this research, with the aim of assessing urban pressure and assigning corresponding values. The following analyses were conducted: solar hours and daylight potential (based on EnergyPlus Weather Data), wind analysis (Global Wind Atlas 3.0), and microclimatic analysis (Copernicus ERA5)[4]. For the study of sunlight duration and shadow patterns, March 21st (the equinox) was selected as a representative date for general urban analyses, as it provides an "average" depiction of annual solar irradiation and is therefore used as a standard reference. The prevailing west wind, 270°, with a frequency of 25%, was adopted as the reference parameter for the microclimatic analysis.

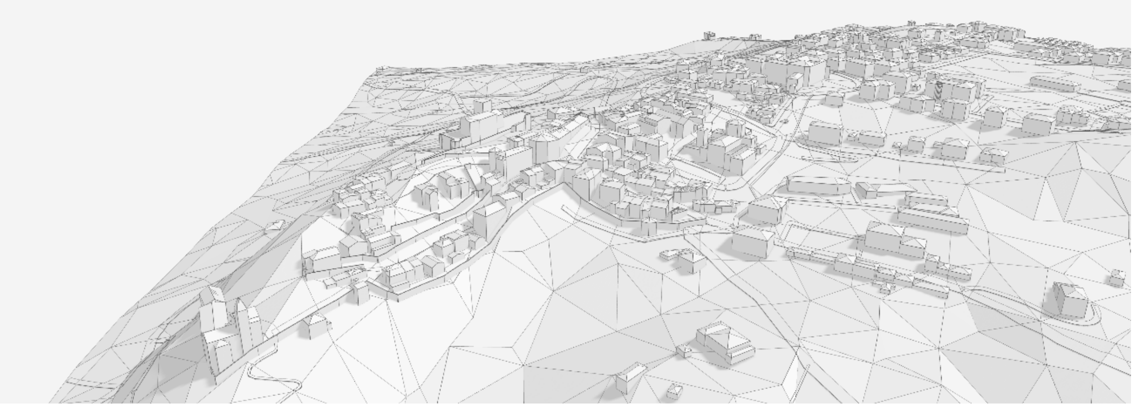


Fig. 6.16 – Shadow study for the historical town of Verucchio, conducted through the CIM model.

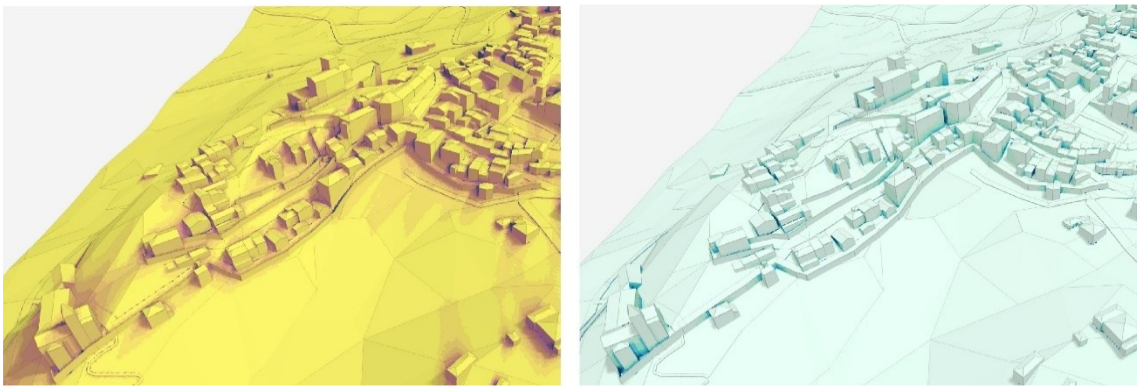


Fig. 6.17 – Analysis of sun exposure (left) and daylight potential analysis (right) within the CIM model.

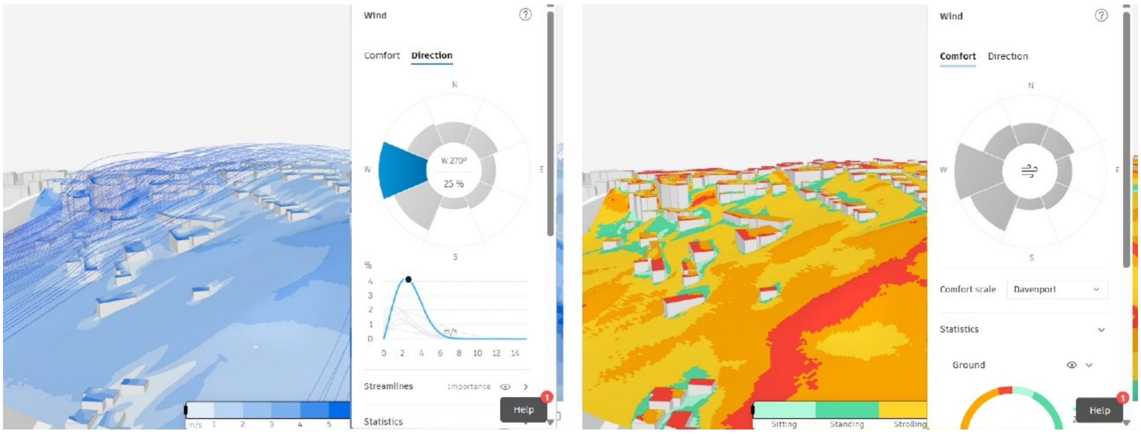


Fig. 6.18 – Wind analysis within the CIM model (left) and wind comfort analysis within the CIM model (right).

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[4] The data sources used by the software to perform the analyses are indicated in parentheses.

In Verucchio, the urban fabric reveals a higher degree of urban pressure in the medieval village area, particularly around Piazza Malatesta, at the base of the Rocca Malatestiana. This area is characterized by a high building density and a compact fabric. To the southeast, the more recently developed area is composed mainly of detached houses and villas with private gardens, indicating a moderate level of urban pressure. However, the orographic context, with the small town built along the slopes of the hill, positively influences the perceived degree of urban pressure. From a planimetric point of view, the pressure in the historic fabric appears reduced because, perceptually, it is mitigated by the presence of wide visual openings toward the Romagna landscape.

Hybridization | Score attribution: 3

The Hybridization indicator expresses the degree of integration among different functions, forms, and uses within the urban space, representing the city's ability to adapt to contemporary transformations while maintaining coherence and quality. It reflects the dynamic and composite nature of the urban context, understood as a continuously evolving social product in which diverse elements interact, generating new spatial and relational configurations. Monitoring this indicator makes it possible to interpret the complexity and sustainability of urban transformation processes, contributing to an understanding of the ways in which the city evolves and regenerates itself.

Verucchio shows a medium level of hybridization, characterized by the integration between the historic village, compact and of strong identity value, and the contemporary residential area, defined by more open morphologies and a greater presence of green spaces. The transition between these areas appears well harmonized, resulting in a continuous and coherent perception of the surrounding landscape. From a functional perspective, the urban core integrates residential uses, local services, and tourist functions, although it still shows a limited presence of innovative and multifunctional activities.

Accessibility | Score attribution: 1

The Accessibility indicator assesses the morphological conditions and usage patterns of the urban space, taking into account dimensional factors, safety, and the expenditure of psycho-physical energy. It assumes a dual role: on the one hand, it represents a condition for social inclusion, measuring the autonomous and safe usability of the urban environment, including for people with motor or sensory limitations; on the other hand, it relates to the temporal dimension of mobility, referring to the concept of urban proximity. This indicator aims to provide information for evaluating the degree of self-sufficiency of a neighbourhood, contributing to the development of sustainable and liveable urban models. Its relational nature highlights how the malfunction of a single element can compromise the overall effectiveness of the urban system.

The orographic configuration of Verucchio entails inherent challenges in achieving a high value for the Accessibility indicator. The altimetric distribution of the urban fabric limits the continuity of pedestrian routes, thereby reducing the degree of self-sufficiency in relation to the few available proximity services. It is a minor historic center, characterized by limited public transport connections with other urban settlements in the Valmarecchia area. Consequently, the complex geographical conditions define an urban context with a low level of accessibility, both in terms of internal mobility and territorial connectivity.

Traffic Congestion | Score attribution: 1

The measurement of the Traffic Congestion indicator makes it possible to correlate the pressure exerted on the road network with the resulting acoustic and environmental effects, as it represents one of the main critical issues in urban mobility systems. It negatively affects both travel times and the overall efficiency of transport flows. Moreover, it influences the general sensory quality of the urban environment, as it constitutes a source of external noise that impacts the perception of comfort and the dynamics of social interaction.

In Verucchio, although the hilly morphology and the road structure of the historic center, characterized by narrow streets with limited capacity, make the urban system particularly vulnerable to vehicular pressure, no significant level of traffic congestion is observed. The town does not serve as a transit area, as the main road network develops outside the historic centre. Public transport services are also limited, reaching the center only at specific times of the day, mainly through school routes. Tourist inflows, concentrated primarily on weekends, cause a temporary increase in mobility but not to the extent of generating notable congestion. Overall, the traffic level in Verucchio can be considered low.

Comfort | Score attribution: 4

The measurement of the Comfort indicator represents well-being in relation to the quality of living, taking into account the main requirements of safety, wayfinding, urban diversity, and the availability of green areas, all essential elements for the proper functioning of the various types of urban activities: necessary, voluntary, and social.

In Verucchio, the lifestyle changes that emerged in the post-pandemic context find a positive correspondence in the scale and character of the village, where the small urban dimension and the accessibility of the historic centre, together with the presence of panoramic spaces, contribute to a high level of perceived comfort. Urban comfort, understood as a balance between safety and spatial orientation, is closely related to the physical configuration of the place: the streets and squares of Verucchio provide spatial conditions that encourage social interaction, although they also present certain limitations linked to the hilly morphology and the discontinuity of public spaces. These characteristics, typical of the historic medieval centres, can make wayfinding challenging in certain situations. In this case, the indicator reflects a level of comfort grounded in perceptual quality and in the capacity of the place to sustain meaningful social interactions, while at the same time enhancing the cultural and identity-related dimensions of the village.

Meaning | Score attribution: 5

The Meaning indicator aims to measure the emotional and affective dimension that the urban scene causes in citizens. In this way, it seeks to highlight the affective value of places, spaces with which citizens identify, and which they are therefore encouraged to care and protect.

In Verucchio, the urban and landscape dimensions foster a strong sense of affection toward the historic village, which, owing to its history and clear legibility within the territory, emerges as a place capable of evoking memory and a sense of belonging. The persistence of a distinctly characterized urban image, together with the perception of continuity between past and present, reinforces residents' emotional attachment and their inclination to preserve the identity of the place. From this perspective, the indicator reflects the village's capacity to encourage attitudes of care and appreciation toward spaces that embody both historical depth and collective value.

Perception | Score attribution: 5

Perceptual processes identify the visual relationships that guide the formation of cognitive habits in relation to the urban environment, which is often perceived distractedly by citizens absorbed in their own thoughts and practical intentions. In such conditions, undelimited space, devoid of recognizable reference points, acts subtly and unconsciously, orienting behavior without full awareness. The perception indicator, primarily governed by sight, therefore emphasizes the sensory apprehension of the urban scene and landscape, with the aim of representing their qualities (that is, their differences and underlying reasons) without preconceptions or hierarchical value judgments.

In Verucchio, the Perception indicator is closely linked to the visual and phenomenological relationships established between the observer and the urban environment, highlighting how the spatial configuration of the town influences the formation of mental images and cognitive habits associated with the urban scene. The arrangement of pathways, the variations in elevation, and the presence of open vistas toward the surrounding landscape define a complex perceptual sequence, in which the interplay between solid and void, and between vertical and horizontal elements, determines the overall visual quality. The perceptual experience of Verucchio is strongly characterized by dominant perspectival effects, resulting from the hilly topography and the succession of panoramic views that accompany the urban route. In this sense, perception is not limited to a static reading of space but takes on a dynamic dimension, shaped by movement and by the continuous variation of the observer's viewpoint. The presence of strong referential landmarks, such as the Rocca Malatestiana, helps preserve the legibility, visual identity, and perceptual value of the environment.

Transformation | Score attribution: 1

The Urban Transformation indicator is proposed as an analytical tool to support the monitoring of morphological and functional changes within the urban fabric. By integrating the temporal dimension, this indicator makes it possible to document transformation processes from a twofold perspective: a retrospective one, aimed at analysing modifications that have already occurred, and a prospective one, intended to estimate the intrinsic propensity for change of a plot, a block, or an entire neighbourhood.

Characterized by a compact urban system and a vertically developed layout, with a medieval structure that has remained substantially stable over time, Verucchio shows transformation processes mainly concentrated in the more recent expansion areas, which represent the zones where the built fabric has evolved the most. As a historic village, its propensity for transformation is limited, being constrained, yet consistent, with the historical and landscape value of the context and with the presence of protection regulations that ensure its preservation. The transformation processes display, in fact, a slow and gradual progression over the years, an intrinsic feature of historic villages and a condition shared by other small settlements scattered along the Emilia-Romagna Apennines.

Conservation | Score attribution: 4

The Conservation indicator aims to identify and make visible the presence of a shared orientation toward the safeguarding of the urban scene. Conservation introduces an additional dimension, one based on a conscious choice, an intentional act that entails deciding which elements to preserve and which to exclude. In this sense, conservation becomes a useful parameter for understanding the relationship between memory, tradition, and the future, highlighting how the distinction between having and not having, preserving or letting go, is decisive in shaping collective meaning. In the case of Verucchio, the conservation indicator highlights a high level of awareness in the protection of architectural and landscape heritage, which represents the structural matrix of the town. There is, in fact, a shared orientation towards the safeguarding of architectural, archaeological, and landscape assets, demonstrating a collective commitment to preserving, over time, the coherence between historical value and territorial identity.

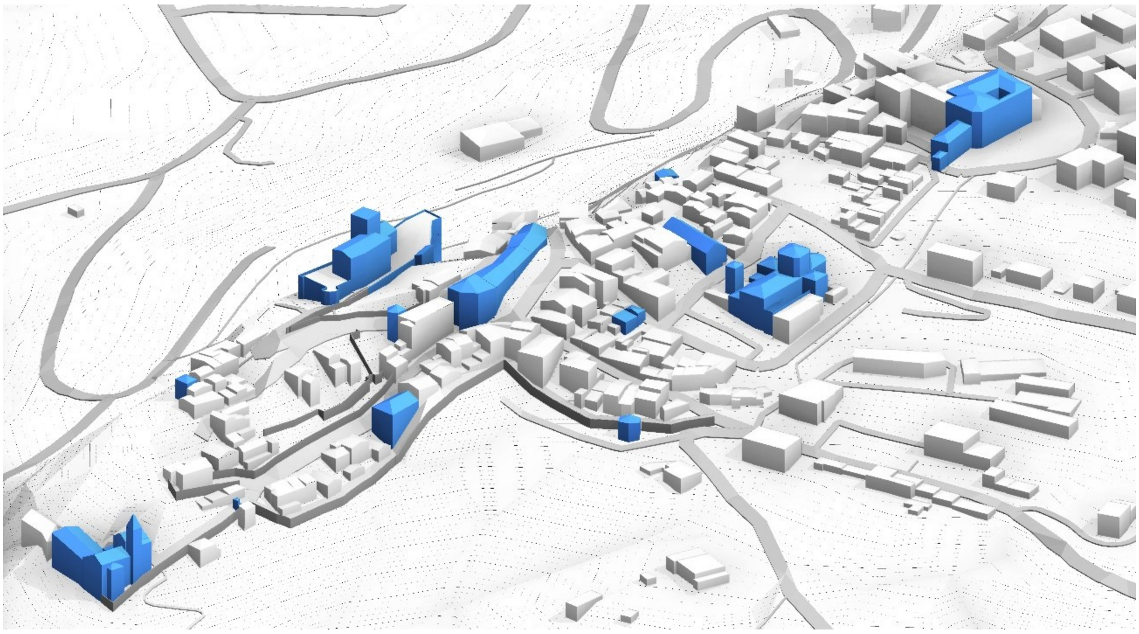


Fig. 6.19 - Verucchio CIM model with historically significant buildings highlighted in blue

Energy Behaviour | Score attribution: 1

The Energy Behaviour indicator aims to begin a cognitive process designed to provide preliminary estimates of building energy performance through an expedited assessment approach. Its main purpose is to support decision-makers in developing informed strategies for energy retrofit planning.

In Verucchio, the energy behavior indicator provides an analytical framework that, through typological classification and the use of simplified models, enables preliminary estimations and the formulation of a synthetic index of urban-scale performance. This tool not only describes the current condition but also allows for the simulation of expected outcomes of interventions, thereby supporting informed planning of energy retrofitting programs while maintaining coherence with the historical identity of the village and ensuring comparability across different urban contexts. Given the historic nature of the building stock, the energy performance generally shows low efficiency levels, accompanied by significant challenges in implementing improvement measures within the ancient urban fabric, due to preservation constraints aimed at safeguarding the image and historical integrity of the settlement.

Structural Behaviour | Score attribution: 3

The Structural Behaviour indicator, aims to synthesise the analysis of the classification of building typologies on an urban scale, with the goal of beginning an exploratory process that can later be refined through more detailed methods and measurement-based tools. This measure proves particularly useful for supporting the planning of extraordinary maintenance interventions and, more generally, for guiding strategies for risk management and urban regeneration.

The indicator, when applied to the case of Verucchio, assumes particular significance due to the presence of a historic and compact built fabric, in which traditional construction typologies and the hilly morphology influence the structural response to dynamic events or geotechnical stresses. The compact urban structure, the medieval layout, and the predominance of load-bearing masonry buildings define a building system with strong typological coherence, yet also intrinsic structural vulnerabilities associated with the age of the constructions, the quality of materials, and the morphological configuration of the site.

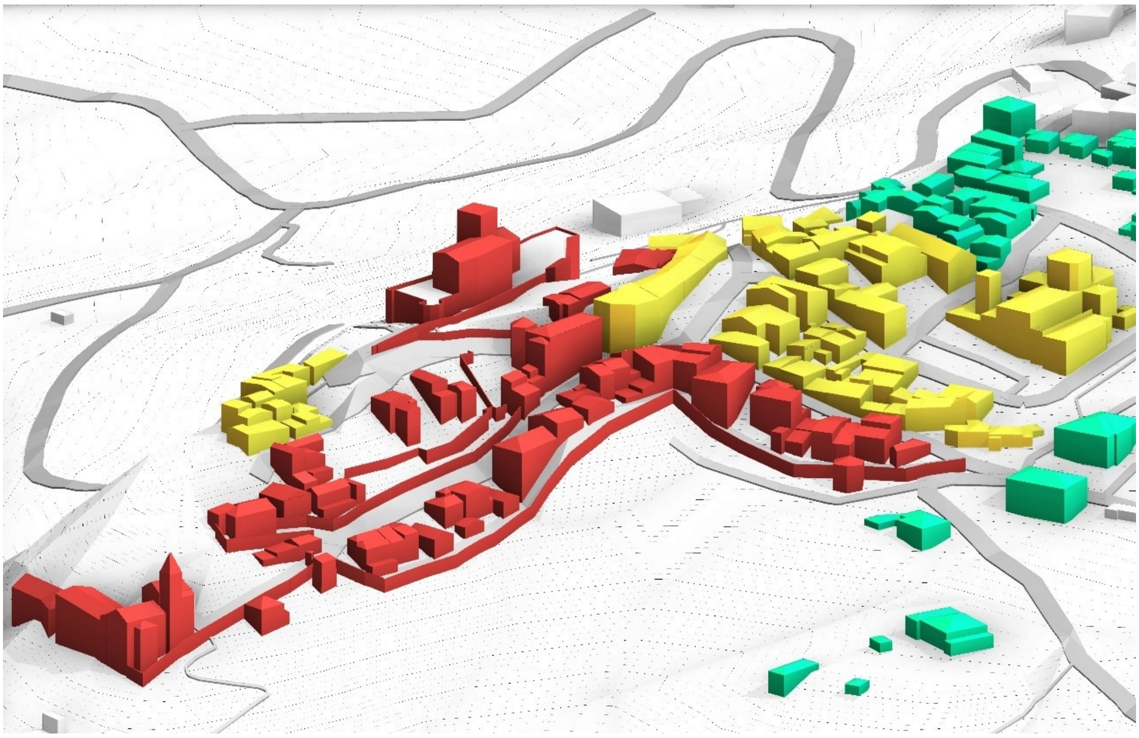


Fig. 6.20 - Simulation-based analysis of Verucchio structural behaviour within the CIM model.

The elevation of the settlement introduces complex geotechnical conditions: slopes, variations in altitude, and the presence of substrata subject to erosion and superficial subsidence. These factors affect the structural response of buildings, particularly in areas at the edge of the historic core, where the interaction between built structures and terrain can generate differential stresses. Within the historic nucleus, the structural behaviour is typical of medieval hilltop contexts of the Emilia-Romagna Apennines: aggregated buildings, non-uniform foundations, and irregular masonry bearing walls, often with limited transverse connections. This configuration results in moderate resistance to seismic actions, leading to greater vulnerability compared with more recent or structurally upgraded constructions. Nevertheless, the low height of the buildings, the density of the urban fabric, and the presence of conservation constraints and protection plans help to mitigate the risk of widespread collapse and support targeted safety interventions consistent with the preservation of the historic image. Overall, the structural behaviour of Verucchio can be considered medium in terms of performance: the urban system demonstrates good overall stability, albeit with localized vulnerabilities within the historic fabric.

Post-Disaster Damage Behaviour | Score attribution: 3

The indicator of Post-Disaster Damage Behaviour is thus conceived as a dynamic measure, one that does not merely describe the pre-existing condition of fragility, but rather the sequence of processes activated in the post-event phase. It seeks to overcome the traditional static conception of vulnerability by highlighting the processual and transformative dimension of resilience. Among the dimensions feeding into the indicator are: recovery time, recovery quality, and the relative level of functionality achieved (total, partial, or transformative restoration); as well as adaptive capacity, understood as the ability to introduce structural and innovative changes in order to reduce vulnerability to future critical events.

In the context of Verucchio, the capacity to respond to disastrous events such as earthquakes, fires, or floods can be interpreted in relation to the compact urban structure of the historic core and its location on a hilly relief. This morphological position reduces direct exposure to flooding phenomena, while at the same time introducing critical issues related to slope stability (landslide risk) and the seismic vulnerability typical of Apennine historic centres. In the event of an earthquake, the response capacity is conditioned by the nature of the medieval urban fabric, composed of load-bearing masonry buildings and narrow urban spaces, which limit its immediate functionality during the emergency phase. However, the presence of conservation constraints and planning instruments aimed at preservation contributes to a heightened awareness of risk and to a coordinated management of safety measures, thereby fostering a gradual recovery over the medium term. With regard to fire risk, the response of the urban system is linked to the physical characteristics of the settlement and its building density: the compactness of the historic centre can amplify the spread of fire, yet the limited presence of industrial activities and the predominance of residential and tourist functions significantly reduce the likelihood of severe events. As for hydrogeological risk, the altimetric configuration of Verucchio limits the possibility of direct flooding, but the hilly nature and the steepness of the terrain make it necessary to monitor rainwater and surface runoff in order to prevent erosion or localised instability phenomena. Overall, Verucchio's capacity to respond to disastrous events can be considered moderate, as it is based on a form of territorial resilience oriented toward conservation: the town demonstrates a strong awareness of the value of its heritage and a risk management approach focused on protection and recovery, yet it remains constrained by the structural limitations imposed by its morphology and the historic character of its built fabric.

Fig. 6.21 - Simulation-based analysis of Verucchio, showing landslide-risk areas and the buildings potentially affected, integrated within the CIM model. (Source: https://geoportale.regione.emilia-romagna.it/)

6.4 Darsena Area in Ferrara, Italy: Indicators Assessment

The area of the Darsena focuses on an urban section of the Municipality of Ferrara, located in the Emilia-Romagna region of Italy. This area, situated along the Po di Volano river to the south of the city, was chosen for its unique characteristics. It intersects various zones as defined in the Municipal Strategic Plan (PSC): historical fabric, consolidated fabric, and to be redeveloped fabric. The urban section is distinguished by several key features: the river embankment; residential areas along Via Argine Ducale and Via del Mulinetto; the historic center along Via Piangipane and Via Ripagrande, which houses the Italian National Museum of Judaism and the Shoah (MEIS); and a section of the historic city walls. Additionally, the area between the walls and the Burana Canal is currently undergoing urban redevelopment, aimed at enhancing its connection to the historic center.

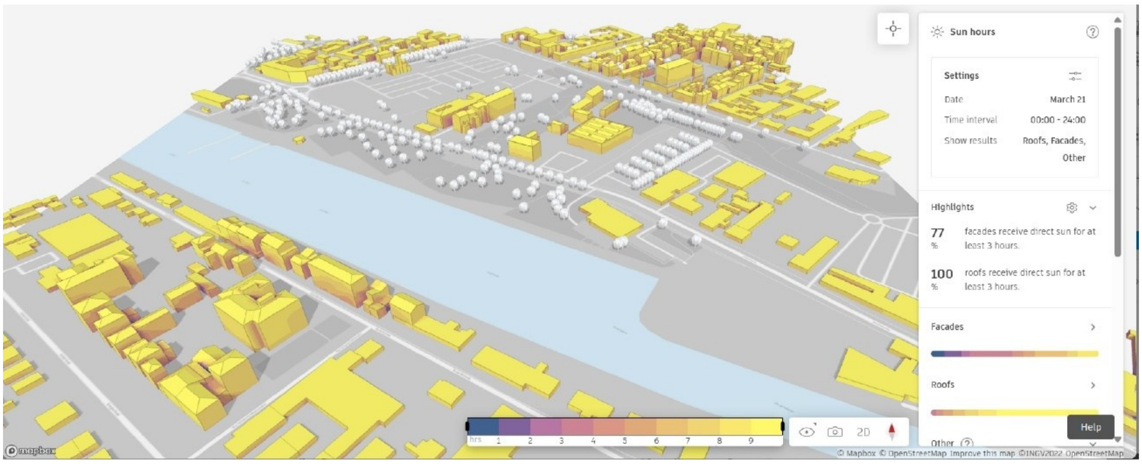
6.4.1 *Indicators Assesment*

Urban Pressure | Score attribution: 1

The Urban Pressure indicator measures the impact generated by the expansion and density of the urban fabric. It also includes factors of spatial constraint, which produce a set of introspective relationships between building façades and smaller-scale structures in adjacent areas. These factors also give rise to specific conditions related to shading and microclimatic constraints.

Fig. 6.22 - View of the Darsena of Ferrara CIM Model.

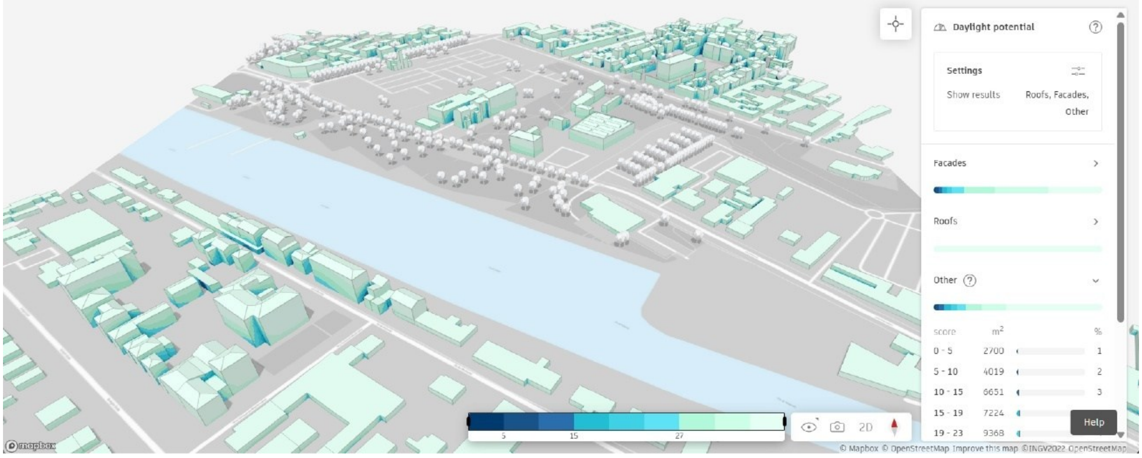
In Autodesk Forma, by implementing the CIM model created with Revit for the selected urban section, expanded to include a broader surrounding area, the following analyses were carried out: solar hours and daylight potential analysis (based on EnergyPlus Weather Data), wind analysis (using Global Wind Atlas 3.0), and microclimate analysis (using Copernicus ERA5 data)[5]. For the solar hours and shadow studies, March 21 (the equinox) was selected as the representative date for general urban analysis, as it provides an "average" overview of annual solar radiation and is therefore adopted as a standard reference.



Settings
Date: March 21
Time interval: 00:00 - 24:00
Show results: Roofs, Facades, Other

Highlights
77 % facades receive direct sun for at least 3 hours.
100 % roofs receive direct sun for at least 3 hours.

Fig. 6.23 – Analysis of sun exposure within the CIM model.



Settings
Show results: Roofs, Facades, Other

score	m^2	%
0 - 5	2700	1
5 - 10	4019	2
10 - 15	6651	3
15 - 19	7224	
19 - 23	9368	

Fig. 6.24 – Daylight potential analysis within the CIM model.

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[5] The data sources used by the software to perform the analyses are indicated in parentheses.

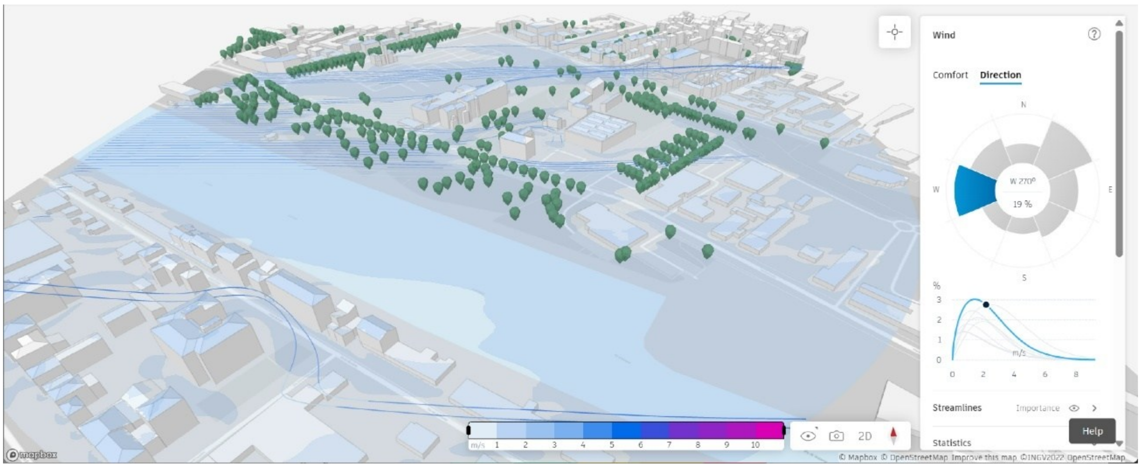


Fig. 6.25 – Wind analysis within the CIM model

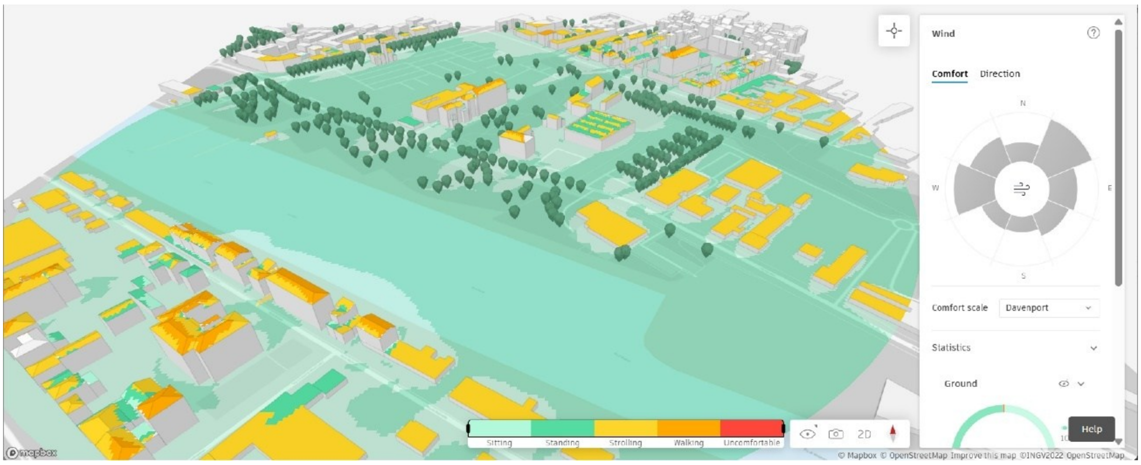


Fig. 6.26 – Wind comfort analysis within the CIM model.

Urban pressure in the Darsena area of Ferrara is low. This urban fabric is characterized by the coexistence of historical fabric, consolidated fabric, and areas to be redeveloped. However, the presence of the Po di Volano River to the south of the city, together with the surrounding vegetation and ongoing regeneration projects, makes it an area of urban decompression.

Hybridization | Score attribution: 4

The Hybridization indicator expresses the degree of integration among different functions, forms, and uses within the urban space, representing the city's ability to adapt to contemporary transformations while maintaining coherence and quality. It reflects the dynamic and composite nature of the urban context, understood as a continuously evolving social product in which diverse elements interact, generating new spatial and relational configurations. Monitoring this indicator makes it possible to interpret the complexity and sustainability of urban transformation processes, contributing to an understanding of the ways in which the city evolves and regenerates itself.

The level of hybridization in the Darsena area of Ferrara is characterized by significant integration among morphological, functional, and environmental components. This area, located along the Po di Volano River to the south of the city, exhibits unique features as it intersects various urban zones identified in the Municipal Strategic Plan (PSC): historical fabric, consolidated fabric, and areas designated for redevelopment. The coexistence of historical, consolidated, and redevelopment fabrics generates a heterogeneous urban system, where built structures and open spaces of different origins coexist and integrate, producing a complex yet coherent structure consistent with the city's historical stratification. Functional hybridization is expressed through the coexistence of residential, cultural, productive, and recreational activities, the result of ongoing regeneration processes aimed at restoring vitality to an area that has long been on the margins of urban development. This multiplicity of uses contributes to the creation of a new urban centrality. The organization of festivals in the Darsena area, together with the activities promoted by the nearby Wunderkammer cultural center, further reinforces this condition of functional hybridization, making the area particularly attractive and dynamic.

Accessibility | Score attribution: 3

The Accessibility indicator assesses the morphological conditions and usage patterns of the urban space, taking into account dimensional factors, safety, and the expenditure of psycho-physical energy. It assumes a dual role: on the one hand, it represents a condition for social inclusion, measuring the autonomous and safe usability of the urban environment, including for people with motor or sensory limitations; on the other hand, it relates to the temporal dimension of mobility, referring to the concept of urban proximity. This indicator aims to provide information for evaluating the degree of self-sufficiency of a neighbourhood, contributing to the development of sustainable and liveable urban models. Its relational nature highlights how the malfunction of a single element can compromise the overall effectiveness of the urban system.

Thanks to recent urban regeneration projects, the Darsena area of Ferrara has experienced a significant improvement in its accessibility index in recent years. Recognized as a strategic area for the city, the removal of walls and fences that once limited its permeability has made the Po di Volano fully perceptible, both visually and experientially. The redevelopment of green spaces, such as the former Camilli area, together with the construction of a large pedestrian crossing equipped with a ramp connecting to the riverbank, has markedly enhanced the connections with the historic centre, also through the integration of solutions supporting people with reduced mobility. At the same time, ongoing urban regeneration initiatives, the presence of local services, cultural functions, and public spaces, such as those within the Wunderkammer complex, have further increased the overall level of accessibility, owing to the attractive capacity of these places.

Nevertheless, despite the progress achieved, the connections with the historic centre through pedestrian and cycling routes, as well as public transport services, remain partially fragmented, revealing potential areas for improvement toward achieving full urban and functional continuity.

Traffic Congestion | Score attribution: 3

The measurement of the Traffic Congestion indicator makes it possible to correlate the pressure exerted on the road network with the resulting acoustic and environmental effects, as it represents one of the main critical issues in urban mobility systems. It negatively affects both travel times and the overall efficiency of transport flows. Moreover, it influences the general sensory quality of the urban environment, as it constitutes a source of external noise that impacts the perception of comfort and the dynamics of social interaction. The analysis of the indicator, applied to the case study of the Darsena area in Ferrara, reveals significant congestion along the main arterial roads crossing the urban section. In particular, Via Darsena shows considerable traffic levels, as it connects key areas of the city, such as industrial zones, the university, and park-and-ride facilities, allowing vehicles to bypass the historic centre without crossing it directly. This condition negatively affects both the acoustic and perceptual quality of the urban environment, contributing, to some extent, to the separation of the Darsena park from the historic fabric. On the opposite bank of the Po di Volano, along Via Argine Ducale, which runs through a predominantly residential area, traffic congestion is equally notable, especially during peak hours. This road constitutes a major urban axis lined with numerous residential buildings, where interferences between vehicular and bicycle mobility are evident. While the presence of a cycle path along Via Darsena ensures safer and more orderly circulation, such infrastructure is absent on the opposite side of the river. Moreover, the limited presence of vegetation, which could act as an acoustic buffer, further worsens the conditions of urban and environmental comfort, linked to the traffic congestion, in this part of the city.

Fig. 6.27 – Visualization of the Darsena di Ferrara CIM model, integrating a typological characterization of the road infrastructures.

Comfort | Score attribution: 3

The measurement of the Comfort indicator represents well-being in relation to the quality of living, taking into account the main requirements of safety, wayfinding, urban diversity, and the availability of green areas, all essential elements for the proper functioning of the various types of urban activities: necessary, voluntary, and social.

In an urban context such as the Darsena of Ferrara, recently interested by regeneration processes, comfort constitutes a central dimension in defining vibrant and livable environments, in line with the transformations in lifestyle that have emerged in the post-pandemic period. The presence of the waterway and the green areas represents an opportunity from the perspective of urban proxemics, positively influencing the degree of perceived comfort. The redevelopment of spaces along the Po di Volano and the enhancement of public areas have fostered the possibility of carrying out diverse urban activities, thereby strengthening well-being and the overall quality of everyday life. At the same time, the presence of pedestrian and cycling routes, green spaces, and places dedicated to social and cultural interaction contributes to building a widespread sense of livability, understood as a balance between social interaction and environmental comfort. However, regarding perceived safety, the area near the Po di Volano is not considered entirely safe at all times of day, particularly during the nighttime hours. Cultural and recreational initiatives, especially those held in the summer months, such as festivals, food events, and concerts, are specifically aimed at increasing people’s presence and, consequently, the perception of safety. On the opposite riverbank, in the residential area, the level of safety is generally good, although greater attention remains necessary during the evening hours. In this sense, the comfort indicator assumes an interpretative value useful for assessing the Darsena’s capacity to provide widespread well-being, while at the same time highlighting the need for a more specific investigation into the dimension of perceived safety.

Meaning | Score attribution: 2

The Meaning indicator aims to measure the emotional and affective dimension that the urban scene causes in citizens. In this way, it seeks to highlight the affective value of places, spaces with which citizens identify, and which they are therefore encouraged to care and protect.

Due to the historically marginal role that the Darsena of Ferrara has played in the life of the city’s inhabitants, the affection indicator registers a relatively low value. This urban area has only recently undergone redevelopment and, in the past few years, has gradually become an attractive space for the local population. The interventions are recent, and the municipal administration has shown a clear commitment to maintaining the structures and ensuring the overall management of the area. Nevertheless, the Darsena still appears as a novelty, more closely connected to the contemporary trend of enhancing riverfront areas, a phenomenon widespread in many European cities, than to an authentic sense of memory or belonging developed over time. It is not yet a place that evokes collective memories or layers of identity, as the process of revalorising the relationship between the city and its river has only recently begun. The sense of attachment is therefore in an initial phase of construction, likely to consolidate over time through continuous use, shared practices, and the progressive integration of this place into the urban memory of the Ferrara community.

Perception | Score attribution: 3

Perceptual processes identify the visual relationships that guide the formation of cognitive habits in relation to the urban environment, which is often perceived distractedly by citizens absorbed in their own thoughts and practical intentions. In such conditions, undelimited space, devoid of recognizable reference points, acts subtly and unconsciously, orienting behaviour without full awareness. The perception indicator, primarily governed by sight, therefore emphasizes the sensory apprehension of the urban scene and landscape, with the aim of representing their qualities (that is, their differences and underlying reasons) without preconceptions or hierarchical value judgments.

In the Darsena area of Ferrara, the Po di Volano waterway was for many years excluded from the urban context, to the point that the city gradually lost its defining character as a river city. Consequently, the river did not contribute to shaping a dominant image within the urban scene. With the onset of the redevelopment process, the horizontality of the watercourse and the surrounding green areas began to enhance visual depth, emphasizing the perspective dimension of the route. This condition, combined with the breadth and continuity of the open space, generates a perceptual experience marked by a strong dynamic component, in which the visual sequence constantly changes in relation to the observer’s movement along the pedestrian and cycling paths. The perceptual processes that are activated in this area of Ferrara differ significantly from those defining citizens’ spatial experience in the historic centre, where enclosed spaces and the dense rhythm of buildings produce a more intimate and introspective perception. The Darsena therefore represents an urban area in which the perception indicator introduces a new facet to Ferrara’s urban scene: the interplay between light reflections on the water, the presence of vegetation, and the visual openness towards the fluvial landscape creates a unique perceptual quality, capable of drawing citizens toward spaces that are both distinct from and complementary to the traditional urban fabric.

Source geometry
Selected: 1

Target geometry
Selected: 5

Visibility levels	%
Complete	0
High	5
Medium	17

Fig. 6.28 – View study of the Darsena of Ferrara within the CIM model, aimed at evaluating the relationship between the built environment, the riverfront, and the surrounding green areas.

Transformation | Score attribution: 5

The Urban Transformation indicator is proposed as an analytical tool to support the monitoring of morphological and functional changes within the urban fabric. By integrating the temporal dimension, this indicator makes it possible to document transformation processes from a twofold perspective: a retrospective one, aimed at analysing modifications that have already occurred, and a prospective one, intended to estimate the intrinsic propensity for change of a plot, a block, or an entire neighbourhood.

The Darsena area of Ferrara, in accordance with the Municipal Strategic Plan (PSC), is characterized by zones identified as "to be redeveloped fabric." In recent years, this area has undergone a significant transformation, from a marginal space to a new district of urban regeneration, aimed at re-establishing a direct relationship between the city and the river, through the progressive introduction of cultural and recreational activities. The presence of residual spaces and plots awaiting completion, together with the area's regulatory designation as "to be redeveloped fabric" in the PSC, highlights, through the transformation indicator, a high potential for future development. The Darsena thus represents an evolving urban system in which morphological and functional dynamics play a strategic role in the overall regeneration process of Ferrara.

Conservation | Score attribution: 3

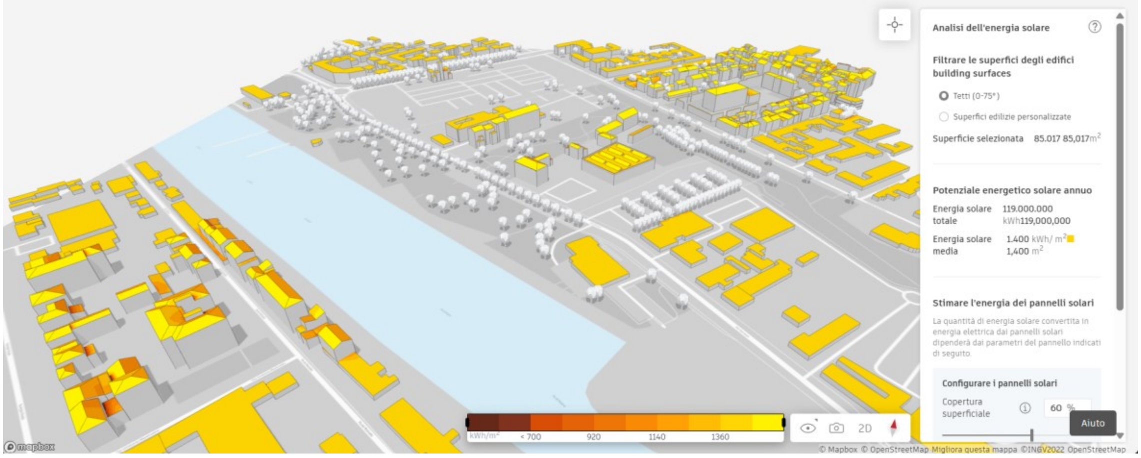
The Conservation indicator aims to identify and make visible the presence of a shared orientation toward the safeguarding of the urban scene. Conservation introduces an additional dimension, one based on a conscious choice, an intentional act that entails deciding which elements to preserve and which to exclude. In this sense, conservation becomes a useful parameter for understanding the relationship between memory, tradition, and the future, highlighting how the distinction between having and not having, preserving or letting go, is decisive in shaping collective meaning.

Fig. 6.29 - View study of the Darsena of Ferrara within the CIM model, aimed at evaluating the relationship between the built environment and the riverfront, and assessing the role of collective memory in shaping the connection between the city and its river.

Energy Behaviour | Score attribution: 3

The Energy Behaviour indicator aims to begin a cognitive process designed to provide preliminary estimates of building energy performance through an expedited assessment approach. Its main purpose is to support decision-makers in developing informed strategies for energy retrofit planning.

In the context of the Darsena of Ferrara, characterized by a combination of historical buildings, repurposed structures, and new developments, the energy behaviour indicator plays a strategic role in defining integrated efficiency strategies. The typological diversity that distinguishes this area requires an analytical approach capable of correlating energy performance with the morphological, functional, and constructional specificities of the built heritage. The analysis of the indicator reveals that the energy behavior of buildings in the Darsena area is heterogeneous. On the opposite residential bank, energy retrofitting interventions, also encouraged by recent funding programs such as the Superbonus 110%, have already initiated a significant process of performance improvement. Conversely, on the Darsena front, this process is still at an early stage, where urban regeneration and functional recovery constitute the premises for future, more widespread, and coordinated energy efficiency measures. From this perspective, the indicator highlights that the energy transition in the Darsena is underway but still in a consolidation phase: a process that, by integrating physical regeneration strategies with environmental efficiency measures, could decisively contribute to the development of a sustainable and resilient urban district.



Analisi dell'energia solare

Filtrare le superfici degli edifici building surfaces

● Tetti (0-75°)

○ Superfici edilizie personalizzate

Superficie selezionata 85.017 85,017m^2

Potenziale energetico solare annuo

Energia solare totale 119.000.000 kWh119,000,000

Energia solare media 1.400 kWh/ m^2 1,400 m^2

Stimare l'energia dei pannelli solari

La quantità di energia solare convertita in energia elettrica dai pannelli solari dipenderà dai parametri del pannello indicati di seguito.

Configurare i pannelli solari

Copertura superficiale 60 %

Fig. 6.30 – Solar energy analysis within the CIM model.

Structural Behaviour | Score attribution: 3

The Structural Behaviour indicator, aims to synthesise the analysis of the classification of building typologies on an urban scale, with the goal of beginning an exploratory process that can later be refined through more detailed methods and measurement-based tools. This measure proves particularly useful for supporting the planning of extraordinary maintenance interventions and, more generally, for guiding strategies for risk management and urban regeneration.

The Darsena area shows a heterogeneous structural behaviour, consistent with its morphological and functional complexity. This typological variety results in a diversified structural performance, both in terms of intrinsic vulnerability and in response to external agents and long-term phenomena such as subsidence. The structural behaviour indicator reveals in the Darsena a condition of evolving balance: a built fabric that has overcome its most critical issues thanks to recovery and maintenance interventions, yet still requires continuous monitoring, particularly for the oldest structures and for the buildings located near the waterline.

Post-Disaster Damage Behaviour | Score attribution: 3

The indicator of Post-Disaster Damage Behaviour is thus conceived as a dynamic measure, one that does not merely describe the pre-existing condition of fragility, but rather the sequence of processes activated in the post-event phase. It seeks to overcome the traditional static conception of vulnerability by highlighting the processual and transformative dimension of resilience. Among the dimensions feeding into the indicator are: recovery time, recovery quality, and the relative level of functionality achieved (total, partial, or transformative restoration); as well as adaptive capacity, understood as the ability to introduce structural and innovative changes in order to reduce vulnerability to future critical events.

Ferrara, due to its geographical position and soil characteristics, is exposed to multiple types of risk, particularly seismic and hydraulic. The 2012 earthquake, which severely affected the Emilia area of the Region, marked a turning point in both institutional and collective awareness regarding emergency management and the strengthening of preventive measures. Following that event, the city launched major consolidation works on public and monumental buildings, updated emergency plans, and enhanced Civil Protection coordination, with the goal of improving structural safety and operational readiness. The management of hydraulic risk also plays a crucial role in the Ferrara area. The Darsena, located along the course of the Po di Volano, lies in a morphologically sensitive zone where water levels are constantly monitored. The reclamation and hydraulic lifting system, active for centuries and continually upgraded, now represents an essential safeguard for flood risk mitigation. Within this framework, response capacity relies on an efficient network of hydraulic infrastructures, supported by alert procedures and municipal protection plans, which together help ensure citizen safety and the protection of regenerated urban areas. The experience of the 2012 earthquake, combined with the ongoing focus on hydraulic risk management, has fostered growing awareness of prevention, maintenance, and risk governance, thereby strengthening the adaptive capacity and overall resilience of the urban system.

6.5 Integration and Visualization of Indicators in CIM Models as Support for Strategic Decision-Making

The aim of this section is to verify the feasibility of graphically representing, within a single integrated system, the set of selected indicators, translating analytical data into a dynamic visualization connected to the CIM model. The proposed indicators are as follows: Urban Pressure, Hybridization, Accessibility, Traffic Congestion, Comfort, Meaning, Perception, Transformation, Conservation, Energy Behaviour, Structural Behaviour, and Post-Disaster Damage Behaviour. Each indicator was assigned a score ranging from 1 to 5 in order to construct a coherent profile of the urban context under investigation. A low score indicates a negative condition, with the exception of Urban Pressure and Traffic Congestion, for which a high value (consistent with the logic of contextual interpretation and value attribution), corresponds to an intensified condition (i.e., high urban pressure indicates a high value due to significant pressure).

The indicators were subsequently correlated through a Kiviat Chart, a graphical tool that allows for the two-dimensional visualization of multiple quantitative variables, each represented along axes radiating from a common origin. It is important to underline that this proposed framework does not claim to be exhaustive. The knowledge factor expresses the degree of depth and completeness of the available informational data: it may progressively increase through the contribution of technicians and specialists with specific expertise related to the parameters that inform each indicator.

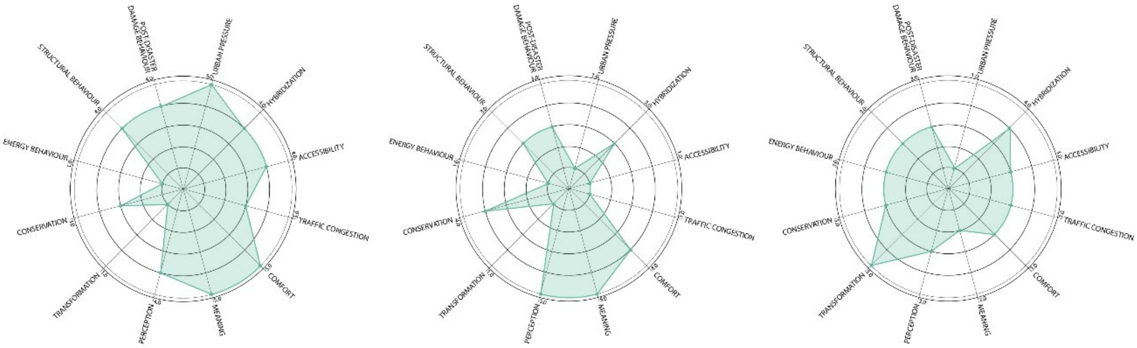


Fig. 6.31 - Visualization of synthetic indicators in CIM models as a support tool for strategic decision-making. From left: Higienópolis (São Paulo, Brazil); Verucchio (Italy); Darsena of Ferrara (Italy).

At this stage, the work takes the form of a simulation of a graphical translation process of informational contents that could potentially be integrated into the CIM model. This simulation aims to explore how the system can visually respond to strategic and scenario-based questions that guide territorial governance and transformation decisions. The response of each indicator thus makes it possible to represent how an increasing level of knowledge can progressively populate and enrich the information base of the model. In this way, the research does not focus so much on the absolute value of the data as on the visualization capacity and communicative effectiveness of the CIM system as a digital infrastructure designed to integrate, update, and interactively represent complex urban phenomena through the City Information Modeling process.

Chapter 7
CONCLUSIONS

7.1 Results

The research led to the definition of a methodological approach that, in a prospective scenario, aims to support urban areas, both metropolitan cities and smaller municipalities, currently facing multifaceted challenges within a context marked by ecological and demographic transitions. In such situations, conventional urban governance approaches frequently prove inadequate in addressing these complex issues, as they remain constrained by fragmented data silos and the absence of a unified, data-driven governance framework (Gil et al., 2011; Soltanifard et al., 2024). The proposed methodological approach, developed through the City Information Modeling (CIM) framework, emerged as a digital solution providing a multidimensional structure for comprehensive urban data management and conscious decision-making. Designed to support governance processes involving a range of stakeholders, including metropolitan administrations, municipal unions, and multi-utility companies, the research responds to the increasing need to represent the complexity of urban environments through the creation of digital platforms capable of managing multiple spatial and administrative scales.

Through the development of three case studies: Higienópolis (São Paulo, Brazil), Verucchio (Rimini, Italy), and the Darsena area (Ferrara, Italy), the CIM process was simulated, from the integration of heterogeneous data from diverse sources for the construction of the model to the definition of indicators and informational parameters. This process aimed to make the CIM framework function as a cognitive tool for interpreting the qualitative complexity of the urban scene. The development of a semantic and parametric model of the case studies, made it possible to correlate geometric, perceptual, and informational dimensions, thereby transforming raw data into a structured decision-support system. Moreover, twelve synthetic indicators were identified and simulated to describe the main factors characterizing the urban environment, thereby validating the applicability of the proposed framework across different urban and territorial contexts. Each context is distinguished by specific features that enabled the testing of the approach under multiple conditions, ranging from fast-metabolism environments characterized by urban growth and morphological transformation to historic towns undergoing processes of urban regeneration.

7.2 Impacts

The research contributes to advancing knowledge in the field of digital territorial management by consolidating CIM as an interdisciplinary process rather than a mere technological product. It serves as a strategic tool for the City Manager in addressing the challenges of transition. The proposed model supports metropolitan administrations, municipal unions, and multi-utility companies in integrating fragmented databases and simulating future scenarios aimed at sustainable governance.

From a scientific perspective, the thesis strengthens the role of representation disciplines in connecting information modelling with a plurality of actors, skills, disciplines, intermediaries, and urban policies across different interpretative scales. Operationally, the CIM approach promotes the integration of data from multiple sources, currently fragmented and, in some cases, difficult to access, into a single database, thereby supporting the use of the documentation system as a basis for intervention proposals. The research analyses and tests interoperability processes among GIS, BIM, and semantic databases, enabling data-driven and informed decision-making.

Within this framework, a further contribution lies in the development of procedures for the utilization of existing databases, recognizing that while surveying remains a valuable means of obtaining reliable data when rigorously conducted, it is neither feasible nor necessary to survey the entire urban and territorial context prior to developing the CIM model. Instead, the process should begin with available datasets to define the context transversally, subsequently employing surveys to deepen analysis in areas identified as critical, following an incremental and targeted approach in strategically relevant zones. An additional impact of the research is its promotion of a renewed interpretation of urban and territorial areas as an informative and dynamic systems, open to continuous interaction between its physical and digital components.

7.3 Discussion

The research proposes a methodological approach based on City Information Modeling (CIM), conceived as a semantic and process-oriented system. It simulates a process designed to leverage CIM’s potential as a strategic descriptive tool, capable of mediating between analysis and decision-making. It is important to underline that this proposed articulation makes no claim to completeness.

The knowledge factor represents the degree of depth and completeness of the available informational data; it may gradually increase through the contribution of professionals and specialists with specific expertise in the parameters underlying each indicator. The multidimensional and integrated visualization of data concerning the urban and territorial context facilitates, in this sense, territorial governance through more transversal competencies, enabling the interpretation of the territory by reading, through the CIM model, the complex relationships between built form, environmental parameters, and social dynamics. However, the research has also shown that the effectiveness of the developed CIM methodological approach depends on the adoption of standardized information protocols and shared ontologies. The discussion highlights that CIM is not merely a system for data collection and management but a tool capable of generating and representing knowledge about the city, in line with the objectives of the digital transition towards more informed and aware urban governance.

Nevertheless, the complexity and scale of urban areas have limited the possibility of fully integrating data into a single model, making it necessary to select representative case studies developed according to a “zoom-based” approach on specific areas. The lack of unified international standards for CIM and the heterogeneity of local data formats have influenced the scalability of the results. The subjective component, linked to the critical interpretation during 3D modeling for CIM definition, often taken for granted, proved to be crucial. To ensure homogeneous models that can coherently respond to the same questions posed by the system in a consistent manner, geometric and informational standardization is required. From a technological standpoint, this gap can be bridged through the structuring of Property Sets (Psets) and the export of files in the open IFC format, ensuring flexibility in the creation of CIM models. However, the interpretative component itself requires shared regulatory frameworks, as the modeling of large urban and territorial portions must be carried out in a way that meets stakeholder requirements while maintaining overall consistency. Finally, although processes of data population and visualization were simulated, the real-time integration of data from IoT networks and Big Data analytics remained beyond the experimental scope of this research.

7.4 Future Developments

City Information Modeling (CIM) has recently attracted significant academic attention across various disciplines as a means to address emerging urban challenges. This growing interest primarily concerns methods for visualizing CIM models in relation to the information and indicators associated with them. The significance of CIM in urban planning and management lies in its capacity to integrate heterogeneous data without redundancy, relying on existing datasets to effectively represent urban contexts through information-based models. The approach presented in this thesis contributes to defining specific standards for the development of a descriptive urban model, thereby facilitating an integrated understanding of urban systems.

In the broader context of urban representation and management, the purpose of CIM lies in integrating heterogeneous systems, with the potential to support stakeholders in developing future scenarios through a structured documentation framework that informs intervention proposals. Although the research is positioned within a forward-looking field, it nonetheless offers reflections on a topic that is increasingly debated within academia, public administration, and multi-utility sectors. Future developments should therefore focus on the operational implementation of the CIM framework within real and complex urban environments, with the aim of increasing its Technology Readiness Level (TRL).

To transition the urban model into a simulation environment such as a Digital Twin, it is essential to further develop a data layer oriented toward Big Data collection. Such a layer is increasingly recognized as a prerequisite for enabling advanced analytical capabilities and integrating Internet of Things (IoT) functionalities (Fialho et al., 2020). There is growing international interest in experimenting with and sharing best practices that can support the *Smart City* transition. This transition leverages digital technologies and data to guide urban transformations, underscoring the role of CIM in fostering innovative, data-driven urban development strategies. By integrating real-time data streams from IoT sensors and AI-based analytical systems, future developments are moving toward the frontier of the Digital Twin (DT), an innovation that some worldwide cities, among them Bologna (Italy), Singapore, and Helsinki (Finland), have started to develop. Furthermore, the Senseable City Lab at the Massachusetts Institute of Technology (MIT)[1] in Boston is an internationally renowned research centre engaged in advancing these topics. This represents one of the main challenges in creating a high-precision digital model capable of monitoring and simulating natural phenomena and related human activities. The integration of digital twins and predictive modeling will enable continuous monitoring and adaptive management of cities, extending the CIM framework toward the broader concept of the Smart City, which several urban contexts are currently developing through innovative projects[2]. In this perspective, by reading and interpreting indicators and sub-indicators within a transitional framework, the City Manager, who will necessarily be equipped with cross-disciplinary competencies, will be able to monitor the urban and territorial system in real time and, through increasingly data-centric approaches, implement simulations and urban management policies that respond to shared performance criteria and contribute to achieving targeted objectives.

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[1] For further details: https://senseable.mit.edu/.

[2] The Digital Twin of Bologna is a major urban innovation project promoted by the Municipality of Bologna and developed with the support of the Fondazione Innovazione Urbana, the University of Bologna, the Fondazione Bruno Kessler, and CINECA. Its objective is to create a digital replica of the city, a dynamic and interactive model capable of collecting, integrating, and analyzing urban data, including real-time information, to support public decision-making and improve citizens' quality of life (Luca et al., 2024).

Finally, a further line of development concerns the usability of these models. While the research has demonstrated how they can be developed and implemented within open-standard platforms, future work should investigate the integration of CIM frameworks into existing databases and platforms accessible to stakeholders, such as GeoSampa, potentially through Application Programming Interfaces (APIs). The implementation of an additional web application layer would constitute an interesting and practical evolution of the process proposed in this thesis, significantly enhancing its usability and operational potential.

LIST OF FIGURES

The list of figures is presented below. In the absence of explicit credits or source information, all images are to be considered the work of the author of this dissertation.

LIST OF REFERENCES

The research topic, which can be only with difficulty ascribed to a specific line of analogous and explicitly documented experiences, finds in this articulated list of references, organized by thematic areas, a means to express, on the one hand, its potential interdisciplinary factors and, on the other, to stitch together a series of contributions and definitions under a shared interpretative perspective. In this sense, the choice was made to present, through a concise set of thematic domains, the majority of the references cited, thus enabling the reconstruction of connections with the notes included in the text.

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