A digital code of practice for the management of historic building heritage at the district scale: approaches, methods and standardization processes

POLITECNICO DI BARI

D.R.S.A.T.E.

08

Doctor in Risk And Environmental, Territorial And Building Development

2024

Coordinator: Prof. Vito Iacobellis

XXXVI CYCLE
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DICATECh
Department of Civil, Environmental, Building Engineering and Chemistry

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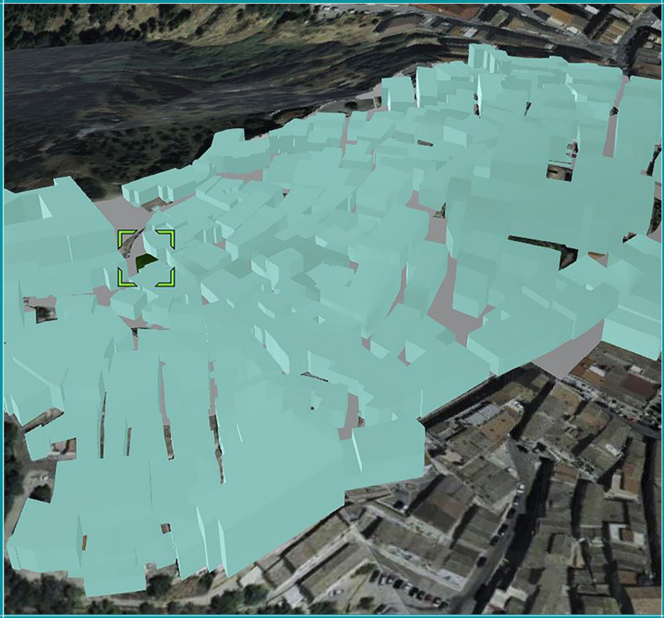

Politecnico di Bari

LIBERATORIA PER L'ARCHIVIAZIONE DELLA TESI DI DOTTORATO

Al Magnifico Rettore
del Politecnico di Bari

La sottoscritta **MARGHERITA LASORELLA** nata a **BARI** il **20/10/1993**

residente a **NOICATTARO** in via **MONSIGNOR VINCENZO PARDO n. 32** e-mail **margherita.lasorella@poliba.it**

iscritta al 3° anno di Corso di Dottorato di Ricerca in **RISCHIO E SVILUPPO AMBIENTALE, TERRITORIALE ED EDILIZIO** ciclo_**XXXVI**

ed essendo stata ammessa a sostenere l'esame finale con la prevista discussione della tesi dal titolo:
A DIGITAL CODE OF PRACTICE FOR THE MANAGEMENT OF HISTORIC BUILDING HERITAGE AT THE DISTRICT SCALE: APPROACHES, METHODS AND STANDARDIZATION PROCESSES

DICHIARA

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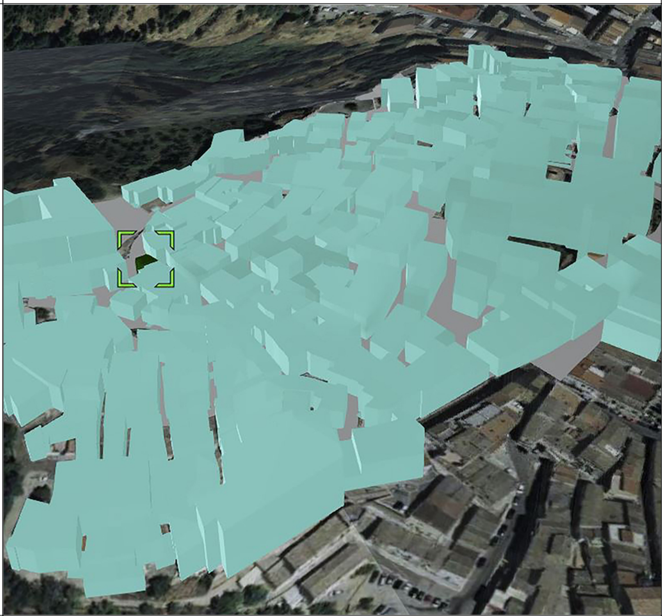

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Un codice di pratica digitale per la gestione del patrimonio edilizio storico a scala distrettuale: Approcci, metodi e processi di standardizzazione

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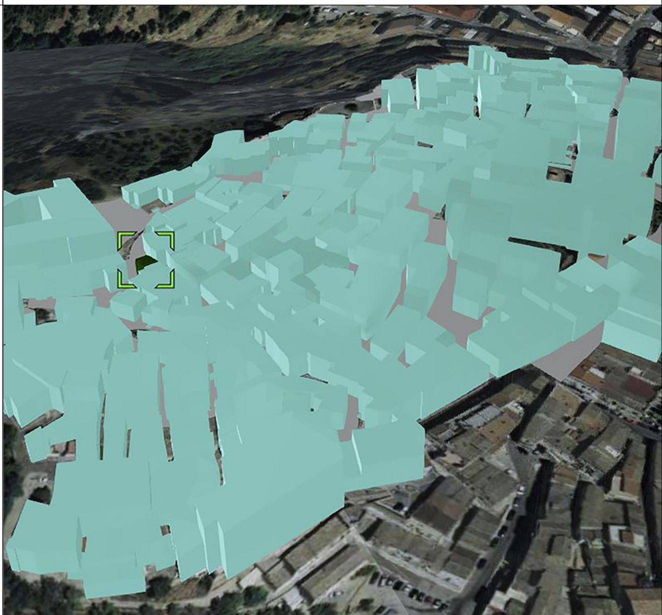


EXTENDED ABSTRACT *(eng)*

The conservation of existing architectural heritage requires a multi-level and multi-thematic process for their analysis and diagnosis, capable of collecting and correlating architectural entities (buildings, churches...) and urban entities (roads, open spaces...), as well as properties of the components (walls, roofs...) and services (water, electricity networks...), in a structured and systemic way. This is in compliance with the landscape relevance and regulations in the management and sharing of priorities and methods of intervention for their transformation. Over time, traditional procedural tools and protocols for crafting and presenting recovery plans have highlighted critical issues in terms of organicity and interpretation of the data collected, as well as an excessive request time for their processing. In parallel, recent research and application activities in the field of IoT systems have showed how digital models based on structured ontologies (CityGML, BIM) and information systems (Geo-Database and relational databases) allow the systematization of technical knowledge and the determination of unique relationships in compliance with existing sector regulations. In this scenario, the research work aims to systematise the technical knowledge information already available and, at the same time, to identify operational-methodological flows aimed at filling the existing incomplete and jumbled procedures through the use of parametric and virtual digital models. Specifically, the objective of the present research proposes a code of digital practice for the conservation and management of existing architectural heritage through the aid of parametric digital models, as well as through expeditious VR-based approaches.

This begins with the analysis of the methodological and technical principles for the development of semantic information systems for the study, modelling, cataloguing, and technical management of architectural heritage in a digital environment. At the basis of the organic structuring of technical knowledge and the decision-making system in the digital model, the qualification of the existing built heritage takes on particular importance, properly based on specific factors. The factors identified aim to convert properties and information into qualitative and quantitative data, in the first instance, and then to structure logical-relational models, according to: i) thematic taxonomies derived from the glossary of decay stones (TT), ii) ontologies existing for the geometric and semantic representation of urban and architectural entities (O), iii) technical regulations for the recovery of cultural and landscape heritage (TR), and iv) consolidated approaches and previous experiences in recovery activities (AE). The digital code of practice is structured on CityGML-based models, implemented with a technical decision support system (T-DSS). Specifically, the work focuses on the qualification of the intervention classes and the related priority levels, considering the state of conservation of the existing architectural heritage (physical and functional obsolescence). The relationships underlying the T-DSS consider the logical and mathematical functions referring to the corresponding thematic regulations: i) UNI 11182, for the identification of the decay of stone material, ii) UNI EN 16096:2012, for the qualitative analysis of the conservative state of the existing architectural heritage; iii) UNI/CEN TS 17385:2019, to quantitatively evaluate the state of conservation of architectural artefacts, and iii) Consolidated Construction Law (Presidential Decree President of the Republic no. 380/2001), which defines the class of interventions. Finally, the T-DSS structure is organized to implement the semantic data in the CityGML-based model (factors and descriptors). The digital code of practice has applied and validated on three emblematic pilot cases with respect to the intrinsic criticalities linked to the physical and regulatory obsolescence of the identified historical area.

Keywords

Technical Knowledge, Technical Decision-Support System (T-DSS), Virtual Reality, CityGML, Existing architectural heritage

EXTENDED ABSTRACT *(ita)*

La conservazione del patrimonio architettonico esistente richiede un processo multi-livello e multi-tematico in grado di collazionare e relazionare entità architettoniche (edifici, chiese…) e urbane (strade, spazi aperti…), nonché proprietà dei componenti (murature, coperture…) e servizi (reti idriche, elettriche…), in maniera strutturata e sistemica. Nel corso del tempo, i tradizionali strumenti e protocolli per la creazione e la restituzione di piani di recupero hanno evidenziato criticità in termini di organicità e interpretazione dei dati raccolti, nonché un'eccessiva richiesta di tempi per la loro elaborazione. Parallelamente, le recenti attività di ricerca e applicazione nell'ambito dei sistemi IoT hanno evidenziato come i modelli digitali parametrici, basati su ontologie strutturate (CityGML, BIM) e i sistemi informativi (Geo-Database e database relazionali), consentono la sistematizzazione dei dati di conoscenza tecnica e la determinazione di relazioni univoche nel rispetto delle esistenti normative del settore. In questo scenario, il lavoro di ricerca mira alla sistematizzazione delle informazioni di conoscenza tecnica già disponibili, e al contempo ad individuare flussi operativi-metodologici finalizzati a colmare le esistenti procedure lacunose e farraginose mediante l'utilizzo di modelli digitali. Nello specifico, l'obiettivo dell'attività di ricerca del dottorato propone un codice di pratica digitale per la conservazione e la gestione del patrimonio architettonico esistente attraverso l'ausilio di modelli parametrici, nonché mediante approcci speditivi VR-based. Ciò, a partire dall'analisi dei principi metodologici e tecnici per l'elaborazione di sistemi informativi semantici per lo studio, la modellazione, la catalogazione e la gestione tecnica del patrimonio architettonico in ambiente digitale. Alla base della strutturazione organica della conoscenza tecnica e del sistema decisionale del modello digitale assume particolare rilevanza la qualificazione del patrimonio costruito esistente. Essa si basa su specifici parametri (descrittori e fattori), correlati tra loro mediante relazioni logico-matematiche derivate da approcci strutturati e normative vigenti.

Difatti, i parametri individuati mirano a convertire proprietà e informazioni in dati qualitativi e quantitativi, in prima istanza, e poi a strutturare modelli logici-relazionali, secondo: i) tassonomie tematiche esistenti (TT), ii) ontologie esistenti per la rappresentazione geometrica e semantica di entità urbane e architettoniche (O), iii) normative tecniche per il recupero del patrimonio culturale e paesaggistico (NR), e iv) approcci consolidati ed esperienze pregresse nelle attività di recupero (AP). Il codice di pratica digitale è strutturato su modelli CityGML-based, implementati coerentemente con un sistema di supporto decisionale tecnico (T-DSS). Nello specifico, il lavoro si concentra sulla qualificazione delle classi di intervento e dei relativi livelli di priorità, considerando lo stato di conservazione del patrimonio architettonico esistente (obsolescenza fisica e funzionale). Le relazioni alla base del T-DSS considerano le funzioni logiche e matematiche riferite alle corrispettive normative tematiche (NT): i) UNI 11182, per l'identificazione dei tematismi di degrado del materiale lapideo, ii) UNI EN 16096:2012, per l'analisi qualitativa dello stato conservativo del patrimonio architettonico esistente; iii) UNI/CEN TS 17385:2019, per la valutazione quantitativa dello stato conservativo dei manufatti architettonici, e iii) Testo unico dell'edilizia (D.P.R. Decreto Presidente della Repubblica n. 380/2001), che definisce la classe degli interventi. Infine, la struttura T-DSS è organizzata in modo da implementare i dati semantici nel modello CityGML-based. Conseguentemente, il codice di pratica digitale è stato applicato e validato su tre casi pilota emblematici rispetto alle criticità intrinseche legate all'obsolescenza fisica e normativa delle aree storiche individuate.

keywords

Conoscenza tecnica, Sistemi di Supporto Tecnico Decisionale (DSS-T), Realtà Virtuale, CityGML, Patrimonio architettonico esistente

INDEX

INTRODUCTION

The existing building heritage constitutes a collection of intricate historical architectural artefacts characterised by specific building elements. Over time, these structures have undergone significant changes that have altered their original configuration, necessitating recovery and restoration work. The primary goal of these interventions has arisen from the essential need to adapt the spaces to the activation of essential services and ensure their safety, as well as preserve their architectural integrity.

Furthermore, recent natural and man-made events have underscored the vulnerability and high exposure of the existing built heritage. Indeed, these factors consistently prompt the scientific and technical community to develop strategies for risk planning and management.

The main aim is to protect and preserve the built architectural heritage, acknowledging it not only as a historical and cultural asset but also as a crucial element in the resilience of communities in the face of environmental and human challenges. Within the built environment itself, Cultural Heritage is particularly vulnerable due to critical issues stemming from the inherent characteristics of these assets.

With regard to the latter, i.e. objective conditions that increase the degree of fragility of architectural artefacts, the following are identified: i) geographical aspects of the site where the asset is located, ii) morpho-typological architectural characteristics of the artefact, iii) degree relative to the state of preservation, vi) intrinsic characteristics relative to the construction materials and v) historical stratification of transformations and interventions that have altered the original construction system.

Actually the management of the existing architectural heritage is regulated on a national scale, identifying principles for its conservation based on previous Restoration Charters. In Italy, the regulatory binding framework for the landscape heritage is entrusted to the regions. This responsibility manifests through "Landscape Plans" (in compliance with Legislative Decree no. 42 of 2004), providing tools and guidelines that are useful for identifying the system of values associated with the complex built district system, irrespective of specific characteristics at the building scale.

In this scenario, the advancement of digital technologies has fundamentally altered the traditional methodological approach to the cognitive and conservative processes of architectural heritage, propelling it into a new digital dimension. Innovative methodologies for analysing the existing built environment through the creation of information models, capable of integrating and correlating a plurality of heterogeneous information, prove to be valuable tools for understanding, archiving, and managing information on architectural heritage. These methodologies are also instrumental in conducting specific analyses related to the multi-risk management to which the built environment is exposed.

Consequently, the bibliographical analysis carried out has highlighted the growing awareness of the potential of digital systems applied to the field of conservation and diagnostics, primarily addressing: i) the definition of methodologies for the acquisition and processing of digital models, ii) the development of interoperable systems capable of managing data and information, iii) the creation of digital archives structured according to defined ontologies, and iv) multi-user (expert, administrative, and end-user), multi-spatial (in situ and on-desk), and multi-scalar (from the urban system to the architectural artefact and building component) participation in the recovery/restoration process of the architectural asset to its final use.

It follows that architectural heritage can be represented by means of Digital Models structured according to specific standards, as well as through the use of Virtual Reality techniques, encompassing different information levels. These levels are valuable for the analysis of the state of conservation and the predictive evaluation of suitable conservation strategies.

Therefore, the implementation of standardised digital models, integrated with information systems that leverage Virtual Reality techniques in the technical understanding of historical artefacts, has opened up new research perspectives that have not yet been fully explored. This development elevates research towards the creation of new methodological and operational approaches.

Research gaps

The heterogeneity and complexity of the characteristics of historic buildings that constitute architectural heritage are correlated with an equally dizzying increase in the types of information. These types differ both in their nature as data and in their disciplinary scope, revolving around the asset. These critical issues - encompassing huge amounts of data, fragmentation, and interoperability of information - constitute a crucial aspect of strategies for the protection and conservation of historical heritage on an urban and building scale.

In this context, the cognitive and conservative process of the existing historical heritage, even on a large scale, represents a fundamental aspect through which to define suitable recovery and/or risk mitigation actions. Moreover, alongside the complex nature of the cognitive process, another aspect of particular importance in the analysis, identification, and definition of actions to protect and safeguard the built heritage concerns the assistance of digital information and decision-support systems.

These systems enable the development of management capabilities for the protection, enhancement, and recovery of the existing built environment.

Indeed, scientific literature has highlighted the lack of standardized protocols for the management and recovery of historical building heritage, especially in the phase of analysing the state of conservation in a punctual manner compared to the phase of diagnosing architectural elements (such as masonry and roof).

In contrast, most studies present an overall analysis of the state of conservation of individual buildings, correlating the conservation-diagnostic data as a global parameter at the scale of the building or individual subsystem.

Furthermore, there is a deficiency in the integration of standards with virtual models for remote surveying and decision support systems for the identification of intervention strategies.

Although the latter potential has mainly been tested and applied for the energy analysis of historic buildings.

With the aim of overcoming the criticalities inherent in the traditional conservation process and in order to achieve the research objectives through the potential of digital systems, the following research topics were investigated:

- identification of standardised parameters for the qualification of historical architectural heritage;
- review and critical analysis, as well as evaluation, of the use of existing ontologies and glossaries with respect to the identified parameters and relationships;
- semantic conceptual structuring to relate cognitive information to the digital model;
- evaluation of the integration of standardised digital models with digital information systems using Virtual Reality techniques;
- analysis, identification and evaluation of information systems for decision support in the process of conservation of the existing architectural heritage;
- implementation and validation of decision-support information systems for the elaborated relational-logical structure;
- development of expeditious systems for the acquisition and analysis of the architectural heritage with the aid of virtual reality techniques.

Research questions

In the outlined research context, the study has been developed by focusing on certain key questions, among which the following research questions stand out:

RQ1. How can the existing architectural heritage be analysed using the CityGML standard?

RQ2. Within the discipline of conservation, preservation, enhancement and management of the existing architectural heritage, for which types of assets is the CityGML ontological framework applied?

RQ3. In which phase of the conservation process (knowledge, diagnostic, intervention) is the CityGML ontology applied?

RQ4. Can the phases of the conservation process be carried out holistically with the help of parametric models integrated with Decision Support Systems?

Research aim

The conservation and protection of historical heritage are topical issues of great interest, highlighting the need to develop specific protocols for the systematisation, analysis and management of relevant information. This is crucial for enabling the planning of adequate risk mitigation and prevention strategies.

Therefore, it is significantly important to connect the semantic richness and geometric complexity of the existing built environment to the multiple and different parameters that characterise the risks it faces. This connection can be achieved through suitable forms of representation and systematization.

To this end, it is indispensable to resort to new codes of practice, both from a procedural-methodological point of view and concerning the use and integration of the most modern tools for the acquisition and digitization of the real environment.

The research work aims to systematise the already available technical knowledge information, and at the same time to identify operational-methodological flows aimed at bridging the existing gaps and cumbersome procedures through the use of parametric and virtual digital models.

Specifically, the aim of the PhD research activity is to establish a digital code of practice for the conservation and management of the existing architectural heritage.

This involves the use of digital models and rapid approaches based on Virtual Reality (VR). The research begins with an analysis of the methodological and technical principles for developing semantic information systems.

These systems are designed for the study, modelling, cataloguing, and multi-risk technical management of architectural heritage within a digital environment. Thus, the objective of developing the digital code of practice is to elaborate a methodological-operational protocol that enhances the technical understanding of the existing architectural heritage. Additionally, it aims to identify conservation strategies through the utilization of Decision Support Systems.

Structure of the thesis

The research is structured in three fundamental parts, each of which focuses on specific aspects related to the structuring and management of technical knowledge of the historical architectural heritage, for the identification of conservation strategies.

Part 1 - Reference Scenario

In this section, the scope of the study is outlined, and the importance of conserving the existing built heritage at the district scale is contextualised. Specifically, the challenges and opportunities related to the understanding and management of cognitive information in a multi-scalar and multi-disciplinary context are analysed. The existing needs and gaps in the field are identified in detail, paving the way for the following sections. The first part comprises four chapters, focusing on the Reference Scenario.

The first chapter analyses the intrinsic and evolutionary meaning of the “Historic Centre”. Particular attention is given to the qualification, especially focusing on the parameterisation procedures for the built and urban environment. This involves a critical analysis at a national level of the regulatory context, including restoration charters and reference regulations for the formulation of recovery plans. Additionally, the chapter examines previous experiences in characterising historic districts.

The second chapter explores existing digitisation techniques for digital acquisition at the building scale, employing methods such as digital photogrammetry and virtual reality techniques. It also examines digitisation at the urban scale, focusing on the use of Spatial Information Systems.

The third chapter investigates theoretical and methodological issues related to the management of information referable to the classification of the existing built heritage, through the identification of existing standards and ontologies for geometric and semantic representation. Therefore, the conceptual basis of knowledge aimed at the recovery of large-scale historic buildings is examined.

The fourth chapter reports a systematic review of the scientific literature on the use of the CityGML standard in the field of historic building heritage conservation and management. In this scenario, it was possible to state that digital systems and models exploit the potential of ontologies whose rules and relations are known, and allow the creation of interoperable information flows in the cataloguing, archiving and systematisation phases of the conservation and maintenance process. The examination of previous research work enabled the identification of the research perspectives conducted.

Part 2 - Theoretical and Methodological Insight

The second part is developed in a single chapter that examines a specific methodological-operational approach for the digitisation of the cognitive and conservation process of historic districts. In particular, this part makes explicit the tools and method underlying the digital code of practice developed for the technical knowledge of the historical architectural built heritage, as well as for the semi-automatic derivation of intervention classes and priorities by a Decision Support System. This was developed through the structuring of a logical-relational scheme for the qualification of the built environment through the use of standardised digital models according to the CityGML ontology, as well as digital systems exploiting Virtual Reality techniques. However, a modular structure has been developed to support a multidisciplinary information system. Where, the central Core is constituted by the geometric models of the buildings, to which are related thematic modules for the in-depth study of specific knowledge domains. In that, the semantic enrichment of digital models on a district scale allows the storage of multiple information (archival, documentary, historical, technical, diagnostic) increasing the geometric reconstruction of architectural artefacts for technical knowledge.

Part 3 - Application and validation to pilot cases

The third part reports the application and validation of the digital code of practice elaborated for the management of the existing architectural heritage through VR-based expeditious approaches, as well as through the use of a multiscale and multidisciplinary digital information system for the analysis, modelling and cataloguing of the chosen survey areas.

In detail, the digital code of practice has been validated on three emblematic pilot cases with respect to the intrinsic criticalities related to the physical and regulatory obsolescence of buildings (number and size of rooms, lack of services and urbanisation systems, lack of maintenance activities and/or rehabilitation interventions). However, the following pilot case studies were identified (Figure 1):

- Historic Centre of Carovigno (Brindisi, Italy);
- El Cabanyal neighbourhood (Valencia, Spain);
- Historic Centre of Ascoli Satriano (Foggia, Italy).

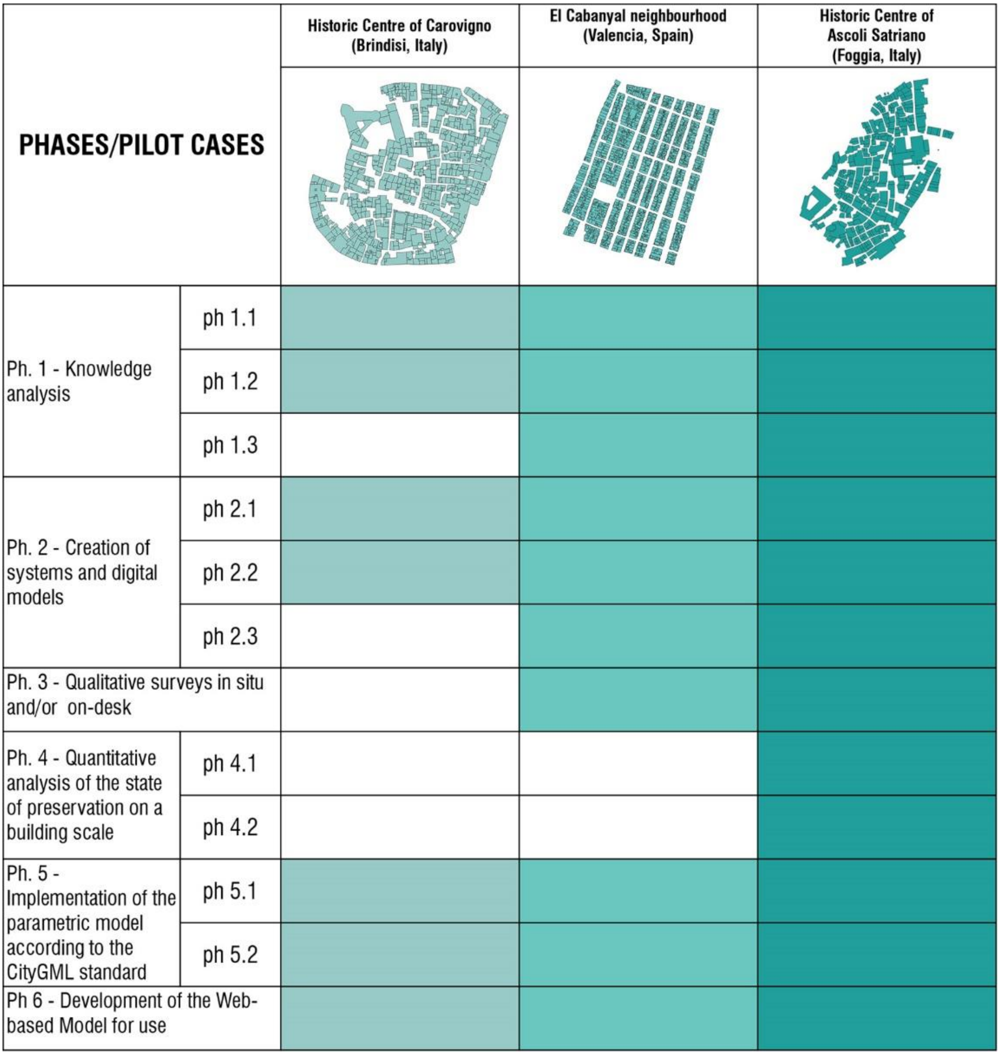


Figure 1-Phases and sub-phases of the digital code of practice applied and validated for each pilot case

In detail, the final result of the experimentation is reported, which allows the dissemination of knowledge during all the phases of the conservation process among the different actors involved, as well as creating a link between institutional-scientific bodies and public bodies in the planning and design phases of interventions for the recovery of Historic Centres/urban scales, solving critical issues related to the abandonment, physical degradation, and functional obsolescence of Historic Centres.

The digital code elaborated is configured as a digital environment that can be implemented over time with the enrichment of the relevant information frameworks. This, with the aim of providing a tool to support the processes that affect the existing built heritage in the field of rehabilitation.

Although the digital code of practice can be used by actors from different sectors, including conservation experts, it is structured with a view to providing a methodological-operational approach useful to public administrations for the identification of predictive strategies for the conservation of the existing built heritage.

Through this tripartite structure, the research provides a comprehensive overview of the semantic and geometric structuring of the cognitive and conservation process, from the theoretical and methodological context to practical applications in specific contexts.

PART 1 RESEARCH OVERVIEW

Reference Scenario

1. THE PRESERVATION PROCESS OF URBAN HISTORIC DISTRICTS

In the field of conservation and management of the existing architectural heritage, historic urban areas are of particular importance. The management of these contexts represents a key element in safeguarding and handing down the historical, cultural and architectural value of our communities. In this scenario, these urban areas commonly referred to as Historic Centres, denoting their well-established settlements and building structures. The Historic Centres constitute a rich diffuse heritage, recognised as a precious reservoir of historical and cultural values, where the deep connection between the environment and the surrounding territory clearly emerges (Pendlebury et al., 2009).

This chapter aims chronologically outline the evolution of the concept of recovery and conservation of historic urban areas. It starts by exploring the inherent significance encapsulated in the term "Historic Centre" and progresses to examine the regulatory changes that have shaped endeavours to safeguard these environments.

The fundamental notion of "Historic Centre" encapsulates the historical and cultural richness of an urban area, representing as a focal point for the preservation of significant remnants from the past, thereby rendering it an invaluable heritage.

Within this framework, the concept of recovery and conservation goes beyond mere physical preservation; it embodies a commitment to maintaining the identity and collective memory of a community. Deepening this concept, early attempts to preserve historic urban areas, often understood as the beating heart of the city, emerged. However, it is as time evolves that the focus on the preservation of historic urban areas becomes a central issue in urban conservation policies (Chandan & Kumar, 2019).

The evolving regulatory framework has assumed a pivotal role in this context. The succession of laws and regulations over the years mirrors an increasing recognition of the significance of conserving historical heritage. This shift from an isolated to a systematic approach is evident in the way regulations have been amended to integrate the preservation of historic urban areas into urban plans (Rodwell, 2018).

Advancements in regulations go beyond safeguarding physical structures; they also aim to encourage the sustainable utilisation of these areas, striving to reconcile conservation with contemporary requirements. This reflects a harmonization between historical heritage and modern dynamics, consequently reshaping historic urban areas into living and functional spaces.

This diachronic overview highlights how the concept of rehabilitation and conservation of historic urban areas has undergone a significant transformation over time, moving from mere physical preservation to an integrated approach that considers history as a fundamental part of contemporary life. Constantly evolving legislation reflects this growing awareness and emphasises the importance of balancing preservation with the dynamic needs of urban communities.

1.1. The concept of the Historic Centre

The concept of the historic centre encompasses a complex plurality of meanings intrinsically linked to various phenomena, including decay and abandonment, that permeate its existence. Understanding it requires the exploration of multiple facets and dynamics that delineate its context and current state. The Historic Centre, as a concept, transcends mere physicality; rather, it is the outcome of a generative process that has moulded its structure and imbued it with layers of signs and languages over time.

However, its intrinsic significance can be derived from phenomena such as physical and functional degradation, which compromise its original aesthetic appeal and practicality.

Degradation can manifest itself through neglect of structures, loss of architectural authenticity and disfigurement of public spaces. Abandonment further complicates the narrative of the historic centre. When buildings and spaces are neglected or deserted, a process of decay sets in, with consequences for the social and economic vitality of the area. Abandonment may also be related to urban dynamics, such as demographic shifts, involved social or economic transformations (Micelli & Pellegrini, 2018).

Over the years, the concept of the historic centre has undergone a significant evolution, manifesting a progressive enlargement both in its physical identification and in its intrinsic meaning.

Originally conceived as an urban and architectural reality of cultural value, this concept has progressively expanded to incorporate social and economic dimensions, thus enriching its complexity and relevance.

In addition to its physical and cultural identity, the Historic Centre has become a place that embodies the social dynamics of the community that inhabits it. This means considering not only the buildings and public spaces, but also the human relationships, daily activities and cultural diversity that help define the social texture of the place. Similarly, the evolution of the concept of the Historic centre has embraced economic dimensions. Business activities, job opportunities and local economic dynamics have become an integral part of its definition. The economic vitality of the Historic Centre can directly influence its overall health, affecting the preservation and enhancement of Cultural Heritage.

This greater transformation has led to a holistic view of the Historic Centre as a dynamic and interconnected urban entity in which physical, cultural, social and economic components converge in a unified context. Therefore, any strategy for the conservation, rehabilitation or development of the Historic Centre must consider this conceptual evolution, addressing in an integrated manner the multiple dimensions that contribute to its overall identity.

At the Italian level, the significance of the Historic Centre is fundamental, both for the historical architectural value that defines these areas and for the numerous studies dedicated to it.

The diffuse historical urban environment, known as the Historic Centre, constitutes a Cultural Heritage of inestimable value, representing tangible evidence of the history and culture of local communities over the centuries. The presence of numerous architectural assets of historical relevance gives these places a unique identity, made up of cobbled streets, historic squares, ancient buildings and monuments that tell stories of the past.

These areas are both repositories of the past and vital spaces that host daily life, cultural events and social activities, helping to shape the essence of towns and villages. Simultaneously, the Historic Centre is the subject of numerous practical studies with the goal of preserving its authenticity and fostering its improvement.

Researchers have developed several studies on the analysis of architectural, urban planning and cultural elements to understand the dynamics that have shaped these places over time. These studies provide the basis for defining conservation, restoration and redevelopment policies aimed at ensuring the protection of this heritage and promoting its sustainable use.

1.2. The conceptual metamorphosis of urban preservation

To comprehensively contextualize the issue of Historic Centres recovery, it is necessary to refer into the primary studies and documents dedicated to the protection and conservation of these areas, while also considering the relevant regulatory frameworks. In Italy, the notion of a Historic Centres, characterised as a dispersed historical urban space, holds paramount significance.

Several studies have been conducted to understand and safeguard Italy's Historic Centres, which serve as repositories of Cultural Heritage. These investigations contribute substantially to the body of knowledge surrounding urban conservation and revitalization efforts. Moreover, the intricate interplay between historical significance and contemporary urban planning necessitates a nuanced understanding of the multifaceted challenges associated with preserving these unique spaces.

The regulatory framework further underscores the commitment to safeguarding Historic Centres. National and local regulations in Italy outline guidelines and directives aimed at maintaining the integrity of these areas. These regulations often address issues such as architectural preservation, land use planning, and sustainable development to strike a delicate balance between the preservation of Cultural Heritage and the evolving needs of modern urban life.

The issue of Historic Centre recovery in Italy is deeply rooted in a rich tapestry of studies, documents, and regulatory measures. This comprehensive approach reflects the intricate relationship between preserving historical urban spaces and fostering sustainable, vibrant communities.

The discussion below emphasizes that in the past, international sources such as restoration charters underscored a close overlap between the disciplines of conservation and architectural restoration. During this period, these two fields were regarded as intricately interconnected, often treated as a unified entity within the realm of safeguarding historic and artistic heritage. In particular, interventions on historical-architectural heritage were guided by an approach that sought to distinguish between old buildings deemed worthy of preservation and those of lesser value that could undergo transformation. This reflected a clear demarcation between structures with high historical or artistic significance and those considered less noteworthy from a historical-architectural standpoint. Conservation policies and practices predominantly centered on physically restoring buildings, with the primary goal of maintaining their original appearance. Simultaneously, structures deemed to possess lower historical value were susceptible to alteration or even demolition. This was exemplified in policies like Haussmann's city redesign, driven by functional considerations, ornamental enhancements, or the isolation of monuments. Over time, this once-clear distinction has started to fade as awareness of the complexity and diversity inherent in Cultural Heritage has expanded. The evolving approach to conservation has ushered in a greater appreciation for all architectural elements, recognizing them as integral components of a broader historical fabric. It can be asserted that the field of Historic Centre redevelopment experienced significant growth and development in the 1960s, with the promulgation of the Gubbio Charter that established the fundamental principles for the preservation and redevelopment of historic urban areas (Concas & Guida, 2022). This charter, promulgated in 1960, laid down fundamental principles for the preservation and revitalization of historic urban areas.

During this decade, there was a notable increase in awareness regarding the crucial need to safeguard and rehabilitate Historic Centres. This heightened consciousness was prompted by the looming threats of urban decay, building speculation, and profound shifts in social and economic dynamics.

The Gubbio Charter, playing a pioneering role, outlined guiding principles for the rehabilitation of Historic Centres in Italy. Emphasizing the importance of integrated approaches, the charter advocated for considerations not only of architectural aspects but also of social, cultural, and economic factors in urban regeneration initiatives. In this way, the Gubbio Charter established a conceptual framework that acknowledged the intricate challenges associated with conserving Historic Centres, providing a model for subsequent urban regeneration efforts.

In contemporary understanding, it is acknowledged that even buildings previously considered of lesser value may possess intrinsic significance, serving as witnesses to specific eras, styles, and customs. The current focus has shifted towards the valorisation of the entire heritage, placing greater emphasis on the diversity and complexity of historical stratifications within a given area.

In this evolving context, interventions are no longer rigidly categorised based on a strict distinction between valuable and less relevant buildings. Instead, they are guided by more inclusive approaches that consider the variety and richness of historical-architectural heritage as a whole. The awareness of the necessity to balance conservation with adaptation to contemporary needs has contributed to shaping a more holistic perspective on heritage protection. As a result, whereas in the past the concepts of conservation and architectural restoration were often considered synonymous, today, conservation has transformed into a broader and more interdisciplinary discipline. It embraces a holistic view of Cultural Heritage and advocates for more inclusive and sustainable practices.

1.2.1. Restoration charters in the international panorama

Restoration charters are documents that provide ethical, scientific and methodological guidelines to ensure accurate and respectful interventions in the conservation and restoration of Cultural Heritage.

The following is a brief diachronic overview:

The Charter of Athens (1931), the first charter of restoration written at the International Conference of Architects in Athens, which affirmed the protection of the architectural heritage by standardising legislation (Iamandi, 1997). One of the main objectives of the Athens Charter is to respect the construction techniques of architectural artefacts. This implies that, when intervening on a historical site or monument, the original identity and morpho-typological characteristics of the building must be preserved and respected. In essence, conservation interventions must be carried out in such a way as to maintain the authenticity and integrity of the historic monument with its surrounding built context.

The Italian Charter of Restoration (1932), issued by the Higher Council for Antiquities and Fine Arts, incorporates the principles asserted by the Athens Charter at the Italian level (Arti, 1932). The Italian Charter of Restoration underscores the conservation of all elements of the monument that have a historical-architectural significance, advocating for the inclusion and restoration of diverse architectural styles that have left their mark on it over time.

The Venice Charter (1964) was adopted in Venice during the Second International Congress of Architects and Technicians of Historic Monuments (Jokilehto, 1998). It underscores fundamental ethical and methodological principles for monument restoration, emphasising the crucial importance of respecting historical and artistic authenticity. This involves employing appropriate forms of systematic maintenance interventions aimed at recovering the historical monument. Simultaneously, it advocates for the preservation of all architectural elements possessing historical-identity characteristics to be protected and upheld. Even in this case, the notion of historic monument encompasses the architectural-insular aspect harmonised in the urban-landscape environment.

The Italian Charter of Restoration (1972), encompasses documentation related to the safeguarding of historical centres and the execution of archaeological-architectural restoration (MINISTRY OF EDUCATION, 1972). Comprising twelve articles, the Italian Restoration Charter introduces and permits the use of new techniques and materials in restoration work to address conservation challenges arising from atmospheric pollution and thermo-hygrometric conditions in environments. In detail, Article 4 of the Restoration Charter (1972) defines “*preservation*” as any conservative measure that does not involve direct intervention on the work, and "*restoration*" as any intervention aimed at maintaining works in good condition, facilitating their comprehension, and fully transmitting them to future generations. Furthermore, Annex D provides instructions for the protection of Historic Centres. It stipulates that both traditional old urban centres and areas where historical aggregates have consolidated, even if transformed over time, characterised by specific historical testimony or elevated urbanistic-architectural features, should be considered for the identification and perimeter of Historic Centres. It also asserts that the primary purpose of restoration work in historical centres is to ensure, through ordinary or extraordinary measures, the enduring presence of historical-identity features over time. In this case, the concept of restoration in Historic Centres goes beyond specific operations focused on preserving individual monuments.

It extends to the comprehensive conservation of the entire urban organism and all elements contributing to its character. The new vision of safeguarding Historic Centres implies a holistic reorganisation within the wider urban and territorial context, also considering connections with future developments. This requires a coordination of urban planning actions aimed at the protection and recovery of Historic Centres, starting from outside the cities and implementing a planning of interventions on a territorial and urban scale. Following this, the building aggregates constituting the Historic Centre should be conserved in their typological aspects, as these reflect the functions that have characterised the use of these elements over time. Within this framework, any restoration effort should be preceded by a detailed historical-critical analysis aimed at assessing and fully comprehending the urban, architectural, environmental, typological, and constructive values of the site. On one hand, the conservative approach should include consistent criteria for interventions throughout the Historic Centre. On the other hand, it is equally crucial to identify and account for varying degrees of intervention, both at the urban and building levels, to ensure an appropriate response to the specificities of each area.

Therefore, the concept of "*Conservative Renovation*" emphasises the need to preserve and restore the original qualities of the Historic Centre without compromising its authenticity. This approach implies a commitment to preserving the typological characteristics of buildings and to ensuring a balance between respect for the historical heritage and the need for adaptations to modern requirements. The Charter outlines the main types of intervention at urban planning level: i) urban reorganisation.

This involves verifying and, if necessary, modifying the urban-territorial structural layout. Special attention is given to existing relationships between the Historic Centre and urban-building developments, particularly from a functional perspective; ii) road reorganisation. This includes analysing and revising road connections and traffic flows that impact the structure of the Historic Centre; iii) revision of street furniture. This comprises modifying and reorganising the connection between built and urban areas (streets, squares, and open spaces); iv) static and hygienic renovation of buildings. This focuses on respecting the typological, constructive, and functional characteristics of building organisms; and v) functional renovation of internal organisms. This addresses the functional adaptation of internal structures. These interventions are executed through the following urban planning instruments: i) General Regulatory Plans, aimed at restoring the relationship between the Historic Centre and the urban area of the city; ii) detailed plans, for the renovation of the significant elements of the Historic Centre; and iii) subdivision executive plans, extended to a block.

The Amsterdam Charter (1975), adopted by the Committee of Ministers of the Council of Europe, also known as the European Charter on Architectural Heritage, represents an important step towards the valorisation and conservation of the architectural heritage in Europe (The Declaration of Amsterdam, 1975). This document underscores that architectural heritage extends beyond individual buildings of exceptional value to encompass historic aggregations, blocks, and neighbourhoods with historical or cultural significance. Further, the Charter emphasises that the conservation of existing heritage is not an isolated or secondary issue, but rather an essential element to be integrated into urban and spatial planning and development. This approach highlights the importance of viewing architectural heritage as an integral part of the community's fabric and identity, rather than a separate or marginal element. Therefore, the charter emphasises the importance of prioritising the conservation of architectural heritage one of the main objectives of urban planning and spatial development. This involves adopting an integrated approach that actively engages citizens, empowering them in the decision-making process. This approach is based on a detailed analysis of the architectural and functional characteristics of spaces in the built-urban fabric, combined with the assignment of functions to buildings that are consistent with current living conditions. Consequently, integrated conservation, as emphasised in the charter, requires the simultaneous consideration of the continuity of existing social and physical realities in urban and rural communities.

The Washington Charter (1987) is an international charter that builds upon the principles articulated in the Venice Charter (1964). It defines the principles and objectives, methodology and tools, to safeguard the quality of Historic Centres. The charter affirms that safeguarding actions must be an integral part of economic and social development, considered across all levels of spatial planning (Charter, 1987).

In particular, the document highlights and identifies the main characteristics of the historic city to be preserved, including: i) the urban form, defined by the urban-building layout; ii) the relationships between urban spaces (built environment, urban, green); and iii) the morpho-typological aspect of buildings.

From a methodological perspective, the analysis of historic towns requires a multidisciplinary approach, as defined in the charter. The preservation plan must be conceived as a document that thoroughly explores the historical, architectural, technical, sociological and economic aspects of historic towns at different scales of analysis. Additionally, the plan must clearly and precisely identify the buildings or aggregates of buildings to be conserved and those that may have to be demolished under specific circumstances. The decision is the result from a prior analysis of the conservation status, meticulously assessing the current condition of architectural elements and taking into account authenticity and cultural value. A crucial aspect highlighted in the charter is that the effective conservation of Historic Centres cannot be limited to the static preservation of existing buildings.

On the contrary, it must integrate new functions and infrastructure, allowing historic towns to evolve and remain viable in the contemporary context. This implies the ability to adapt historic spaces to modern needs, while ensuring respect for distinctive architectural and cultural characteristics. For this reason, the charter emphasises the importance of permanent maintenance interventions of the built environment. These ongoing interventions are essential to preserve the integrity and beauty of historic buildings over time, helping to prevent deterioration and ensuring long-term sustainable preservation.

The Krakow Charter (2000), evolving from the Guidelines for the Conservation of Cultural Heritage, places a strong emphasis on the concept of sustainable development and integrates the needs of Cultural Heritage with those of local communities. It reiterates the principles outlined in the 1964 Venice Charter, underscoring the importance of preserving individual elements of architectural heritage as bearers of significant values. Furthermore, the Krakow Charter emphasises that proper preservation requires the elaboration of a *Conservation Plan*, which implies the definition of decisions. These decisions must be translated into a restoration project drawn up according to appropriate technical and structural criteria. The need to protect individual built elements as repositories of architectural heritage values underscores the unique and identifying characteristics of each element. This approach aims to preserve the authenticity and integrity of the individual components, recognising them as bearers of cultural and historical significance. The elaboration of a *Conservation Plan* is a crucial step in the preservation process. This plan includes the definition of clear and considered strategies for the protection of the architectural heritage, identifying short and long-term priorities and objectives.

1.2.2. The Italian Regulatory Framework

At the national level, two reference periods can be delineated: a first period focusing on the protection of individual properties, and a second period relating to the planning of the restoration of historic areas.

The first period is associated to Bottai Laws No. 1089 and No. 1497 of 1939, which aimed to safeguard the historical, artistic, and Cultural Heritage, with a specific focus on buildings and areas of exceptional architectural value. In particular, Law No. 1089 of 1939 concentrated on protecting individual items of historical and artistic significance, imposing specific constraints on buildings and urban spaces deemed to possess cultural value.

This law placed restrictions on alterations or demolitions of these assets, aiming to preserve their historical and artistic integrity. This legislation established a crucial framework in Italy, defining: i) the "*Protection Bond*" for Cultural Heritage, a legal restriction imposed on certain cultural assets. This constraint prevented or regulated demolition, transformation or maintenance works that could compromise the integrity and historical-artistic value of the property; ii) "*Cultural Heritage*". The law identified "*Cultural Heritage*" as movable and immovable objects of historical, artistic, archaeological, ethnographic and bibliographic interest; iii) concerning the "*Protection of Movable and Immovable Property*", specific protective measures were outlined for both movable and immovable property. Buildings and monuments of particular historical or artistic significance were subject to restrictions, imposing limitations on their alteration or demolition; iv) The "*Superintendency*" was established as part of the law, creating the Central Office for the Protection of Cultural Heritage, which serves as the predecessor to today's Superintendencies. The primary task of this office was to apply and enforce the provisions stipulated in the law.

In contrast, Law No. 1497 of 1939 represented a significant advancement in heritage protection as it focused on the preservation of complexes of assets.

This law addressed the safeguarding of entire historical and environmental areas, taking into account the urban, environmental, and landscape context in which the properties were situated. Bottai Law No. 1497 of 1939 introduced crucial provisions for the protection of Italy's Cultural Heritage. In detail, it established the concept of "*environmental constraint*", a legal mechanism designed to protect entire landscapes, monumental complexes, and natural environments of particular value.

This provision has had a substantial impact on the safeguarding of historical, artistic, and Cultural Heritage.

The Bottai Law introduced several key provisions, including:

i) Landscape Restrictions, the law allowed for the declaration of areas with special landscape value, subjecting them to restrictions. This entailed specific regulations on land use and building activities within these designated areas.

ii) Protection of Monumental Complexes, in contrast to Law No. 1089, which primarily concentrated on safeguarding individual assets, Law No. 1497 adopted a broader perspective, emphasizing the protection of entire monumental and environmental complexes.

iii) Protection and Conservation Interventions, the law outlined specific interventions aimed at conserving and protecting heritage. These interventions encompassed restoration projects and measures designed to preserve the historical and artistic integrity of the assets.

Although subsequent legislation has amended and supplemented this law over the years, the concepts of landscape constraints and the protection of monumental complexes remain pertinent in the ongoing efforts to conserve Italy's Cultural Heritage.

These measures provided the regulatory basis for the current Italian system of Cultural Heritage protection, which continues to evolve over the years (Table 1).

In 1967, Law No. 765 was enacted, amending and supplementing Law No. 1150 of 1942. Article 1 of Law No. 1150 had initially articulated that, in the renovation and expansion of buildings in cities, traditional characteristics must be respected. Subsequently, Article 17 of Law No. 765/1967 introduced provisions for the planning of interventions in historical areas, specifying that: "... *if the urban agglomeration is of historical or artistic character or of particular environmental value, only consolidation or restoration works are allowed, without alteration of volumes*...".

Article 17 introduces two fundamental aspects that are particularly important in urban planning: i) the consideration of the Historic Centre in General Urban Planning, in order to preserve and enhance the city's historical and Cultural Heritage within an overall vision for urban development; and ii) the identification of Specific Urban Standards.

The article establishes the need to identify specific urban standards that impose respect for particular typological and formal aspects of urban agglomerations.

In accordance with Article 17 of Law No. 765/1967, Interministerial Decree No. 1444 of 1968 is introduced, defining homogeneous territorial zones. The decree specifically places Historical Centres within Zone A, which encompasses "…*the parts of the territory affected by urban agglomerations of historical, artistic, and environmental value or portions of them, including the surrounding areas, which can be considered an integral part, due to these characteristics, of the agglomerations themselves*...".

The primary legislative reference governing the revitalization of the existing building stock, particularly through the establishment of "R*ecovery Zones*", was Law No. 457 of 1978, also known as the norms for residential construction. Specifically, Law No. 457/1978 introduced the inaugural executive urban planning instrument with specific significance: the "*Recovery Plan*". Within these "*Recovery Zones*", the law permitted the identification of buildings, complexes, blocks, and areas that required special attention through the formulation of specific plans.

However, the legislation did not explicitly outline the purposes that the building and urban heritage within degraded areas should serve. Given that the law primarily focused on residential construction, it was initially understood that rehabilitation plans should predominantly address buildings designated for residential use.

Additionally, the law established a framework for defining and categorising interventions on existing buildings, a distinction that had not been legislatively specified before, particularly in comparison to new construction.

This provided administrations with a dedicated executive tool aimed at conservation and recovery, with specific emphasis on urban areas where the degradation of the housing stock was more pronounced. Subsequently, the law that concretised the development of "*Recovery Plans*" was Law No. 179 of 1992 "*Rules for public residential building*". In detail, Law No. 179 of 1992 introduced important tools for the redevelopment of the territory through the "*Integrated Intervention Programme*" referred to in Article 16.

These programs signify a more comprehensive and integrated approach compared to the intervention strategies outlined in previous regulations.

The distinctive feature of these programs lies in their capacity to harmonize diverse functions, which may encompass the reorganization of urban spaces, the enhancement of green areas, the adaptation of infrastructures, and the promotion of solutions that consider the needs of the local community.

These interventions aspire to bring about a comprehensive restructuring of urban settings, encompassing both public and private spaces in an integrated approach. The goal is to establish urban environments that not only address housing needs but also foster social cohesion, environmental sustainability, and the enhancement of architectural heritage.

Consequently, the "*Integrated Intervention Programmes*" offer a broad and articulated response to the challenges of urban regeneration, integrating a range of functions and types of intervention on a large scale with the objective of positively and synergistically redefining the urban landscape.

Subsequently, Law No. 493 of 1993 defines the "*Urban Renewal Programmes*" as:

"... *a systematic set of works aimed at the construction, maintenance and modernisation of primary urbanisation, with particular attention to the problems of accessibility of network facilities and services, and of secondary urbanisation, the building of completion and integration of existing urban complexes, as well as the insertion of elements of urban design, ordinary and extraordinary maintenance, restoration and renovation and building renovation of buildings*..." (Art. 11).

In addition to these programmes, the following were introduced in 1998 by ministerial decrees: "*Neighbourhood Contracts*" and "*Urban Regeneration and Sustainable Land Development Programmes*".

Table 1 Diachronic legislative framework

Ref.	Tools	Aims
Art. 27 – L. 457/78	Recovery Plan	Definition and classification of interventions in the existing building stock
Art. 3 – L. 179/92	Urban Regeneration Programme	Spatial and functional regeneration of degraded parts of the city, through building and functional rehabilitation, and an organic set of interventions covering both primary and secondary urbanisation
Art. 16 – L. 179/92	Integrated Intervention Programme	Urban and environmental regeneration through the definition of a plurality of functions and types of intervention
Art. 11 – L. 493/93	Urban Recovery Programme	Renovation of economic and social housing districts, through renovation and building maintenance, the inclusion of services and residential and non-residential operations on contiguous areas.
DM. 1997	Neighbourhood Contract 1	Recovery of degraded neighbourhoods also from the point of view of social cohesion
DM. 1998	Urban Regeneration and Sustainable Land Development Programmes	Interventions on infrastructures. Construction of industrial, commercial and artisanal settlements.
DM. 2001-2003	Neighbourhood Contract 2	Realisation of infrastructure in deprived neighbourhoods through private investment

1.3. The crucial role of the preservation process in Historic Centres

The theme of the recovery of Historic Centres analyses the identity and territorial dimension of places through an integrated, multidisciplinary, and multi-scalar approach. Beyond documentary and regulatory notions concerning the management and conservation of the diffuse built heritage, it is essential to outline the key points of analysis within the traditional methodological and operational approach that has been implemented over time for the preservation of these historical areas.

Various researchers of thought on the analysis of the existing built heritage, with a focus on its conservation, have evolved over time.

The conservation approach to Historic Centres has consistently been grounded in the traditional stages of the recovery process, involving a dual scale of analysis. This dual scale examines the existing built heritage at both the building-urban compartment level and the architectural artefact level (Ciardini & Falini, 1980).

In a general standpoint, the conservative approach to Historic Centres is based on the following main phases:

i) the qualification and codification of the historical territorial layout, are essential for delineating the perimeter of the historical urban area. In the context of qualification, the aim is to identify and assess the distinctive features that characterize spatial planning across different eras, emphasizing cultural, social, and economic transformations and influences. This phase entails the analysis of architectural structures, urban development patterns, infrastructure, and spatial relations. The process involves a comprehensive analysis and identification of the main historical urban patterns that have contributed to shaping the territorial fabric over time.

In other way, the codification of the urban fabric also requires translating this information into a system of rules and regulations to guide the future development of the historic urban area. This may encompass defining protection zones, promoting restoration and redevelopment, and stabilizing key elements of the urban landscape.

ii) the analysis of the building types that have contributed to the current configuration of the Historic Centre is essential. The structure of the Historic Centre encompasses a complex array of artefacts, including architectural landmarks (churches, castles, and noble palaces) and fundamental constructions (residential buildings).

Regarding residential buildings, it is possible to enhance the depth of understanding through the classification of building types, such as terraced houses and tower houses. The categorization of building types plays a crucial role in organizing structures within the Historic Centre, enabling a detailed analysis of their interiors, the evolution of their construction, and the way they are integrated into the overall urban fabric. This classification extends to both buildings and open spaces, facilitating the examination of building transformations.

iii) the analysis of the state of conservation of the identified historical area. The survey of urban and built environmental features is aimed at identifying indicators of the quality or degradation of the urban (streets, squares and open spaces) and built environment (buildings). This phase aims to identify indicators that reflect the state of the streets, squares, open spaces and buildings. In detail, at the urban scale, the focus is directed towards the condition of streets, identifying signs of deterioration such as cracks or depressions. This includes an assessment of the overall condition of urban elements, the maintenance of squares and open spaces – encompassing factors like cleanliness, the presence of public greenery, and the preservation of architectural elements. Additionally, the analysis extends to the functionality of street furniture and the utilization of these spaces by the community.

At the built environment scale, it is evaluated:

i) the state of conservation of historic buildings, examining the presence of structural damage and the effectiveness of restoration operations;

ii) the architectural typology of modern buildings, considering their visual impact and consistency with the surrounding style;

iii) the quality of materials and sustainability of architectural solutions.

Finally, the data collected is synthesised to clearly identify quality indicators, highlighting both positive aspects, such as the preservation of the historical heritage, and aspects of degradation, such as the presence of abandoned areas or buildings in a poor state of physical, functional and technological conservation. Through this detailed dual-scale analysis, a comprehensive overview of the conservation status of the historic area is obtained, allowing for the development of targeted interventions to restore and enrich the urban and environmental heritage.

2. DIGITAL APPROACHES FOR THE MANAGEMENT OF KNOWLEDGE AND INFORMATION

In recent years, the advancement of Information and Communication Technologies (ICT) and the growing demand of intelligent systems for the representation, analysis, qualification, and valorisation of existing heritage have fostered new methods of analysing historical architectural heritage. These methods are aimed at supporting conservation, valorisation, and management activities (Bertellini et al., 2020).

This has produced a significant revolution in the diagnostics and assessment sectors of historical and architectural heritage. This transformation has been made possible by the widespread adoption of new tools for environmental data acquisition, such as laser scanners, digital photogrammetry, and panoramic photography. These tools allow for the collection of detailed information about historical and architectural structures. Additionally, the ability to manage this data as multidimensional digital environments has emerged, enabling the association of various types of information, including metric, geometric, diagnostic, and documentary data. Furthermore, the real breakthrough lies in the capability to manage this acquired data as multidimensional digital environments. This approach allows for the integration and association of different types of information, ranging from metric and geometric data to diagnostic and documentary details. The synergy of these advanced tools and the capacity to create comprehensive digital representations has ushered in a new era in the preservation, understanding, and documentation of our Cultural Heritage. These technologies have empowered professionals to capture intricate details with a remarkable level of accuracy and precision(De Fino et al., 2020). Simultaneously, within the field of recovery and conservation of the existing architectural heritage, three-dimensional photorealistic documentation is an essential tool for: i) recording and comprehending the state of conservation of an asset; ii) planning appropriate intervention strategies; iii) developing digital recovery plans/projects capable of documenting the diachronic evolution of conservation and maintenance activities (Mateus et al., 2019). Nevertheless, digital approaches can be utilised to acquire and manage data on historic buildings throughout the conservation process.

The digitisation of architectural heritage complements and extends the *modus operandi* of the traditional cognitive process. Indeed, the activities leading to the definition of the diagnosis and potential intervention strategies are encompassed within this process. The primary activities involve: i) acquiring metric and colorimetric data through the execution of digital surveys; ii) creating digital models in the form of textured point clouds; iii) analysing the state of conservation by identifying and mapping the main themes of degradation. The evolution of digital techniques has given rise to novel approaches for analysing and mapping the conservation status of existing architectural heritage (Brozovsky et al., 2024). Moreover, the development of state-of-the-art surveying techniques (laser scanning and digital photogrammetry) and parametric digital modelling (BIM/HBIM, 3DCityModel) combined with Augmented and Virtual Reality techniques have led to the generation of new survey scenarios and protocols, using structured models capable of representing historical artefacts with different levels of information (Banfi, 2020). This has highlighted the importance of three-dimensional (image/VR-based) digital models and Spatial Information Systems (GIS-based) precisely in the phases of the cognitive, diagnostic and conservation process. In this chapter, the main approaches used in the literature for the technical knowledge of the historical building stock at district and building scale are analysed (Figure 2).

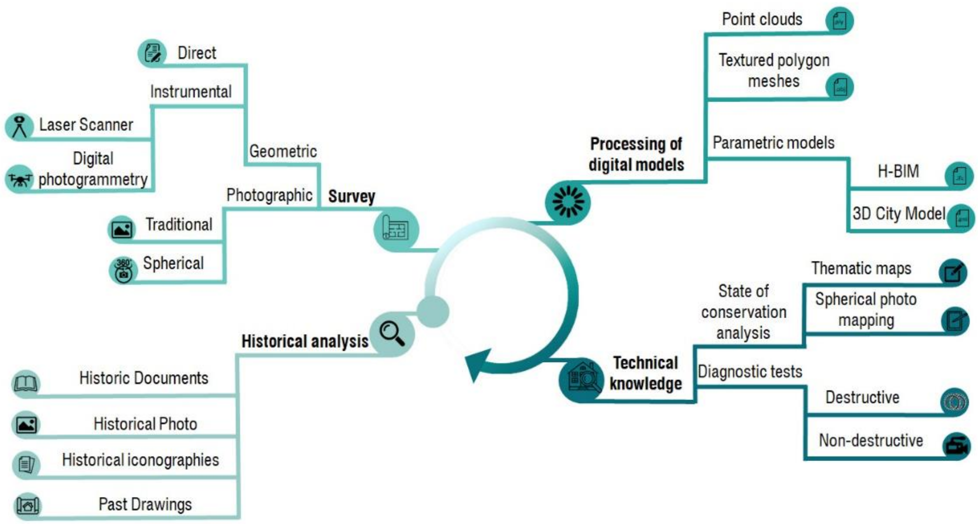


Figure 2 The process of technical knowledge

2.1. The digitisation processes for gathering technical knowledge of the existing architectural heritage

The digitisation process of the existing architectural heritage involves the integration and combination of digital techniques and methodologies aimed at capturing the real environment through the generation of photorealistic three-dimensional models (Remondino & Rizzi, 2010). Reality-based techniques, such as photogrammetry and laser scanning, use both hardware and software to accurately capture reality, documenting the actual or “as-built” situation of a place and reconstructing it using real data. In contrast, non-reality-based approaches rely on computer graphics software, such as 3D Studio, Cinema4D, Sketchup. The latter allow the generation of 3D data without the need to carry out specific surveys or to have detailed knowledge of the object under study. In (Mendoza et al., 2023), a systematic review of the literature on the main digital technologies for Cultural Heritage conservation is proposed.

Modern technologies and methodologies for documenting Cultural Heritage were discussed by Ikeuchi and Miyazaki in 2008, allow the creation of extremely realistic 3D results, both in terms of geometry and texture (Ikeuchi et al., 2008).

These results find application in various disciplinary fields, including: archaeological documentation, digital preservation, restoration purposes, Virtual and Augmented Reality applications, 3D repositories and catalogues, web geographic systems.

The main digital reality-based techniques on which the processing of three-dimensional models of historical artefacts is based are:

- Image-based, defined in the literature as architectural photomodelling, exploits SFM (Structure From Motion) algorithms for the three-dimensional representation of architectural artefacts from photographic images(De Luca, 2011);
- Range-based, detects the real environment through terrestrial (TLS-Terrestrial Laser Scanning), mobile (MMS-Mobile Mapping System) and/or airborne (ALS-Airborne Laser Scanning) laser scanning, acquiring three-dimensional metric data (x, y, z) in the form of textured point clouds (Bitelli et al., 2018).

Three-dimensional image/range-based reconstructions often involve interactive procedures for architectural structures, where a limited number of reference points and geometric primitives are not sufficient to describe the 3D geometry. Consequently, for the elaboration of digital models of complex architectural aggregates and artefacts, i.e. characterised by intrinsic (constructive, material, architectural and morpho-typological) and extrinsic (state of preservation, environmental and geographical aspects) peculiarities that may affect the level of operability, approaches integrating the two technologies have been experimented. This, in order to fill the gaps produced by each methodology and, therefore, acquire the architectural artefact in its entirety (Bertellini et al., 2020). On the other hand, automatic matching procedures of digital techniques are also used for objects that require accurate models in the form of dense point clouds to accurately capture all discontinuities and features of the object. With regard to the latter, the recent scientific literature evaluated the comparison between 3D reconstructions resulting from them and demonstrated a good level of overlapping between points clouds derived from those different techniques. These results moved scientists in using photogrammetry above all for the creation of virtual realities, so useful for dissemination, cataloguing and enhancement of Cultural Heritage. Furthermore, the restrained costs of equipment (cameras), the ease acquisition and processing of data (image or video files) and the high reliability of produced outputs (thanks to the improvement of Structure-From-Motion algorithms) allow to archaeologists, experts in Cultural Heritage, architects, engineers and researchers to have powerful info-graphic tools that increasingly support, or even replace, three-dimensional models obtained with the range-based techniques (D’Auria, 2018).

In the following paragraphs, the focus is on the image-based approach, a digital technique used in this research work.

2.1.1. Digital Photogrammetric approach

Photogrammetry is recognised as the leading technique for analysing image data, capable of producing accurate and detailed results at different scales of application. It provides three-dimensional information with precise and reliable estimates of unknown parameters through correspondences extracted from measured images, either automatically or semi-automatically, according to object specifications. Digital photogrammetry is a discipline belonging to the field of indirect surveying that allows for the reconstruction of the geometric form of a spatial, urban or architectural area through the processing of multiple images. Originally derived from descriptive geometry, it is based on the principles and concepts of projective geometry to explore the unambiguous relationships between a three-dimensional reality and its two-dimensional representation (Paris, 2012).

The integration of photogrammetric principles with the computational field gave rise to the Image-Based approach, hence the term "*Photomodelling*". This approach enables the modelling and representation of architectural objects using images as input data. In this context, the relationship between the real object and its image is enriched with a new dimension, allowing the direct projection of the texture extracted from high-resolution photographs onto the reconstructed geometry (De Luca, 2011). The application of photomodelling for the creation of three-dimensional textured models of architectural heritage relies on an understanding of the geometric principles of perspective. These principles enable the measurement, modelling, and rendering of a real object in three dimensions based on a two-dimensional datum (image). All stages of the image-based approach, from the acquisition of the frames to the return of the photogrammetric digital model, are highly dependent on the photographic shooting strategy and the quality of the photographs. The tool for carrying out a digital photogrammetric survey is a camera, which is capable of capturing light on an electronic medium. This sensor numerically encodes the acquired information into a matrix of luminance values. Basically, the principle of forming a digital image is characterised by a sensor capable of measuring incident light, which is converted into electrical voltage with proportional intensity, and this in turn is converted into bits of information.

One of the main factors affecting the final outcome of the three-dimensional model is precisely the photographic acquisition phase.

During a digital photogrammetric survey campaign, it is crucial to consider specific photographic techniques for the comprehensive acquisition of the morphological features of buildings. It is necessary to acquire images following a defined plan in order to cover the entire surface of the object and ensure a sufficient degree of overlap between different consecutive images. A point is rendered in three dimensions only if it is visible in at least two images taken from two different viewpoints. For this, it is necessary to observe the same point on the object from several viewpoints, i.e., from at least two images. Subsequently, the acquired images are processed using specific software that leverages Structure from Motion algorithms, capable of generating three-dimensional digital models in the form of new points and textured polygonal meshes (Westoby et al., 2012).

2.1.2. Image-based digital models to support the analysis of the state of conservation

Image-based digital models are important tools for the analysis of technical knowledge, as by combining accurate metric information with a high-quality photographic description, it is possible to obtain information regarding the state of preservation of surfaces. Indeed, thanks to the acquisition of radiometric/colourimetric characteristics, methodological approaches have been developed for the technical knowledge of historical assets and aggregates with the aid of textured three-dimensional models.

Three macro applications derive from this potential within the conservation process:

- cognitive, for which the information-semantic level is increased through the linking of multidisciplinary information bound according to specific targets to the three-dimensional model (Bertacchi et al., 2018);
- diagnostic, manual (CAD/GIS-based) and semi-automatic point cloud segmentation and classification procedures used for the recognition and definition of degraded surfaces. In particular, the semi-automatic approach involves the application of Artificial Intelligence algorithms, more appropriately Machine and Deep

Learning (ML/DL), which, starting from specific input data, base subsequent decisions useful for the semantic segmentation of the three-dimensional model. Where, segmentation consists in the grouping of points (x, y, z) having common parameters, subsequently the sets of points are classified through the association of specific attributes(Galantucci et al., 2023; Grilli et al., 2017);
- monitoring the deterioration of stone surfaces, at predetermined time intervals, using and comparing three-dimensional data sets(Galantucci & Fatiguso, 2019).

2.2. The technical knowledge of the historical architectural heritage through Virtual Reality

Alongside geometric digital models, Digital Models exploiting Virtual Reality techniques were also analysed for the development of digital application systems (e.g. virtual tours and digital reconstructions), as well as for the creation of databases useful for technical knowledge, conservation and management of the built heritage (Di Giulio et al., 2021). On the other hand, advancements in digital technologies have facilitated the creation of tools and methodologies for capturing geometric information from artefacts of varying sizes with a high degree of accuracy and resolution. Additionally, these technologies enable the recreation of artefacts in virtual representations of reality (Manferdini & Russo, 2015). The virtualisation of the built environment can be interpreted using Milgram and Kishino's (1994) Reality-Virtual Continuum taxonomy, which establishes a connection between Virtual Reality (VR) and Augmented Reality (AR).

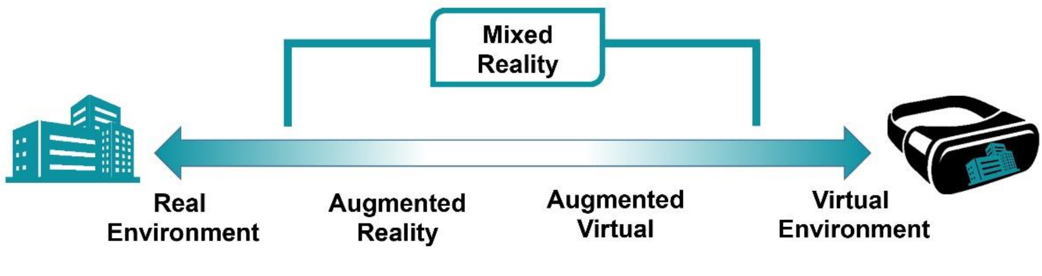


Figure 3 Reality-Virtual Continuum. Source: (Milgram & Kishino, 1994)

In this taxonomy, the Real Environment (RE) or Built Environment (BE) is one of the poles, standing in contrast to the Virtual Environment (VE). Augmented Reality (AR) is positioned closer to RE, as the presence in the real world takes precedence over virtual data. The array of systems situated between the real and virtual environment is termed Mixed Reality (MR), encompassing Augmented Reality (AR), which is close to the real environment, and Augmented Virtuality (AV), which is close to the virtual environment (Figure 3) (Milgram & Kishino, 1994).

Virtual Reality (VR) or Virtual Environments (VE) enable users to immerse themselves in digitalized surroundings, closely resembling the real world but without geographical constraints. VR facilitates the observation of environments and objects in high-resolution, three-dimensional formats, allowing real-time interaction. Users experience a complete engagement within reconstructed environments, offering a rich and lifelike encounter with the virtual re-built environments(De Paolis, 2012).

Moreover, Virtual Reality serves as a sophisticated IT tool and a repository of multidisciplinary information. The interaction between users and their virtual environment is facilitated through conventional interfaces such as monitor, keyboard, and mouse, as well as through cutting-edge devices like helmet, visor, and motion sensors. These advanced tools represent the outcome of technological innovation, significantly enhancing the ways in which individuals perceive and engage with the created digital environment. Furthermore, they elevate the user experience from a mere virtual engagement to a truly immersive level. Moreover, focusing on the visible relevance of such digitalised environment, the use of Virtual Models allows the re-creation of faithful and accurate virtual copies of real architectures to be fruited and analysed in remote view and with different immersive levels: full immersive or semi-immersive (Cipresso et al., 2018). Due to these features, VR represents a system of multidisciplinary tools applied in several fields as the medicine (Fuchs et al., 1998; Pietrzak et al., 2006) the aeronautics (Julier et al., 1999), the pedagogical and educational sectors; for them, it aimed at the dissemination of knowledge and its verification in an innovative and interactive way (Ben-Joseph et al., 2001; Cobb et al., 2002; Gillet et al., 2004; Kaufmann &

Schmalstieg, 2002). Moreover, VR already reaches the widest application in entertainment field, from the gaming (De Souza e Silva & Delacruz, 2006; Rashid et al., 2006) to the free time activities (Romero et al., 2004; Roussou, 2004).

In the domains of history, architecture, and archaeology, the visualization and reproduction of environments, coupled with the elucidation of artefacts, encompass primary objectives. Virtual Reality (VR) has played a pivotal role in supporting these sectors through its instrumental capabilities. The use of VR tools is evident in facilitating the creation of immersive environments, aiding in the recreation of historical settings, architectural designs, and archaeological sites. Furthermore, VR serves as a powerful medium for conveying both tangible and intangible values associated with artefacts. This technology, with its interactive and three-dimensional features, has become an indispensable tool in enhancing the exploration, understanding, and communication of historical, architectural, and archaeological narratives(De Paolis, 2012).

In this scenario, the development of virtual historical environments serves a functional purpose in representing not only the historical and scientific values but also in assessing the temporal transformations of these environments. This approach is instrumental in scrutinizing past processes and holds potential for forecasting and evaluating ongoing transformations. By employing virtual reality, one can intricately capture and recreate historical settings, enabling a dynamic exploration of how these environments evolved over time. This helps to preserve historical and scientific values by providing new ways of analysing the processes that have shaped these environments.

Moreover, the capability to project into the future allows for an anticipatory assessment of ongoing transformations, making virtual historical environments a versatile and forward-looking resource for researchers.

Therefore, in the field of Cultural Heritage, Virtual Reality finds its implementation in two main areas:

i) The primary objective is to utilize, communicate, disseminate, and enrich Cultural Heritage. This involves incorporating applications that cater to diverse user groups, such as WebGIS-3D platforms, for knowledge sharing (De Fino et al., 2020). These platforms enable the transcendence of geographic limitations, providing an initial understanding of cultural sites without the necessity for users to be physically present at the location(Cardaci & Versaci, 2013). In this context, digital models serve as the fundamental data for navigating platforms, enabling the remote exploration of Cultural Heritage that is frequently inaccessible or unfamiliar to the broader public (Gabellone, 2014). The generated virtual environments are designed as platforms where various representations (maps, satellite images, 3D models, and links to documents) and related information are organized across different scales. These platforms serve as spaces for sharing knowledge, fostering multidisciplinary collaboration, and promoting interoperability of datasets (Meschini, 2011).

Here, two projects are part of that application field:

a) ARCHEOGUIDE (Vlahakis et al., 2001) (Augmented Reality-based Cultural Heritage On-site GUIDE), funded by the European community, was developed with the objective of offering a personalized assistant to tourists visiting specific cultural sites. The system utilised Augmented Reality (AR) technology to reconstruct ancient ruins and dynamically render environments in real time. This involved considering the precise position and orientation of the tourist within the site, providing an interactive and immersive experience.

b) iTACITUS (Zoellner et al., 2007), European project in the objectives of the "Mobile Augmented Reality (AR) Guide Framework for Cultural Heritage (CH)", was proposed as a mobile information system of Cultural Heritage. Its primary objectives involve gathering and presenting digital content to tourists. This content is meticulously organized and linked to the actual environment, providing historical and architectural information about the site within a 3D digital environment.

In this context, Virtual Reality technologies have played a crucial role in elevating and enriching the experience of historical environments, offering insights into their evolution and showcasing distinctive features. Navigating within the virtual environment enables the observation of details situated in less accessible areas, providing more comprehensive information compared to traditional methods.

Virtual Reality systems additionally have the capacity to lead users through unreal spaces, facilitating exploration along specific paths tailored to the diverse interests of various users. In particular, some authors have experimented with Virtual Reality techniques, through the visualisation in an immersive environment of three-dimensional textured models, produced by the integration of image- and range-based techniques, to increase the degree of tourist enjoyment of cultural assets, even those sometimes characterised by a low level of accessibility (Paladini et al., 2019).

ii) The second significant area is associated with data management and cataloguing achieved through the establishment of databases. In this regard, all aspects of heritage, along with any pertinent data such as historical documentation, historical photographs, and metric measurements, are systematically categorized in the most suitable manner. This approach, adopted from business applications, is crucial in providing essential support for the safeguarding and preservation of Cultural Heritage. Following that purpose, the INSITER project (Roders et al., 2016) (Intuitive Self-Inspection Techniques using Augmented Reality for construction, refurbishment and maintenance of energy-efficient buildings made of prefabricated components) explored the applications of Augmented Reality (AR) and Virtual Reality (VR) techniques for managing data and processes related to heritage across different periods. It's noteworthy that these investigations were closely intertwined with the management of energy efficiency processes.

2.2.1. The features of a Virtual Model

A Virtual Model comprises two primary components: the virtual environment, which serves as the backdrop where the end user engages through the application, and the interface, encompassing a collection of elements that enable user interaction for navigation within the environment and control over the overall experience (Figure 4).

When delving into its composition, the virtual environment essentially encompasses three fundamental elements:

1. Content. This refers to the collection of information existing within the environment. Various types and formats of data contribute to the content, including three-dimensional models (such as CAD, point clouds, or polygonal mesh), media files (images, videos, and audio), or text files (comprising archive documents and reports).

2. Geometry. This pertains to the structure of the generated virtual space, intimately connected to the dimensions and proportions of the environment. It involves the spatial configuration that shapes the virtual world.
3. Dynamics. This involves the relationships and interactions among the contents within the virtual environment. It encompasses the dynamic aspects of how different elements within the environment relate to and influence each other over time. In essence, these three components, content, geometry, and dynamics, collectively contribute to shaping and defining the virtual environment and the user experience within it.

Focus on the geometry, the virtual environment can be created using three-dimensional CAD models or point clouds and polygonal meshes derived from the laser scanning or digital photogrammetry techniques. In addition to the geometric model, the conceptual model of the contents within the virtual model holds particular significance. Specifically, the contents are interconnected both with each other and with the virtual environment through specific relationships.

The relations in virtual environment can be classified into three macro-categories:

a) *Hotspots* represent sensitive zones enabling interactions within the virtual environment, serving various purposes including navigation, triggering pop-up windows containing internal data, and establishing connections to external content (e.g., web links)(Aznoora et al., 2009);
b) *Orientation maps* serve as plans of the virtualized environment where morpho-distributive information is linked to the environment. These maps are particularly valuable for establishing correlations and connections between various virtual elements in the environment through radars, which act as specific hotspots. In the case of extensive or multi-level architectures, the utilisation of orientation maps proves instrumental in enhancing the overall user experience significantly.
c) *Menu* is the list of environments that constitute the virtual model.

The creation of a Virtual Model by spherical images consists of three main phases:

1. importing the acquired images and processing them in the virtual tour creation software;
2. connecting the scenes by hotspots;
3. implementing information and documentary contents.

In detail, the elaboration of virtual environments based on Virtual Models uses 360° panoramic photos, which can be acquired through conventional or more advanced photographic acquisition tools. Alternatively, these panoramas can be generated from three-dimensional geometric models, be they solid or parametric in nature.

More specifically, the employment of spherical images enables the continuous representation and visualisation of individual digital sub-environments within the virtual environment. These spherical images, serving as the elementary unit of the overall object to be presented virtually, facilitate user-environment interactions both horizontally (±180°) and vertically (±90°) as described by Zonno et al. (Zonno et al., 2012).

The use of spherical photos stands out as a cost-effective technique due to the affordability of the required tools, including a spherical head, tripod, and remote control for remote photo shooting. Additionally, the creation of spherical images involves a relatively inexpensive process, typically handled by the camera itself, which includes the acquisition of wide-angle images, alignment, and photo-stitching, as outlined by Cardaci et al. (Cardaci et al., 2013). Nonetheless, the nature of photographic shots necessitates a careful assessment of the inherent characteristics and geometric features of each sub-environment prior to acquisition. The resulting spherical scene from a single shot is most representative when capturing spaces with similar geometric characteristics in all three dimensions. If a sub-environment exhibits a predominant feature, such as heights in cloisters or length in corridors, multiple acquisitions become necessary to ensure a satisfactory level of overlapping and accurate representation.

Ultimately, Virtual Tour software, employing panoramic images, facilitates the formation of digital environments structured as an organized system of spherical images connected by specific relationships.

Specifically, the basic components of a Virtual Tour are identified as follows (Figure 4):

- the scenes allow the fruition of the single virtual sub-environment;
- the media as the additional contents of scenes having various nature (.jpeg, .pdf, .tiff, .doc);
- hotspots define the relations between each entity according to which:
    - each Virtual Tour is generated by n scenes;
    - each scene is connected to n hotspots,
    - each hotspot links a media.

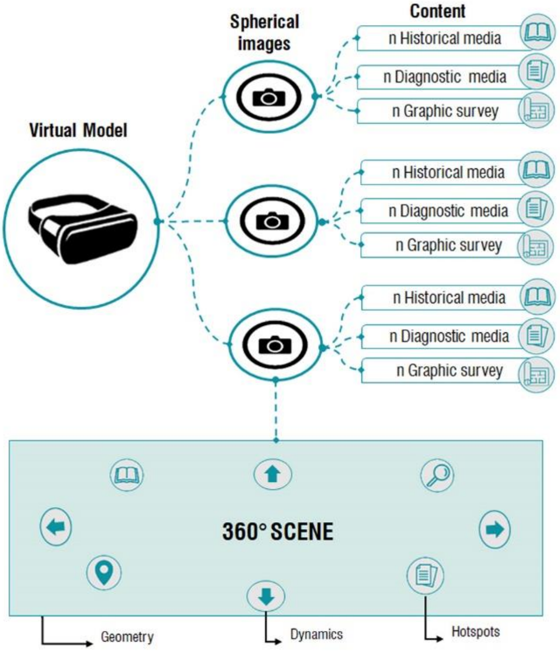


Figure 4 – Structure of the Virtual Model

Nowadays, the software designed for creating virtual models represents advancements from the initial Krpano program, the brainchild of the Austrian programmer K. Reinfield. The original application lacked a graphical interface and was exclusively implementable in the .xml language. Notable among the commercial alternatives are Tourweaver©, 3D Vista Virtual Tour©, Panotour©, My 360©, Real Estate Virtual Tours Creator©, and VirtualTourEasy©, widely utilized for the specified purpose(Cardaci & Versaci, 2013).

2.2.2. The Virtual Model as an information database for technical knowledge

In the realm of preserving Cultural Heritage, virtual digital models have been explored at both the micro level (focusing on architectural artefacts) and the macro level (encompassing the built environment), for the management of historical architectural heritage through the creation of visual databases (Ferrari & Medici, 2017; Harun & Mahadzir, 2021).

Furthermore, Digital and Virtual Models play a crucial role in enhancing diagnostic and recovery efforts for Cultural Heritage. They facilitate interaction with digitised buildings, allowing for the exploration, analysis, and management of pertinent technical content (Comes et al., 2020; Di Giulio et al., 2021; Maiellaro et al., 2018). Conversely, the utilisation of Virtual Models (VMs), which are specialized structured DMs employing Virtual Reality (VR) techniques, highlights the potential to effectively coordinate information exchange among various stakeholders involved in the Cultural Heritage recovery process (Banfi, 2020).

Specifically, certain authors have explored the application of Virtual Reality techniques to study architectural assets with distinct artistic value. They advocate for the incorporation of virtual models at a precise phase in the conservation process, namely positioned between the survey phase and the creation of the three-dimensional parametric model.

In this context, the Virtual Model is regarded as a valuable tool for the efficient analysis of the architectural asset under study. Within this model, multi-disciplinary information, organized both thematically and in terms of data nature, is systematically catalogued and localised. This facilitates the subsequent development of digital information models and systems (I Trizio et al., 2019). The additional capabilities of the Virtual Model are highlighted by the establishment of a Historic Digital Twin. This involves enhancing the model's interoperability by incorporating active sensors and integrating it with other web-based systems (Ilaria Trizio et al., 2021).

At the urban scale, authors have experimented with digital systems leveraging Virtual Reality techniques on established web platforms (such as Google, Bing Maps, OpenStreetMap) for seismic vulnerability analyses of Historic Centres.

The exploration involved testing the capabilities and assessing potential challenges associated with the approach and tools utilized during the rapid and remote phase of gathering and analysing building characteristics (Columbro et al., 2022).

Indeed, Virtual Models (VMs) can be structured as digital databases where information is interconnected both within the databases and across visualized scenes. At their foundational structures, VMs can be integrated with various information systems, including hierarchical, network, relational, and object-oriented database systems, to enable the digital storage and efficient management of data (De Fino et al., 2022).

Furthermore, VMs can be linked to Decision Support Systems, facilitating the correlation of technical information, organized as parameters, through multi-criteria relations and Artificial Intelligence algorithms, such as Machine Learning (Stefani et al., 2014). A systematic literature review on the applications of such virtual models is proposed in (Rubio-Tamayo et al., 2017). From this, it becomes clear how the evolving immersive digital environments contribute to various applications, improving our understanding of existing built heritage. They enable precise planning and design of future scenarios, effectively representing, communicating, and preserving concepts and knowledge. This is accomplished through the contextual interaction of multiple users within a unified digital system. One of the primary strengths of these models lies in their capability to represent, utilise, and manage the real environment and associated information through the development of innovative methodological approaches.

Specifically, Virtual Reality (VR) technologies are employed for representing and managing/sharing data through a “virtual” approach. This innovative tool is introduced in the diagnostic phase to precisely assess the state of conservation of Cultural Heritage (Cantatore et al., 2020). As a result, the process of editing photos aimed at representing the virtual environment, specifically the RGB elements, involves projecting raster information, including solid lines and screens, onto a spherical image (Figure 5).

This projection can be done in two ways: either as a simple image or directly onto a spherical visualization. In the first scenario, where spherical images are being mapped, any photo-editing software or image manager like Autocad®, Paint, or Photoshop® can be used.

However, when it comes to mapping in the spherical projection, specific non-open-source software, such as Photoshop CC®, becomes essential.

Figure 5- Equirectangular mapped image in the photo-plane visualization

Despite being non-open-source, this option offers advantages, especially for technicians involved in on-desk mapping activities, as it allows for a more extensive and uninterrupted exploration of the environment. This capability becomes particularly valuable in resolving potential discontinuities in mapping, especially along the upper (ceiling) and lower parts (floor) of the scene. This is crucial for addressing issues such as cracks and damp surfaces involving vaults and adjacent walls. In the study conducted by (Margherita Lasorella et al., 2021), Virtual Models integrated with information systems structured according to specific rules were employed as a supportive tool for expert users in the decision-making process related to diagnosis and subsequent recovery or restoration interventions (Figure 6). The authors outlined a streamlined methodological approach designed for remote utilisation and the application of technical knowledge in dealing with artefacts that are inaccessible or have low accessibility. This approach leverages Virtual Reality (VR) to create a Virtual Model, representing the digitised environment through advanced VR techniques and incorporating various information levels. At the foundation of these information levels lies specialized technical knowledge derived from the cognitive process of the architectural asset. This includes elements such as historical analysis, graphic elaborations, and diagnostic reports.

This knowledge is intricately localised within the Virtual Model and is further catalogued and correlated within a Relational Database. Particularity, when digital systems are configured and structured correctly according to specific logical relationships and/or with the sector ontologies, can provide crucial support to experts in the field during the analysis and technical knowledge phase of the conservation process.

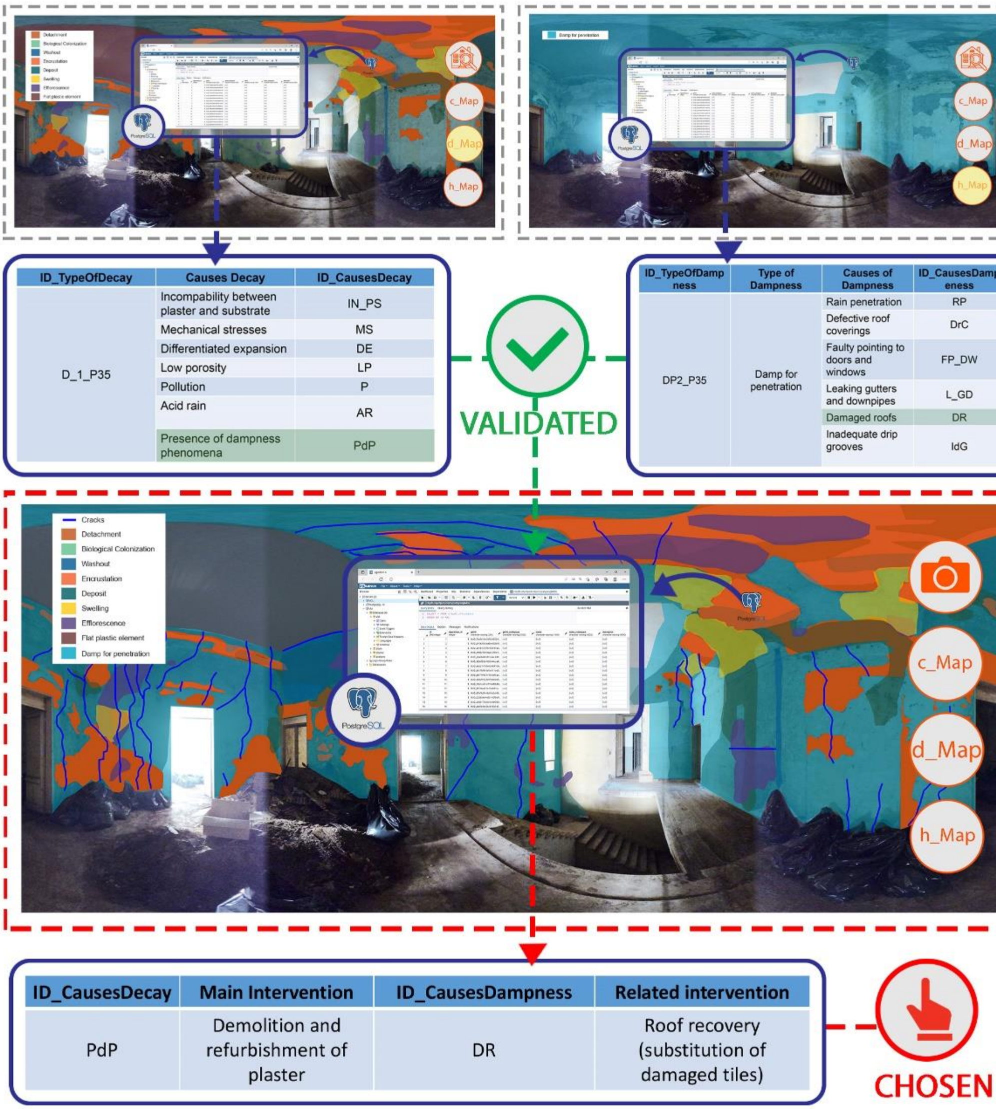


Figure 6 Schematic conservation process of Virtual Models integrated with DSS. Source (Lasorella et al., 2021)

By harnessing the potential offered by these technologies, it becomes possible to enhance the technical knowledge of Cultural Heritage, making it accessible to diverse user groups. Furthermore, leveraging these technologies allows for the initiation of a digitisation process for existing architectural heritage.

The main purposes of digital Virtual Models are: i) faithfully reproducing the real environment through computer graphics simulations, thereby generating a sense of immersion and interaction for the user with the surrounding environment, and simplifying the methods of accessing and enjoying it; and ii) establishing real information systems for the existing built heritage, ensuring the visualisation, implementation, and management of data and information.

In this context, Virtual environments can therefore contain specialist data, useful to different and pertinent sub-fields such as diagnostics information in defining the state of conservation and decay of Cultural Heritage (Paolini et al., 2005) after specific tests.

2.2.3. Review of Virtual Models in the preservation process

To gain insights into the utilisation of virtual models for the analysis of the present built heritage, along with exploring the relationships between virtual models (VMs) and the digital tools employed for this purpose, an examination of recent scientific projects conducted in Europe was conducted. Specifically, seven projects engaged in the analysis, diagnosis, and preservation activities for Cultural Heritage were chosen, and their outcomes have been summarized in Table 2 (Al-Mukhtar et al., 2016; Bertacchi et al., 2018).

Table 2 - European Projects: Focusing on Analysis, Diagnosis, and Preservation in Cultural Heritage

Name Project (Ref)	Goal	Digital Model Types	Database Type	Users
SACRE (The Declaration of Amsterdam - 1975, 1975)	Creation of a tool for the management of digital contents and monitoring stone alterations	3D Mesh texturized	Relational Database (MySQL)	Cultural Heritage Experts in preservation

Sistema senza contatto per la diagnostica con realtà aumentata di manufatti di rilevante interesse culturale e di difficile accessibilità (De Fino et al., 2018)	Elaboration of digital models for the remote technical knowledge	Virtual Tour and 3D Point Cloud	-	Diagnostic experts for the recovery of Cultural Heritage
VOLUBILIS (Al-Mukhtar et al., 2016)	Development of a scientific and technical approach to map, manage and store data collected in recovery processes	3D Mesh VirtualModel 3D mesh texturized	Geo-Database	Archaeological Experts in preservation Tourists
INCEPTION (Di Giulio et al., 2021)	Creation of an Open-standard semantic web platform to enhance knowledge, value and dissemination of European Architectures	HBIM and 3D Virtual Model	Relational and not-relational Databases (MS SQL No-SQL)	Researchers Practitioners Not expert users
SACHER (Bertacchi et al., 2018)	Development of a smart Cloud Platform to manage the Life cycle of Tangible Cultural Heritage	3D Mesh texturized	RDBMS - Relational Database Management System (MySQL)	Cultural Heritage experts (various) Citizens Tourists

HeritageCARE (Ramos et al., 2018)	Development of an immersive VR-tool for the monitoring and the preventive conservation of historic and Cultural Heritage	Virtual tour, 3D Point Clouds and HBIM	Geo-Database	Building owners Practitioners Administrative Universities
VERBUM (Fatiguso et al., 2021)	Development of a platform VR-Based for the technical knowledge of Cultural Heritage	Virtual Tour, 3D Point Clouds and HBIM	Not-relational Databases (NoSQL)	Practitioners Administrative Experts in Cultural Heritage for preservation

The critical analysis of these experiences underscores a growing recognition of the capabilities of disruptive technologies, primarily focused on i) establishing methodologies for acquiring real architectures and generating digital models, ii) devising interoperable systems for handling data and technical information, iii) constructing digital storage founded on structured ontologies, and iv) enabling the involvement of diverse users (experts, administrative personnel, and end-users) in multi-spaces, incorporating both in situ and remote, or entirely remote, experiences in the recovery process. Moreover, the analysis brings to light the capabilities in managing tools, external references (e.g., databases), and the potential for disseminating and communicating content among diverse users involved in these experiences.

2.3. Spatial information systems to support the characterisation of the existing built heritage

The need to document the current state of the existing built heritage and to understand the regulatory evolution and transformations of historic urban areas requires the use of Spatial Information Systems (SIS). The traditional operational and methodological practice for the creation of recovery plans for Historic Centres is based on two main aspects: i) the geometric representation of the historic urban area and ii) the description of the characteristics of the buildings (period of construction, transformations, state of conservation). In traditional practices, these two categories of information, although related, remain physically separated. Geometrical and thematic data are represented graphically in the form of drawings, while the descriptive information is given in textual documents such as the technical report and the plan standard.

In addition, the documentation of urban transformation processes constitutes a continuous flow of information characterised by different levels of interpretation, corresponding to the various phases of the design and management of the architectural artefact. In recent years, this criticality has been overcome through the use of Spatial Information Systems specifically designed and structured for this specific purpose. The peculiarities and specificities of SIS allow the integration of spatial data analysis functions with a level of geometric-semantic specialisation functional to the representation of the complexity of the historical architectural heritage.

Spatial Information Systems (SIS) offer the opportunity to represent information in specific ways, delving into both geometric data with varying levels of detail and thematic data with distinct semantic values. Within this framework, a pivotal role is assigned to spatial data and their integration with thematic data across different scales of representation. This integration enables a comprehensive analysis and interpretation of urban transformations, providing a more intricate and detailed perspective both in terms of geometry and thematic elements. The ability to navigate through information at different levels of detail and semantic attribution facilitates a deeper understanding and more effective management of the urban transformation process.

In this context, the present section explores the crucial role of spatial information systems in the realm of knowledge and conservation processes concerning historic urban areas.

2.3.1. Basics of Spatial Information Systems

A Spatial Information System (SIS) can be defined as a digital environment in which each type of geometric and semantic information can be georeferenced according to a known spatial reference system. Where, the information-semantic level is related to the spatial data by means of a logical-conceptual model called database. However, a Spatial Information System is composed of a spatial system, in which the physical objects are delocalised; and an information system (Database), in which the semantic information is systematised and stored according to a defined logical-relational structure (Laurini & Thompson, 1992).

The processing of a Spatial Information System is possible with the help of a computer-based tool called a Geographic Information System (GIS). Consequently, a Geographic Information System (GIS) can be defined as the set of hardware and software resources capable of systematising, processing, analysing, archiving and returning graphic information related to alphanumeric data of a territory (Nedovic-Budic, 1999).

The origins of the term "Geographical Information Systems" date back to 1966 when it was initially employed to describe the Land Inventory System of the Canadian Forestry Department, as identified by Tomlinson (Tomlinson, 1967). The precise definition of GIS has been a subject of extensive debate in literature, as exemplified by Maguire (Maguire, 1991). Among the widely embraced definitions, especially in the UK, is the one presented in the Chorley Report. According to this definition, GIS is defined as "*A system for capturing, storing, checking, manipulating, analysing, and displaying data which are spatially referenced to the Earth*" (Coppock, 1987).

Over the years, the term Geographic Information System has acquired various meanings and definitions, including:

- "*…a Geographic Information System is a powerful set of tools for acquiring, storing, extracting at will, transforming and visualising spatial data from the real world*" (Burrough, 1986);
- "…*a Geographic Information System is a facility for preparing, presenting and interpreting facts about the earth's surface. GIS is a configuration of computer hardware and software, specifically designed for the acquisition, maintenance and use of cartographic data*" (Tomlin, 1990);
- "…*a Geographic Information System is an information system designed to work with data referenced by spatial or geographic coordinates...it is both a database system with specific capabilities for spatial reference data and a set of operations for working with the data...In a sense, a GIS can be thought of as a higher order map*…" (Star & Estes, 1990);
- "…*a Geographic Information System is a group of procedures that enable spatial input, storage, access, mapping and analysis for both spatial data and attributes to support organisational decision-making activities*…" (Grimshaw, 1999).

2.3.2. Technical Requirements of a Spatial Information System

When integrated into a Spatial Information System (SIS), geographic information undergoes a series of steps, including interpretation, organisation, and digitisation, to render it usable. In the initial phase, the information must be interpreted based on models that emphasize its features relevant to comprehending specific phenomena. This interpretation entails the careful selection and definition of meaningful parameters that enhance the understanding of the interrelationships among geographic data (Fischer & Nijkamp, 1992).

Subsequently, the geographical information needs to be structured into information formats that facilitate efficient processing by mathematical algorithms.

This process includes establishing organized geographic databases where information is interconnected in a logical and cohesive manner.

The databases may be associated with vector data (such as points, lines, and polygons) or raster data (grids of cells), depending on the characteristics of the geographic data. In the last step, for utilisation by software, geographic information must be presented in standard digital formats that software can comprehend and interpret. This may necessitate the transformation of geographical data into formats like shape files, GeoJSON, KML, or other formats compatible with GIS software. The selection of the format is contingent upon the nature of the data and the specifications of the system in operation. Consequently, real-world physical entities are stored within a Spatial Information System (SIS) according to two representation models:

- An Information Model, also known as Geo-DB, facilitates the systematic organisation, management, and archival of alphanumeric information. This model comprises three main components: a conceptual model, a logical model, and a physical model. The conceptual model articulates a particular problem or a specific facet of the physical object being represented (Figure 7).

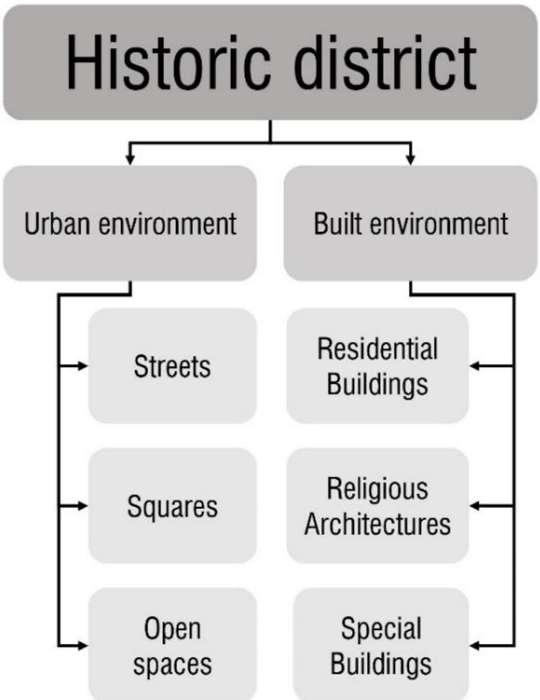


Figure 7 - Visual representation of the conceptual model involves depicting entities within boxes, with links indicating relationships between them.

Whereas, the logical model describes the entities and relationships identified in the conceptual model by means of a defined structure for implementation in the SIS. The logical model most commonly used for the elaboration of a structured information system is the entity-relational (E/R) model or its "*object-relational*" evolution. The logical-relational model, represented in Figure 8, consists of: entities, entity classes, relationships between entities and entity classes, attributes for each entity, cardinality of relationships.

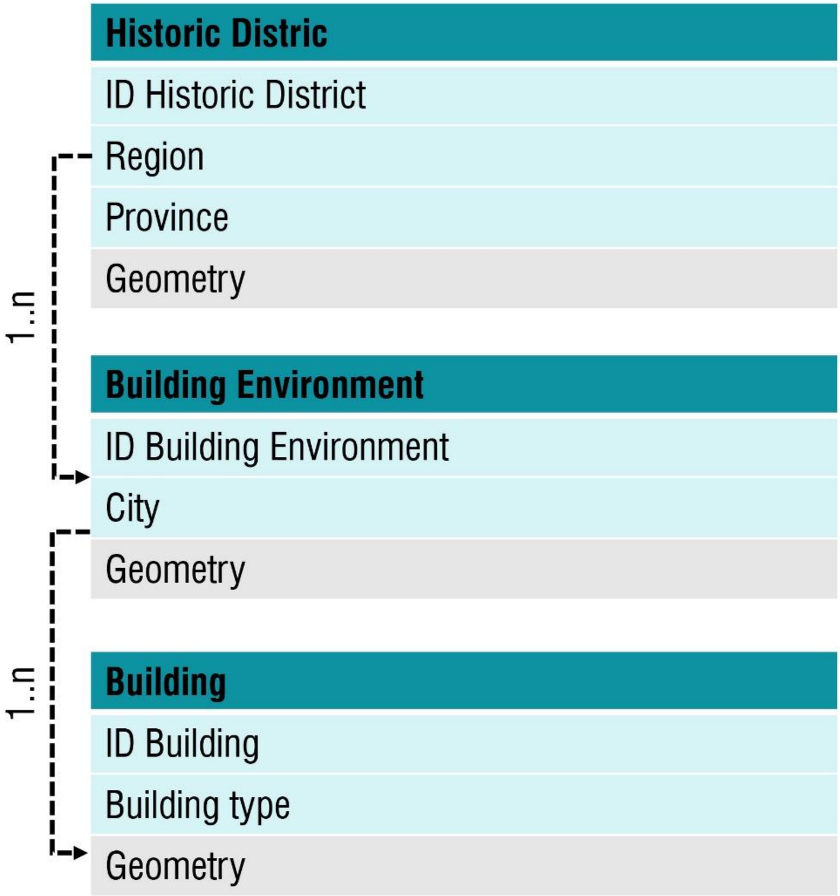


Figure 8 - The logical-relational model

In detail, entity classes are represented by an attribute table, the columns of which are defined as fields and the rows as records/tuples. Each row defines the specific entity.

Whereas, each column defines the properties related to the individual entities. Therefore, each entity table/class is characterised by an identifier field that is called the “Primary key”. This attribute allows the unique identification of a given entity within the Geo-DB.

Attribute name	DataType	Dimension	Description
ID Historic District	Integer	10	Primary key
Region	Character	30	Name of the Region
Province	Character	30	Name of the Province

Figure 9 - The physical model

Further, the physical model, illustrates in Figure 9, defines the structuring of the conceptual-logical model through the identification of: i) the relationships between tables; ii) the nomenclature and dimension of the alphanumeric value of entity classes, entities and attributes; and iii) the relational-topological structure of geometric features.

- A Geometric-spatial Model, which enables the representation and georeferencing of physical objects (Figure 10). At the geometric level, physical entities can be represented using a vector and/or raster structure. Vector data represents physical entities in the form of points, lines and polygons (features). The main characteristics of geometric features are: the georeferencing, by means of geographic coordinates, of all entity points; the correlation of the geometric datum to the individual attributes of the information model; and the presence of a topological structure, thanks to which entities are organised in such a way that descriptive information can be associated with each of them, enabling the creation of spatial analyses. However, the main feature of the vector model consists in the discretisation of the built environment according to different analysis themes, which take on the name of Layers. In fact, each feature can be linked to an alphanumeric value, stored in the Geo-DB, which allows the creation of thematic analysis layers. For each of these layers, the topological structure must be generated.

In parallel to the vector model, physical objects can also be represented using the raster model. The raster model describes the urban environment in the form of pixel/cell matrices, each containing a representative value of the area covered by the cell. Therefore, the level of detail represented by the raster data is a function of the resolution (cell or pixel size) of the model.

The raster model encompasses georeferenced digital aerial photographs, satellite images, digital terrain models (DTM), and digital surface models (DSM).

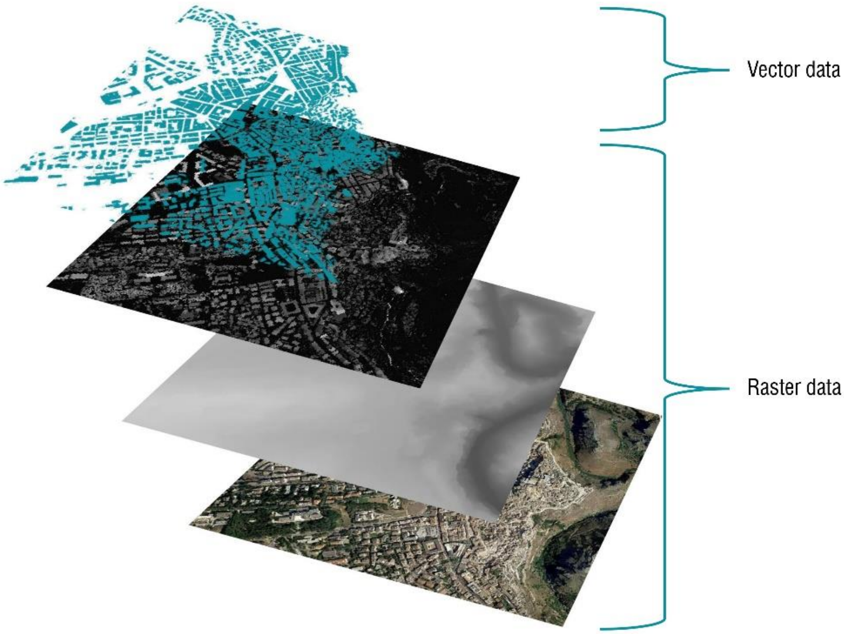


Figure 10 – The Geometric-spatial Model

In a spatial digital environment, information is organized by defining georeferenced geometric entities within a specific reference system, linked to an information system known as Geo-DB. The digital environment facilitates the localisation of individual geometries and the correlation of information at a semantic level.

Indeed, a key feature of spatial information lies in the dual analysis of geometric-spatial and thematic-informative data within a unified digital system. This allows the integration of the Spatial Information System with geometric (image-based) and virtual (VR-based) digital models, increasing the level of technical knowledge.

The following is an overview of the research conducted in this topic.

2.3.3. Overview of Spatial Information System for technical knowledge of the built heritage

In the field of knowledge and conservation, the use of spatial information systems (SIS) in the scientific landscape has shown a close correlation between the assessment of the built environment at both the district and building scales.

When delving into understanding the material, technical, constructional, and architectural characteristics, as well as the state of conservation, and the diachronic functional and structural changes that assets undergo, the micro scale scrutinizes each individual asset as a distinct entity, detached from its surrounding context. Concurrently, on the macro level, the asset system (Historic Centre, neighborhood) is analysed in its entirety, taking into account the interrelationships and recurring distinctive features that define it (Campisi, 2020).

However, the level of analysis requires the integration of micro-scale data and information to a broader context, allowing the development of additional technical knowledge approaches that are crucial in the decisive stages of designing recovery strategies (Kioussi et al., 2013).

In detail, research studies in this subject area have mainly dealt with three themes according to the degree of detail:

1. at the district scale- Characterisation of the historic urban environment for risk management (seismic, flooding)(Bernardini et al., 2024);
2. at the level of systemic architectural entities - Knowledge of a plurality of assets scattered geographically over the territory and identifiable as structured networks of simple units that are systemic in terms of morphology and/or

construction technology and/or function (e.g. defence systems - towers, castles, ... , - rural systems - farms, farmhouses, ... - production systems - power stations, paper mills, ...)(Lasorella et al., 2024);

3. at the building scale - Qualification of the built environment for the knowledge of extrinsic (morpho-typological, constructive, material characteristics) and intrinsic (previous and current use, period of construction, evolution of architectural transformations) characteristics (Delegou et al., 2013);
4. at the building component level - Definition of the state of preservation through mapping and management of the technical-knowledge data within the spatial information system (decay thematic gis maps)(De Fino et al., 2024).

3. THE ONTOLOGIES IN THE PRESERVATION PROCESS OF ARCHITECTURAL CULTURAL HERITAGE

In recent years, there has been a growing focus on the role of structuring technical knowledge in the management of Cultural Heritage. This heightened interest pertains specifically to the identification, protection, and conservation of both movable and immovable cultural assets, including historic buildings, archaeological sites, and cultural landscapes (Bold, 2009). Indeed, in the process of analysing and managing the built heritage, critical issues arise from the correlation between multidisciplinary and heterogeneous, as well as complementary, information. These challenges can be addressed through the utilisation of formal and conceptual representations such as ontologies. Ontologies hold significant importance in various realms of scientific research, including knowledge engineering, natural language processing, collaborative information systems, intelligent information integration, and knowledge management.

These ontologies provide a basic tool that enables a shared understanding of a given domain. Such shared understanding can be effectively communicated among individuals and distributed application systems with varying characteristics.

Consequently, ontologies play a key role in structuring data and information, enabling a precise semantic representation of concepts and relationships within a specific domain. This semantic clarity facilitates information sharing and mutual understanding between different actors and systems in the context of complex, distributed applications. Furthermore, ontologies contribute to enhancing interoperability between heterogeneous systems, thereby enabling improved integration and search capabilities for information. Additionally, they promote more effective knowledge management across various domains (Fensel, 2001). Addressing the subject of ontological structuring in the applied field of historical architectural heritage requires, as a prerequisite to delving into the topic, a thorough understanding of the inherent meaning of the term "*ontology*", along with its associated concepts.

The term "*ontology*" has acquired various meanings depending on the context in which it is applied. Guarino et al. explain the use of the term "*ontology*" within two primary frames of reference: i) philosophical, denoting a systematic relation of existence, and ii) computational, wherein what exists is what can be represented (Guarino et al., 2009). The concept of "*ontology*" primarily originates from the realm of philosophy. However, in recent years, ontologies have been developed and applied in the field of Artificial Intelligence (AI) to streamline and enhance knowledge sharing.

In computer science, the main definitions include:

i) "*explicit specification of a conceptualisation*" (Gruber, 1993);
ii) "*formal specification of a shared conceptualisation*" (Borst et al., 1997);
iii) "*an ontology is a formal, explicit specification of a shared conceptualisation*"(Studer et al., 1998);
iv) "*a shared and common understanding of a domain that can be communicated between people and application systems*" (Fensel, 2001).

Based on these axioms and meanings, an "*ontology*" can be defined as the formal specification of a shared, explicit conceptualisation. An explicit conceptualisation refers to an abstract model in which each object is represented through specific concepts, names, and explicit definitions. On one hand, the name establishes the terminology associated with the object, while on the other hand, the definition provides the specification of the inherent meaning of the concept or relationship. Thus, the formally represented body of knowledge relies on a conceptualisation of objects, concepts, and entities that exist in a specific area of interest, delineated by the relationships between them. Consequently, conceptualisation is ingrained in the formal property of explicit specification through a defined language. As a result, ontologies depict objects from various knowledge domains by means of:

i) Definitions, which identify the name of the specific entity and elucidate how the entities are interrelated;

ii) Classes, which represent specific entities within the conceptual model (objects, concepts);

iii) Relations, which connect classes based on a defined structure (network or taxonomy of classes and subclasses);

iv) Attributes, which detail the characteristics of entities belonging to a specific class by defining their properties (Gruber, 1995).

Hence, an ontology is a conceptual model that provides a structured and well-defined basis for the representation of a specific reality or domain. It is an abstract model that represents a specific reality or domain in terms of a semantic vocabulary.

This vocabulary consists of a set of definitions specifying the meaning of the associated terms and concepts used to describe the pertinent domain. The vocabulary of an ontology can be articulated through various languages and notations. For instance, it is customary to employ diagrams that depict classes, attributes, and relationships between concepts. These diagrams provide a clear visualisation of the structure and organisation of concepts within the ontology.

Depending on the type of language used, a continuum of ontology types has been outlined by (Uschold & Gruninger, 2004), as depicted in Figure 11, which shows the different approaches for structuring ontology models.

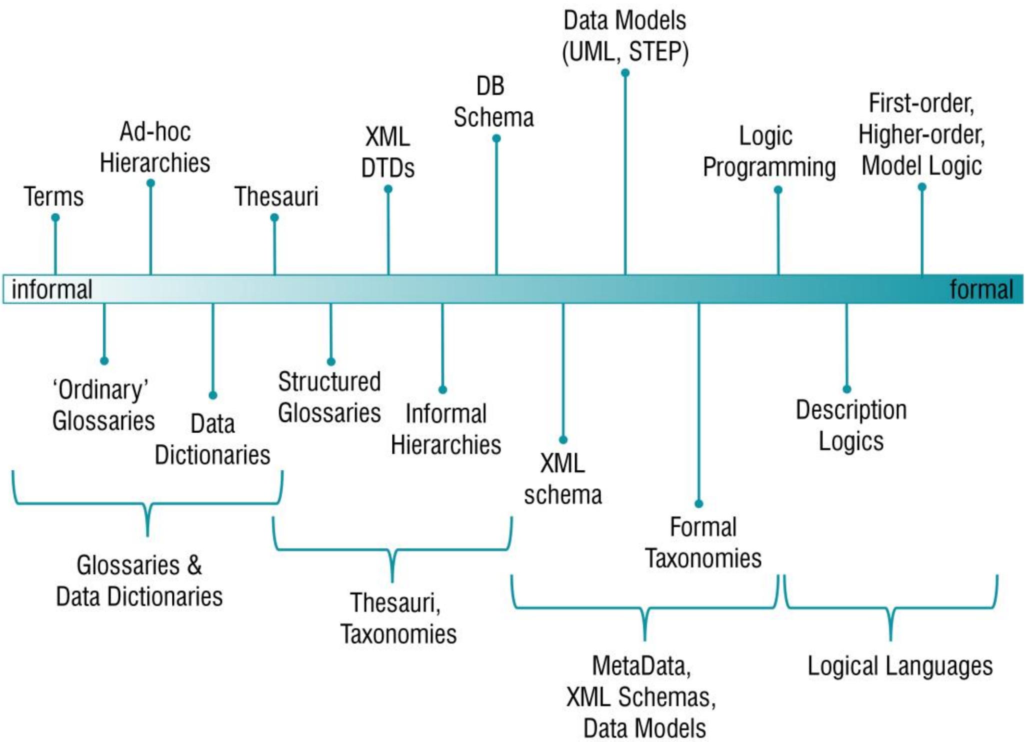


Figure 11 - Continuum of ontology types depending on the language used.
Source (Uschold & Gruninger, 2004)

The continuum illustrated in Figure 11 delineates four primary categories of ontologies:

i) Highly informal ontologies, defined as simple, characterised by terminology that is not extensively specified;
ii) Semi-informal ontologies, characterised by a simple yet structured language;
iii) Semi-formal ontologies, expressed through formally defined artificial languages;
iv) Highly formal ontologies, comprising rigorously formalized theoretical and logical approaches, where terminology adheres to a formal semantics.

Furthermore, an increase in the degree of explicitness of meaning can be observed in the continuum analysis, as well as an increase in the level of formalisation.

Ontologies can also be classified based on: i) the specification of the conceptualisation of a knowledge domain and ii) the subject of the conceptualisation. In the first classification, the level of generality of an ontology allows for the identification of the following categories:

i) Foundational ontologies (upper ontologies or top-level ontologies), describe highly general concepts to which more specific terms of lower-level ontologies (domain ontologies) can be related (e.g. SUMO - Suggested Upper Merged Ontology, DOLCE, and CIDOC-CRM ontologies).
ii) Domain ontologies, where the conceptual model is developed from controlled vocabularies, languages, theories, and principles specific to the relevant generic domain.
iii) Task ontology, which provides the basic knowledge of a task, consisting of axioms and concepts, for structuring higher-level ontologies.
iv) Application ontology, which describes the knowledge domain useful to an application by mediating a specialisation of domain ontologies.

In the second type, there are:

i) Application ontologies, describing the fundamental concepts useful for modelling the knowledge of a specific application. In this case, the ontology model uses terms from generic ontologies and extends generic or domain knowledge through specific terminology related to the application domain.
ii) Domain ontologies, representing the knowledge of a well-defined application-disciplinary field by elevating the level of concepts within a specific domain.
iii) Generic ontologies, specifying generic concepts applicable to different domains.
iv) Representation ontologies, outlining domain and generic ontologies with the aid of primitive meanings.

Ontologies play a key role in semantic-based technologies, encompassing knowledge representation. They also serve as tools for structuring information in repositories, facilitating the systematisation and classification of information systems designed for this purpose. Through the amalgamation of information models, such as relational databases, and more comprehensive conceptual models like formal ontologies, there arises an implicit correlation in the structuring and systematisation of knowledge. The distinguishing factor between a conceptual model (ontology) and an information model (database) lies precisely in the systematisation of the knowledge domain according to a defined semantic structure.

In this context, it can be asserted that ontologies are fundamental tools for achieving semantic interoperability, as they conceptualize a domain and serve as mediators for the integrated search of digital objects across different repositories. Consequently, they facilitate the governance of knowledge domains and the integration of information to establish a shared structure aligned with the scope of investigation (Biagetti, 2016).

3.1. Semantic structuring of Architectural Cultural Heritage data

Considering the challenges inherent in the knowledge and management of Architectural Cultural Heritage information, these can be attributed to: i) the multidisciplinary nature of data, involving theoretical concepts found in textual and graphic documentation; ii) the heterogeneity in the nature of the information, in relation to the format and extension of the data (information consisting of textual documentation of different format/extent, photographs, drawings); iii) the hierarchy of the information level, referring to the degree of detail provided in the information, ranging from general to particular character; iv) the complex granularity of data storage in existing digital and non-digital archives, stemming from the absence of a common logical structure for data storage and management (Khalil et al., 2021).

These critical issues highlight the need to address challenges related to the diversity, hierarchy and complexity of data in the context of Cultural Heritage management. In response to these critical issues, international standards for the analysis and evaluation of architectural assets have been developed. These standards are based on: i) guidelines, which facilitate the comprehension of fundamental concepts categorized into subcategories, fields, and relationships within the knowledge domain; and ii) vocabularies, which enable the development of standardized taxonomies and the structuring of technical knowledge. The main standards developed since the early 1990s are:

- Core Data Index to Historic Buildings and Monuments of the Architectural Heritage, standard adopted by the Council of Europe in 1995 serves as a classification system for buildings and sites. Its primary objective is to categorize them based on distinct categories, subcategories, and fields (Ministers, 1995).
- International Core Data Standard for Archaeological Sites and Monuments, published in 1998, aims to classify archaeological sites according to main sections(Co-operation, 1999);

- Dublin Core Metadata Element Set, a flexible metadata schema that can be used for sharing and integration between different digital sources, typically used in the library environment (ISO & STANDARD, 2009);
- MIDAS Heritage, british Cultural Heritage standard for recording information on buildings, archaeological sites, shipwrecks, parks and gardens, battlefields, areas of interest and artefacts (Lee, 2007);
- ICOMOS (International Charters for Conservation and Restoration), it provides guidelines and criteria for the evaluation of architectural heritage in order to contribute to its conservation and management. The main tools developed by ICOMOS for the understanding and evaluation of architectural heritage are: guidelines and recommendations for the conservation, restoration and sustainable management of architectural heritage, and International charters. ICOMOS has published international charters that provide guiding principles for heritage conservation, including the "Venice Charter" (§1.2.1) that focuses on the conservation of monuments and historical sites (Patiwael et al., 2019).
- EUROPEANA Data Model, interoperable framework that allows us to collect, connect and enrich Cultural Heritage metadata (Doerr et al., 2010).

3.2. Systematising technical knowledge of Architectural Cultural Heritage from an international perspective

Internationally, the existing and most widely used standard for the representation and correlation of information in the field of knowledge of the built environment is the CIDOC-CRM ontology and its extensions. CIDOC- CRM (Conceptual Reference Model) is a unique conceptual reference model for Cultural Heritage. This conceptual reference model was developed by the International Committee for Documentation (CIDOC) of the International Council of Museums (ICOM) as a conceptual model and has become an ISO standard (ISO 21127:2006). CIDOC-CRM functions as a formal ontology designed to facilitate the exchange and integration of information and documentation among diverse sources in the Cultural Heritage domain, including museum collections, archaeological sites, monuments, and archival documentation(Doerr, 2003). CIDOC-CRM is founded on conceptual and semantic modelling principles, offering a standardized set of classes, properties, and relations to represent essential concepts and relationships within the Cultural Heritage domain. This model consistently and interoperable describes information about objects, events, places, people, and others within the Cultural Heritage context. Specifically, it is designed to support the cataloguing and documentation of data about museums, archives, libraries, archaeological sites, art collections, and more. This ensures the organisation of information through a defined semantic model. The ontology, in particular, relies on a relational structure that connects "physical" objects (cultural assets), the physical asset and the events influencing it, and the entities (people and organisations) that interacted with it (Oldman & Labs, 2014).

The conceptual model consists of taxonomies structured according to a standardised set of elements:

1. Classes. CIDOC-CRM defines a set of core classes representing the main objects and concepts within the Cultural Heritage domain. Some of the main basic classes include "*E1 Creation*", "*E2 Temporal Entity*", "*E3 Condition State*", "*E4 Period*", "*E5 Event*", "*E6 Destruction*", "*E7 Activity*", "*E24 Physical Man-Made Thing*", "*E39 Actor*", "*E53 Place*", "*E77 Persistent Item*" and "*E78 Collection*".

2. Properties, which define the relationships between classes in the conceptual model. These properties allow objects and concepts to be linked by specifying how they are related to each other. For example, some common properties include "*P4 has time-span*", "*P45 consists of*", "*P107 has current or former member*", "*P129 is about*" and "*P140 assigned attribute to*".

3. Key Concepts, which provide a conceptual basis for heritage data modelling. These key concepts include "*identity*", "*time*", "*place*", "*activities*", "*collections*", "*events*", "*artefacts*", "*actors*", "*states*" and "*properties*".

The structure of CIDOC-CRM is organized hierarchically, with classes interconnected by properties and relationships. This conceptual model is intentionally designed to be extensible, allowing institutions and communities can adapt it to their specific

Cultural Heritage documentation and management requirements. Its adoption contributes to standardizing data representation in the Cultural Heritage sector, promoting interoperability across diverse systems and institutions.

Widely employed in Cultural Heritage information management and sharing projects, CIDOC-CRM has played a crucial role in enhancing the accessibility and understanding of Cultural Heritage on a global scale.

However, it is possible to extend CIDOC-CRM by adding specific classes, properties and relationships to adapt it to specific application cases. These extensions can be developed to address specific requirements or to integrate CIDOC-CRM with other standards or ontologies:

1. *CRMgeo-Spatiotemporal Model* adds classes and properties for modelling geospatial information, enabling the representation of places and their relations to cultural objects. The extension uses concepts, coding standards and topological relationships defined by the Open Geospatial Consortium (OGC).

2. *CRMdig* (CIDOC-CRM for Digital Provenance) implements the model with digital objects, such as photographs, digital documents and other digital objects that are part of the cultural heritage, enabling the traceability and management of digital resources.

3. *CRMsci* (CIDOC-CRM for Scientific Observation Data) enables the modelling of scientific observation data, allowing the representation of scientific information, measurements and relationships between observed objects by means of a global schema integrating metadata related to the branch of natural sciences.

4. *CRMba* (CIDOC-CRM for Intangible Cultural Heritage) integrates the modelling of intangible Cultural Heritage, oral traditions, rituals, legends and other elements of non-material Cultural Heritage.

5. *CRMinf* (CIDOC-CRM for Information) allows the modelling of digital information and documents, enabling the representation of metadata, relationships between digital documents and other related information.

6. *CRMarchaeo* (CIDOC-CRM for Archaeological Data) implements the conceptual modelling of archaeological data, enabling the representation of archaeological sites, finds, archaeological contexts and relationships between them.

7. *CRMtex* (CIDOC-CRM for Textual Data) implements textual data and document modelling, enabling the representation of texts, textual metadata and relationships between historical documents and cultural objects.

Each CIDOC-CRM extension is crafted to customize the basic model according to specific industries or contexts, enabling more precise description and management of data within those domains. These extensions provide increased specificity and flexibility in modelling data within their respective contexts. However, it's crucial to highlight that the utilisation of extensions necessitates a structure that aligns with the fundamental CIDOC-CRM model to guarantee interoperability between systems and institutions sharing data in the Cultural Heritage field.

In this context, it is essential to highlight one of the primary applications of the CIDOC-CRM ontology in the realm of architectural heritage, specifically within the conservation process. This application was implemented in the MONDIS project, with the primary aim of creating an ontological framework for the automated analysis of the conservative state of built heritage, diagnosis, and potential interventions (Blaško et al., 2012; Cacciotti et al., 2013).

The conceptual model was developed as the IT layer of a mobile/desktop platform useful for the management of the knowledge required for the understanding and analysis of degradation phenomena affecting historic buildings. The MONDIS platform allows: i) the acquisition and implementation of data in situ and/or on-desk, through the compilation of a report; ii) the modification of the implemented data and the integration of further information according to a controlled access system; iii) the validation of the technical knowledge collected in order to admit the data to the diagnosis section, as well as to the subsequent section of possible intervention strategies. Specifically, the input data are related according to the damage-centred conceptual model prepared on the basis of the Monument Damage Ontology (Cacciotti, 2015).

Specifically, the MONDIS ontological model consists of six thematic classes:

1. Architectural Components, shows the hierarchical structure of the building system, consisting of sub-components and elements. Physical (material and construction characteristics) and functional (performance and use characteristics) factors are related to each of them.

2. Events, identifies the possible fast-acting natural events (floods, earthquakes) and slow-acting natural events (climate change, pollution) that may compromise architectural artefacts. The class of events is related to the subclasses: i) natural event, which identifies the type of disaster; ii) object modification, which identifies the type of effect of the event on the asset (functional or structural); iii) location modification, which identifies the modifications of the geo-morphological, hydrogeological and environmental structure of the site.

3. Diagnosis and intervention strategies, a subclass of the class "*Events*" identifies the type of damage (cracks, degradation), the activation mechanism (related cause), the agent (main cause) and the interventions (chosen strategy).

4. Risk assessment, defining possible mitigating factors.

5. Measurement, a class independent of the main structure that allows the quantification of the geometric (height, thickness) and physical (masonry tension, presence of water, surface temperature) characteristics of an architectural component and the damage investigated (extent of degradation phenomena).

6. Other, a class that allows the extension of the ontological model by means of other existing ontologies.

The MONDIS ontological model uses existing taxonomies extracted from the scientific literature(Cacciotti et al., 2013).

Furthermore, glossaries, vocabularies, and classifications play a crucial role within the framework of heritage classification.

Specifically, the Getty Institute Vocabularies present a hierarchy of terms and definitions related to the heritage domain, with the goal of classifying works of art and architecture, names of artists or architects, and geographical categories.

One notable vocabulary within this framework is the Art and Architecture Thesaurus (AAT) (Wielinga et al., 2001).

The AAT is an authoritative structured vocabulary and thesaurus used for describing and indexing art and architecture-related information. It's a valuable resource for cataloguing and organizing art and architectural materials in libraries, museums, archives, and other cultural institutions. In addition, AAT provides a standardised and controlled vocabulary for describing various aspects of art and architecture, including terms related to artists, art movements, architectural styles, materials, techniques, and more. It helps ensure consistent and accurate metadata and indexing for artworks, architectural structures, and other related artefacts. It is characterised by a semantic structure with a high level of granularity, such as to allow the definition of all the elements of a cultural asset. Finally, AAT is often used in conjunction with other standards and systems, such as the Getty Vocabulary Program's other vocabularies, to enhance the accessibility and retrieval of art and architectural information. The Getty Vocabulary Program is part of the J. Paul Getty Trust and provides several important controlled vocabularies for Cultural Heritage documentation.

3.3. Standardised cataloguing and documentation of Architectural Cultural Heritage in Italy

In the context of Italy, it is noteworthy to consider standards and ontologies developed by the Ministry for Cultural Heritage, Activities and Tourism (MIBACT).

Specifically, the Italian Central Institute for Catalogue and Documentation (ICCD) has spearheaded the development of standards and tools for the cataloguing, documentation, and preservation of cultural assets (Knowledge, 2017).

The elaboration of a reference standard at Italian level stems from the need to catalogue and share information on the existing architectural heritage, among the many (public and private) subjects operating in the Cultural Heritage sector, as foreseen by Art. 17 of the Cultural Heritage and Landscape Code[1].

[1] The President of the Italian Republic. Legislative Decree No. 42 of 22 January 2004, "Code of Cultural and Landscape Heritage", pursuant to Article 10 of Law No. 137 of 6 July 2002, (2004). Italy.

Nevertheless, to facilitate the consistent cataloguing and sharing of knowledge at the national level, the ICCD has formulated a standard, outlining specific tools and guidelines for implementation.

Specifically, the standardised system defined by the ICCD is mainly based on three macro-components: i) descriptive models, records that allow the systematisation and archiving of alphanumeric data according to pre-established parameters (norms); ii) terminological tools, conventional definitions, vocabularies, thesauri, to standardise and formalise languages; iii) compilation rules, methodological approaches for defining how the records and terminological tools are used. These components are correlated by means of specific relations capable of constituting a nationally unified knowledge system.

The ICCD standard is applied to archaeological, architectural and landscape, historical and artistic, and anthropological heritage. Therefore, the descriptive models are divided according to three categories of assets (immovable, movable and intangible) and nine subject areas (archaeological assets, architectural and landscape assets, anthropological assets, photographic assets, musical assets, natural assets, numismatic assets, scientific and technological assets, historical and artistic assets).

The ICCD conceptual model, set out in the form of compilation sheets, is structured according to: paragraphs, fields and subfields. In detail, the relationships are: i) each paragraph contains n simple fields and/or n structured fields; ii) each structured field contains n subfields. The standards defined by the ICCD have undergone a number of updates and modifications over time, both in terms of data structure, i.e. the way bibliographic information is organised and recorded, and in terms of the compilation standards and terminological tools used.

These adjustments have proven essential in response to the progression of scientific research across various disciplinary fields and the growing intricacies of cataloguing demands. Over the years, the increasing complexity and nuances in cataloguing have necessitated changes. Ongoing developments in technology, new discoveries, and shifts in cataloguing methodologies have mandated a continual adaptation of standards. This is crucial to guarantee a precise and uniform representation of information. The ICCD oversees the entire cataloguing process using the General Catalogue Information System, known as SIGECweb. In particular, SIGECweb is an information system that serves as a centralized platform for handling bibliographic information and cataloguing resources in Italian libraries. It stands as a pivotal tool to ensure the organisation and streamlined access to bibliographic resources throughout the country. The system enables the recording, management, and standardised sharing of bibliographic data, thereby facilitating the exchange and retrieval of resources across different libraries. Based on the descriptive models of the ICCD standard, the Knowledge Graph of Italian Cultural Heritage, called ARCO (Architecture of Knowledge), was developed. Arco can be defined as a network of ontologies capable of describing the different types of Cultural Heritage, catalogued according to the ICCD forms(Carriero et al., 2019). Additionally, the ICCD conceptual framework was used in the application area of the vulnerability seismic and energy of Historic Centres (Vitiello, 2023). Specifically, the Risk Map was drawn up (Fiorani et al., 2023).

3.4. Standards for the representation of the built and urban environment: the CityGML

The increasing challenges associated with overcoming interoperability issues among existing urban and spatial databases, coupled with the necessity to integrate diverse multidisciplinary data sources, have sparked interest in employing ontologies in the realm of existing building asset management.

The growing difficulties in addressing interoperability challenges within urban and spatial databases, alongside the imperative to integrate diverse data sources from various disciplines, have prompted a keen interest in the application of ontologies within the domain of managing existing building assets. Indeed, the ontologies provide a structured and standardised way to represent knowledge, allowing for a common understanding of concepts and relationships within a given domain. In the context of existing building asset management, ontologies can play a crucial role in overcoming interoperability challenges and facilitating the integration of diverse data sources.

Recent activities in managing technical knowledge about Architectural Heritage have resulted in the structured organisation of technical knowledge. This organised knowledge serves as the foundation for creating parametric digital models at various scales, including building, district, and urban levels. This effort aligns with the Scientific community emphasis on transitioning to digital processes, methods, and models for community activities and services. In this scenario, BIM, IndoorGML, INSPIRE, and CityGML-based models are indeed considered effective tools for the representation and systematisation of information in the field of architecture and urban planning. Each of these technologies brings specific capabilities, at a building scale:

- BIM (Building Information Modeling) is a collaborative process that involves creating and managing digital representations of physical and functional characteristics of a building. It encompasses the entire lifecycle of a construction project, from initial planning and design to construction and operation. It enablies efficient collaboration, reduces errors and rework, and facilitates better decision-making throughout the construction process;

- IndoorGML (Indoor Geography Markup Language) is an open standard developed by the Open Geospatial Consortium (OGC) and is designed to ensure interoperability and data exchange between different software and systems. It provides a common framework for representing indoor spatial data and introducing the “cellular space” concept. It provides a framework for modeling the geometry and semantics of indoor spaces, allowing for interoperability and exchange of indoor spatial data. In detail, it supports various applications such as indoor navigation, facility management, and emergency response planning;

and at urban scale:

- INSPIRE (Infrastructure for Spatial Information in the European Community) is a European initiative aimed at creating a European spatial data infrastructure for the sharing of environmental and geographic information. It defines common standards and interoperability requirements for spatial data related to the environment. Promotes the sharing of geospatial data across European countries, supporting better decision-making in areas such as environmental management and policy development.

- CityGML is an OGC standard for the representation and exchange of 3D City Models. It allows for the representation of various aspects of urban environments, including buildings, terrain, vegetation, and transportation infrastructure, in a standardised format. The CityGML standard facilitates the integration of 3D City Models into different applications such as urban planning, energy simulation, and disaster management.

These standards and ontologies contribute to a more comprehensive and standardised approach to managing spatial information in the context of architecture and urban planning. By incorporating these models into the ontology-driven approach, stakeholders in architecture and urban planning can enhance their ability to manage existing building assets effectively. The integration of ontologies and standardised models contributes to a more seamless and interoperable digital representation of architectural heritage, aligning with the broader digitalisation goals set by the Scientific community.

Within this context, one of the pivotal reference ontologies on the urban scale is the CityGML standard.

CityGML, an acronym for City Geography Markup Language, stands as an open standard designed for representing and exchanging 3D geospatial information pertaining to cities and urban environments (Figure 12). Developed by the Open Geospatial Consortium (OGC), an international organisation dedicated to establishing standards for geospatial and location-based data, CityGML defines an XML-based data model and encoding for the representation of 3D city models (Kolbe et al., 2005).

The primary aim behind the development of the CityGML standard was to establish a shared definition and understanding of the essential elements, characteristics, and connections within a 3D City Model. Accordingly, the CityGML standard provides a structured and standardised approach for storing and exchanging data about urban objects, encompassing their geometry, semantics, and relationships.

The main key features of CityGML standard include:

- Geometry-topological model. CityGML can represent the geometry of city objects - such as buildings, streets, and terrain -, allowing for detailed and accurate modelling of cities and urban environments. CityGML employs a subset of the geometric model GML3, which implements the ISO 19107 standard. Following this, the geometries of geographical features are depicted as objects with inherent identities and supplementary geometric substructures. Furthermore, CityGML employs the XML concept of XLinks, facilitated by GML (Geography Markup Language), to implement topology. Each geometry object, as the item to be shared among various geometric aggregates or distinct thematic features, is assigned to a unique identifier. This identifier can then be referenced by a GML geometry property through an attribute.
- Semantic-thematic model. This part of the CityGML modelling is represented through specific taxonomies (feature class taxonomy) and aggregations, following a hierarchy structure of classes (Figure 13). It includes a set of semantic information, enabling the description of the function and attributes of urban ob-

jects. The semantic level of the model follows the ISO 19100 standard, according to which geographical features are abstractions of real-world objects. The objects are modelled through a hierarchy of formally defined classes using UML notation. Thus, a CityGML-based model is structured according to the UML semantic as a system of:

i) "*Element*" which takes the name of "*Class*".

ii) "*Attribute*" that lists and describes properties of the associated "*Class*".

iii) "*Relationship*" which links two or more classes.

iv) "*Operation*" is an executable process within the "*Class*".

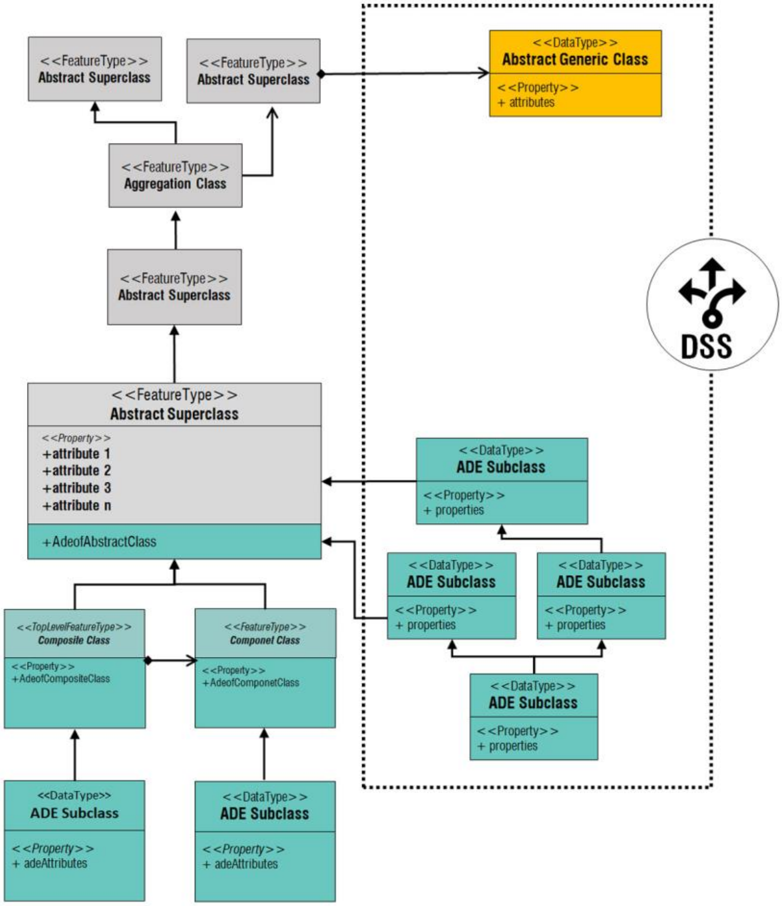
A name is linked with each "*Class*", identifying the digitalized object (building, street, bridge), and its "*Stereotype*" which identifies the inherent scope of the class (Type, FeatureType, Top Level Feature Type). At the same time, a stereotype defines the extensibility mechanism that can be used to better identify the purpose of the model element to which it applies. They can be applied to the classes and relations of the conceptual model. The hierarchy of types of "*Class*" can be identified in coherence with the type of "*Relationship*" that links classes:

- The relationship *Abstraction* links different classes having the same concept but describing it in multiple variations. The system of classes connected using *Abstraction* relation is the "*AbstractClass*" and it contains the common properties of all the classes in the model (i.e., function, use).
- The *Inheritance/Generalisation* relationship links a "*SubClass*", as a specialised class of the model to a "*Superclass*" which is a general one.
- The *Aggregation* relationship connects and associates two or more classes being a part of the aggregate class. The meaning of the relationship is "*part of*". Therefore, the "*Component Class*" is part of the "*Aggregate Class*".
- The *Composition* relation is a specialisation of the aggregation relationship and it is useful for describing parts of a higher class. Here, the existence of the relationship is a function of the connected element.

In this sense, this relationship connects multiple "*ComponentClasses*" to one "*CompositeClass*".

- The relationship *Association* relates elements of different models.

This makes it possible to represent not only the physical geometry but also the meaning and purpose of different elements in the urban environment. Starting with the first version (v1.0), the CityGML standard is functionally organised into several modules, each of which addresses specific aspects of urban and landscape modelling. These thematic modules were implemented over time with subsequent versions of the standard (v2.0 and v3.0)(Stadler & Kolbe, 2007).



UML Structure

Figure 12 - A general example of hierarchical structures of "Class" types using the UML diagrams

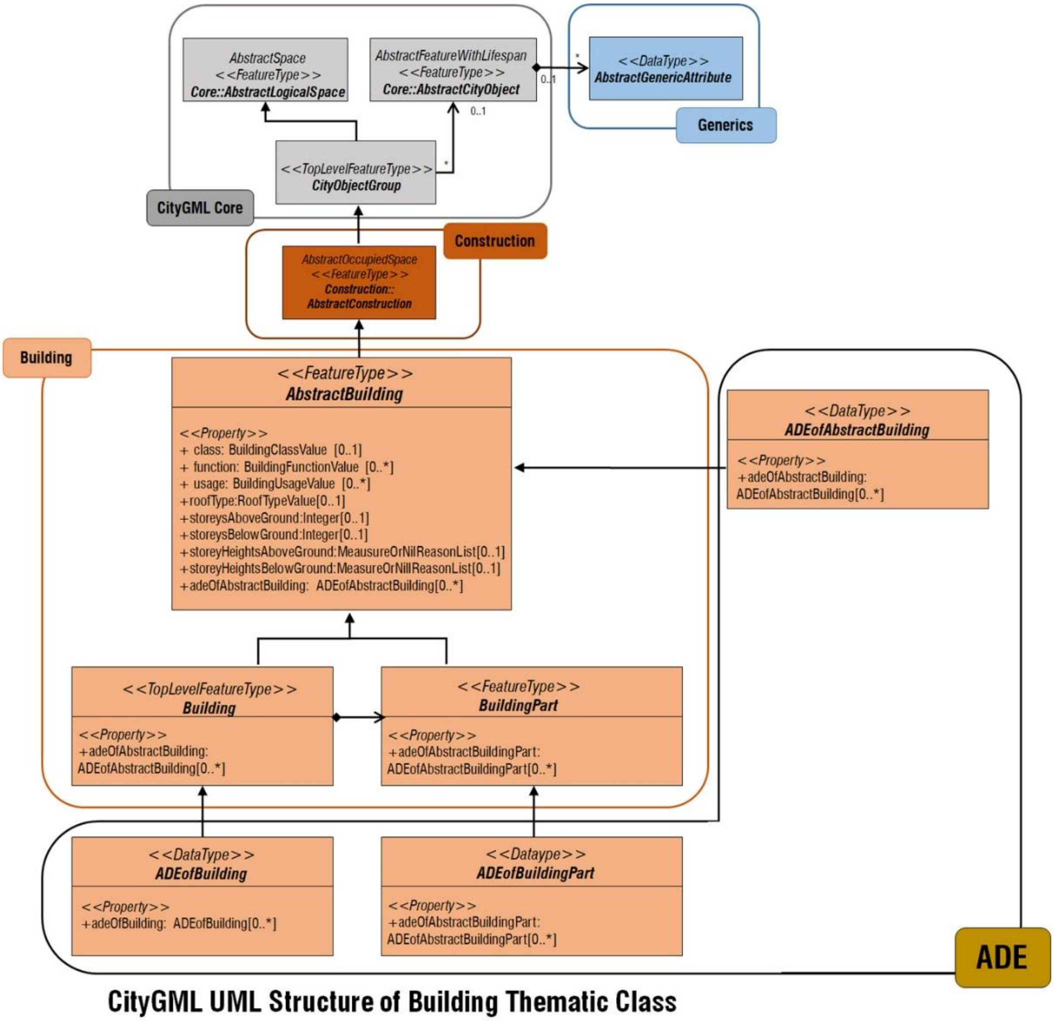


Figure 13 – The CityGML UML Stracture of Building Class

Conversely, the thematic structure comprises horizontal modules (CityGML Core, generics, and appearance) that are universally applied to all specific thematic modules. In addition, there are vertical modules serving as thematic extension modules within defined application-disciplinary domains constituting the urban environment (see Figure 14). The main modules including *Appearance*, *Bridge*, *Building*, *CityFurniture*, *CityObjectGroup*, *Generics*, *LandUse*, *Relief*, *Transportation*, *Tunnel*, *Vegetation*, *WaterBody*, and *TexturedSurface*.

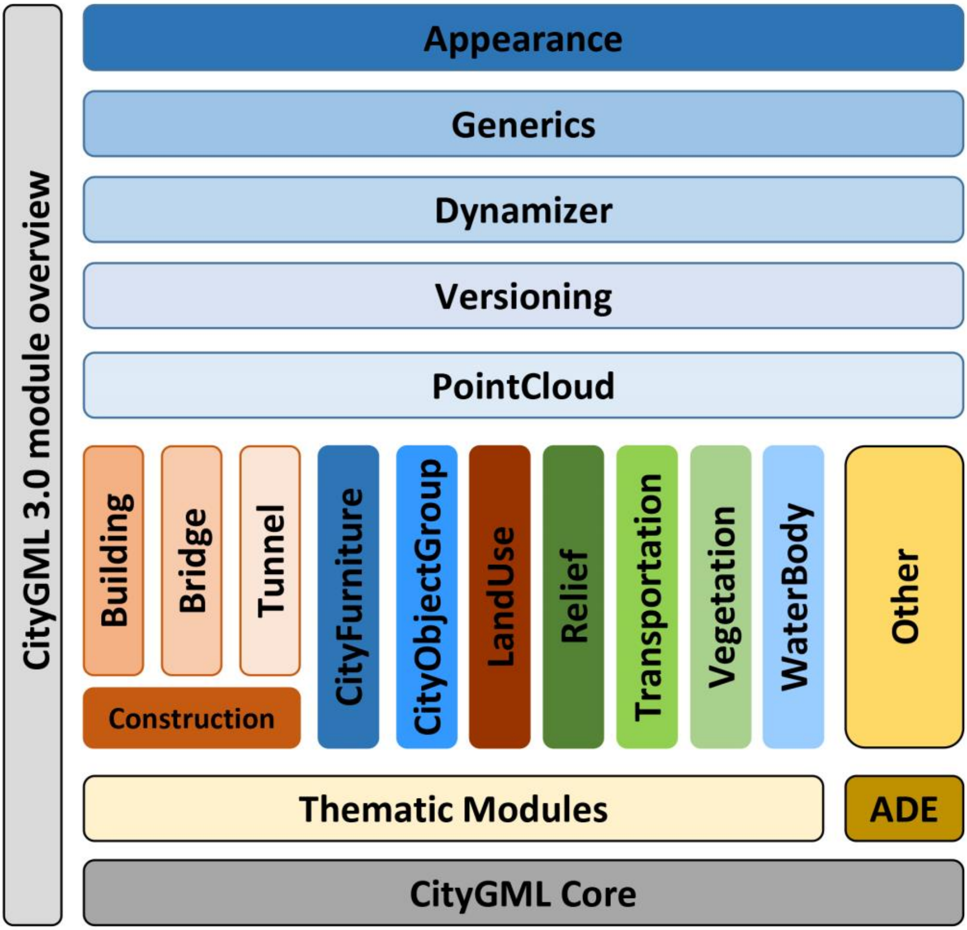


Figure 14 - Overview of vertical and horizontal modules within a CityGML-based model v.3.0

The base class of all thematic classes is the "*AbstractClass*" CityObject.

Consequently, all the attributes and characteristics of subclasses - related to specific thematic areas and properly defined according to the thematic modules – are hierarchically associated under the CityObject. Additionally, these characteristics can be accompanied by optional metadata. For each characteristic, attributes are defined, including class, function, and use. On the one hand, this structured approach facilitates the implementation of the CityGML standard in a modular manner; on the other hand, it allows for partial implementations and easy expansion through the inclusion of additional thematic models.

- Levels of Detail (LoD), CityGML supports multiple Levels of Detail (LOD0 to LOD3 with increasing accuracy and structural complexity), allowing users to represent the same urban object at various levels of complexity. This is useful for applications requiring different levels of detail for different purposes, such as urban simulation, visualisation, and analysis (Figure 15).

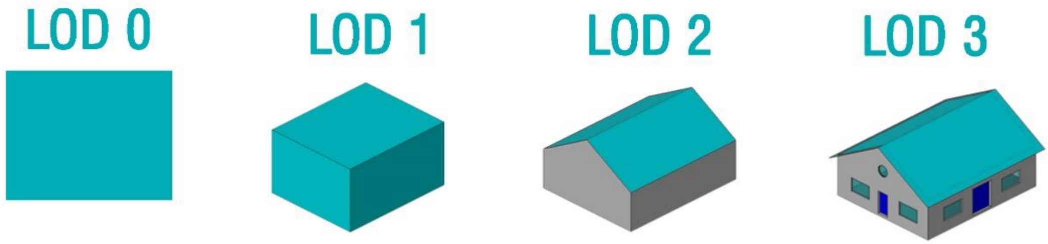


Figure 15 - Representation of the building in the Levels of Detail 0-3

- Extension properties, CityGML provides an extension mechanism allowing users to add custom attributes and elements to the standard schema to meet specific domain or application requirements. The standard CityGML data model can be extended through the *GenericCityObject* and *_genericAttribute* classes, defined in the Generics horizontal module. Both ways allow the modelling and exchange of 3D objects that do not fit into any other theme class or that require unstructured attributes in the CityGML schema. Thus, using the Generics module, each *CityObject* can be assigned an arbitrary number of generic attributes to implement additional properties specific to the processed city model. These classes define the extensibility characteristic of the standard CityGML data model. Simultaneously, a *CityObject* may be linked to objects in other datasets or external databases by an arbitrary number of *ExternalReferences*. These references may point to representations of an object in land registries, enterprise resource management systems or other application-specific data.

A second way of extending the CityGML model consists of the development of specific *Application Domain Extensions* (*ADEs*). The creation of ADEs allows the introduction of new properties and classes to the existing CityGML schema. In the latter case, unlike the first method, it is necessary to process an XML schema definition file.

4. CITYGML APPLIED TO ARCHITECTURAL CULTURAL HERITAGE: A SYSTEMATIC REVIEW

The chapter presents the results of a systematic analysis of the literature about the spatial ontology of the CityGML standard applied in the recovery of the architectural and built Cultural Heritage (CH) considering the constructions (a-CH) or the built environment (b-CH) featured by cultural or historical significance. The review work aims to analyse how parametric models are applied in the disciplinary fields of reference and, if integrated with decision support systems, how and what methods of implementation are used. To achieve these objectives, the systematic review analysis was conducted by analysing the scientific research in the literature.

4.1. Method

The protocol adopted for the state-of-the-art review of the CityGML standard applied to architectural and built Cultural Heritage is "Prisma" approach (Rethlefsen et al., 2021). The search protocol follows the schema in Figure 16, where the phases of analysis and the inclusion/exclusion criteria are shown, while in the following section, details are outlined (Page et al., 2021).

4.1.1. Search of scientific contributions

The first phase concerns the collection of scientific contributions relating to the research topic in the Scopus scientific database. Relevant keywords for the review goals include:

i) "*CityGML and 3DCity model*" for the identification of papers using the standard.

ii) "*Cultural Heritage*" is used to include all the significant cases in the field of application, avoiding the loss of some specific ones, even if "Heritage" is also included to consider exceptionalities in writing.

Moreover, "*Historic*" and "*historical*" are added to encompass applications related to architectural built environments featured by historical relevance (e.g., historic buildings or open spaces in the urban ancient core, systemic historic buildings which are not listed).

These keywords are thus combined with the Boolean operators "And" and "Or" of the scientific database, to search in "Title, Abstract and Keywords" the starting sample. Specifically, the search string used is:

"*CityGML OR 3D City Model** AND *Cultural Heritage* OR *Heritage* OR *Historic* OR *Historical*"

The search result returned a total of 177 articles. These were systematised and archived in a Database (DB) in order to store the preliminary research data and support subsequent statistical and qualitative analysis of the data, through the implementation of filters and mathematical-statistical functions.

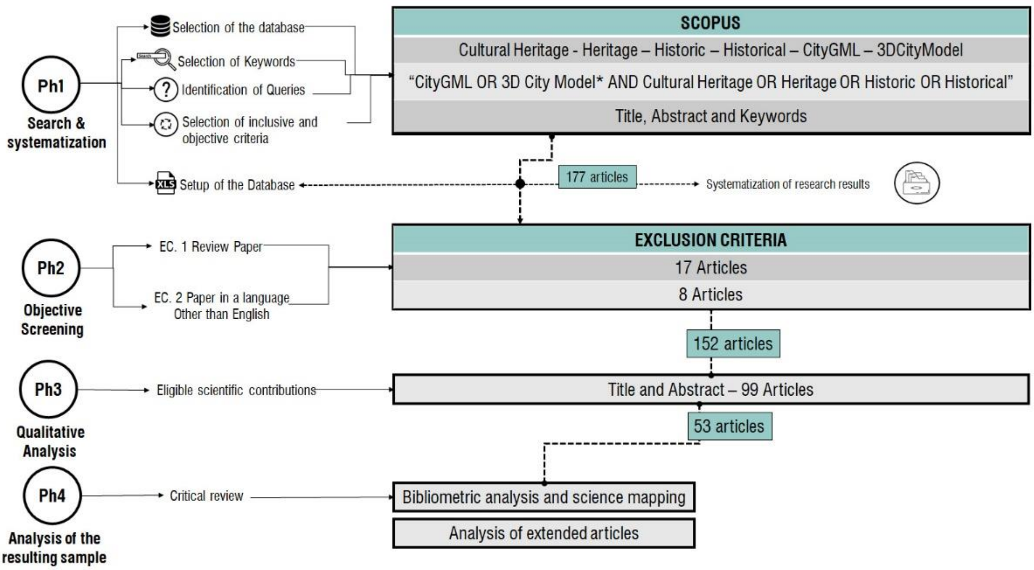


Figure 16 - Schema of the search protocol applied in the systematic review search

4.1.2. Objective screening

The resulting sample was admitted to the objective screening phase, through the identification of specific exclusion criteria. The objectivity of this phase derives from the lower qualitative-critical contribution identified.

Specifically for the scope, the applied filters into the DB have pursued the following exclusion criteria (CE) (Figure 16):

- CE.1 Review type paper
- CE.2 Paper in a language other than English.

This phase has kept out 25 articles, while 152 articles were included in the next phase.

4.1.3. Qualitative analysis

In this phase, the eligibility of scientific contributions is assessed by employing further exclusion and inclusion criteria, selected according to the research questions (QRs). Specifically, the relevance of papers to the disciplinary field has been assessed, excluding 99 scientific contributions which use the CityGML for the only geometric representation. Moreover, the inclusion criterion was applied to the DB concerning both the applicative and disciplinary scope, identifying the final sample -53 scientific articles.

4.1.4. Analysis of results

The last phase of the research protocol involved the in-depth examination of the scientific papers derived from the previous screening and eligibility assessment phases. This was achieved using two main steps, where specific details are described in the following paragraphs.

Firstly, in paragraph 4.2, the 53 articles were analysed in order to examine the bibliometric data of the resulting sample. In detail, the resulting sample has been studied according to the bibliometric analysis (section 4.2.1), aiming at highlighting the performances of the scientific literature about the theme. Specifically, the number and the type of publication, citations and geographic distribution of publication represent the most significant indicators for scientific performances, due to the opportunity to assess the impact of literature production in the scientific academy (Solorzano &

Plevris, 2022). Following, the sample has been analysed according to the science mapping (section 4.2.2). Here, the main goal is to find main clusters of thematic applications, focusing on the relationships among keywords and their co-occurrences (Solorzano & Plevris, 2022). For this aim, VOSviewer (version 1.6.19) was used.

In section 4.3, the papers were studied in depth in order to discuss the research queries as defined in the starting phase of the review work (Figure 16). In detail, the research elements were analysed and classified based on the main application areas covered by the research query, and following the main clusters derived from the bibliometric analysis. However, the analysis of the contributions was structured to correlate the individual application cases identified in the research query with the information transversally related to the subsequent thematic clusters. This was done to define a treatment centred on the typologies of the built environment and declined to the emerging fields, key concepts and operational, decision-making and ontological tools, following the research objectives.

4.2. Quantitative analysis of research results

4.2.1. Bibliometric analysis

In line with the bibliometric analysis, the first results pertain to the bibliometric examination of the sample. An in-depth analysis reveals that the number of publications related to the application of CityGML in the context of Cultural Heritage exhibits a variable trend between 2009 and 2023, with a notable peak in 2018 (Figure 17). Despite this irregular trend, the application of CityGML ontology to the architectural Cultural Heritage represents an increasing issue when the absolute number of papers per year is examined, as well as the cumulative frequency (Figure 17). 36 papers are recorded in the Scopus database as “Conference paper”, representing 69% of the whole sample. The remaining 17 papers are journal articles. Coherently with the paper types, the sample has been processed to show the most relevant journal about the theme (Figure 18). Specifically, the ISPRS collections have gathered more than a third of the papers (ISPRS Archives 28.3%, ISPRS annals 5.7%).

All the other scientific works are distributed in other journals, according to the thematic applications (i.e., Energy and Buildings, Journal of Cultural Heritage, Journal on Computing and Cultural Heritage) or, in general, to the applied sciences (e.g., Applied Science, Applied Geomatics).

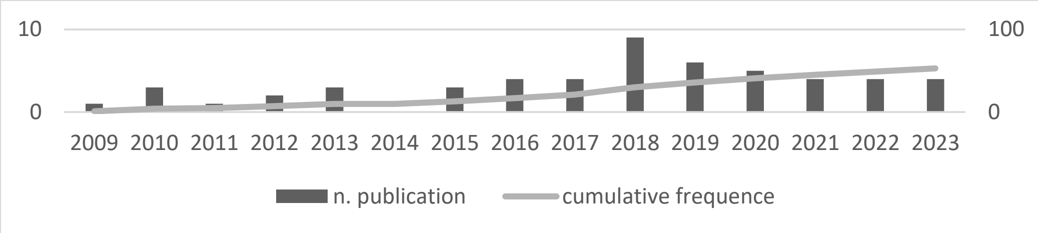


Figure 17: Distribution of paper in the period 2009-2023

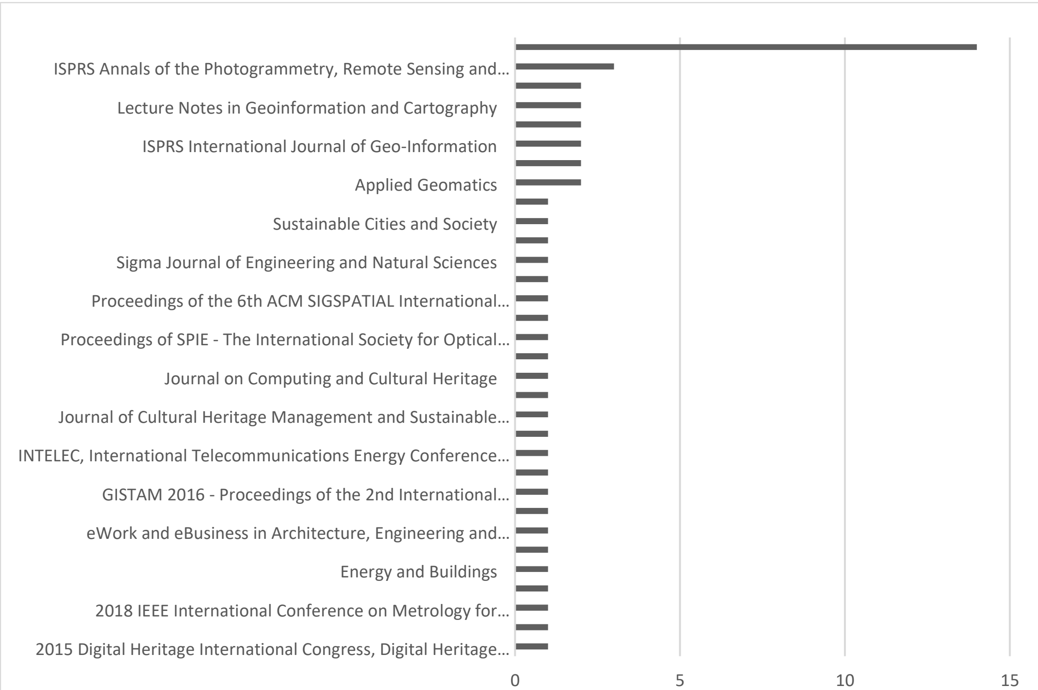


Figure 18: Publication details

Focusing on the results of the recurrences of authors in all the analysed papers, Figure 19 highlights Noardo, Spanò, Colucci, Lingua, Matrone and Costamagna, Egusguiza, Izakara and Prieto two of the most productive groups of authors (Politecnico of Torino and Tecnalia, respectively), as well as the most experts in the theme.

This observation is consistent with the analysis of the number of citations and scientific production related to these organisations. As depicted in Figure 20, the main scientific literature is related to the Politecnico of Torino, producing 20 articles throughout the entire period. The National Technical University of Athens, Delft University of Technology and Tecnalia Research & Innovation constitute the second group of most productive organisations. In terms of citation performance, Politecnico of Torino and the Dublin Institute of Technology have achieved the highest values, with 311 and 180 citations, respectively.

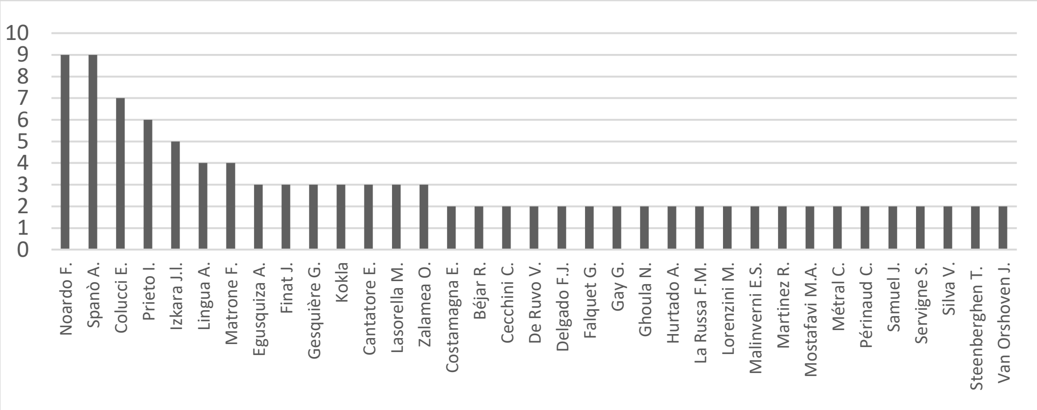


Figure 19: Author counting in the analysed papers, when counted more than 2 times

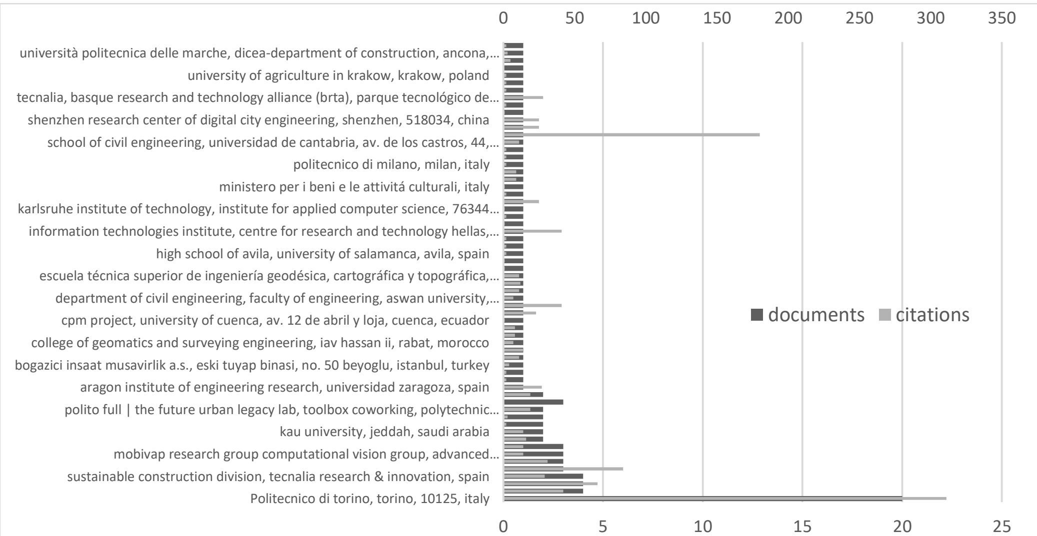


Figure 20: Number of citations and paper production for the analysed papers

4.2.2. Science mapping

All the resulting papers were thus analysed through the VosViewer tool to derive preliminary findings related to the themes of this review.

Specifically, Figure 21 presents the results of keywords co-occurrence for the sample, illustrating their relationships based on identified links. This analysis has revealed four main thematic clusters, determined by a threshold of 3 for each keyword co-occurrence. In detail, clusters can be explained according to the applications to the Cultural Heritage (CH), following four general frameworks:

The integration of CH representation and data management matching thematic ontologies and the analysed standard (Red cluster).

The interoperability of CityGML with other standards (INSPIRE, IFC, …) for CH Architectural Design (Green Cluster).

The discussion of CH represented in the CityGML standard for their 3D visualisation, aiming at their preservation (Blue cluster).

The assessment of CH in urban or sub-urban decision necessities related to the sustainable development of the built environment and urban planning activities (Yellow cluster), also involving web services.

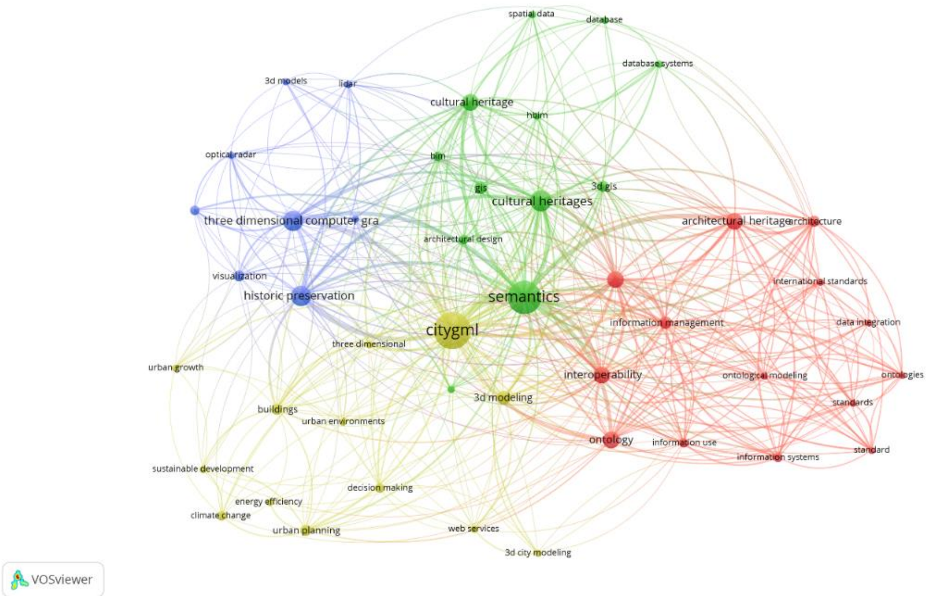


Figure 21: VOSviewer results of co-occurrence of keywords

4.3. Discussion of results

This paragraph discusses the research results of the selected scientific contributions according to a critical-qualitative approach and coherently with the queries of the systematic work.

Following the analysis process (§4.1), all the papers in the sample were analysed according to three recurrent categories of the built Cultural Heritage for the application of the CityGML standard:

[S] Single architectural heritage in the broadest sense, i.e., buildings with particular historical, cultural and architectural values;

[HD] Historic districts, as aggregates of historic assets properly identified at both urban and architectural levels.

[Ot] All the other classes of built heritage, resulting from the sample analysis.

4.3.1. Single Architectural Heritage

Starting from the technical knowledge phase and the analysis of documentary surveys, Yaagoubi et al 2019 (Yaagoubi et al., 2019) developed a three-dimensional CityGML-based database, called SEH-SDB, which aims at disseminating the cultural significance of Cultural Heritage towards public administrators and citizens. In detail, the historical-technical data and information, deriving from the phases of acquisition, collection, collation and analysis, were conceptualised in a defined ontological structure. The proposed ontology extends the thematic-semantic level of the Building thematic class of the CityGML standard through the implementation of three further classes: i) *Material Class*, concerning the data on the construction techniques and the material characteristics of the single component: ii) *Historical Class*, which conceptualises the information deriving from historical analysis; and iii) *Social Class*, which systematises data at a socio-cultural level. Each of these classes has a triad hierarchy of sub-classes:

- The "*Material Characteristics*" qualifies the building components according to the sub-classes of materials (wood, stone, plaster) providing technical information about material for single building elements through specific attributes.

- "*Historical*" implements archival-documentary information through temporal relations linked to the "Room" class of the "*abstractBuilding*". This allows to associate the historical name, the historical events, the function of each room and the overall architectural building over time.
- Finally, the "*Social*" class links the following subclasses to the fabric: i) owner, which identifies the name of the owner and the date of purchase through attributes; ii) inhabitants, reporting the name of the single inhabitants and the type of residence; and iii) social events, identifying possible events that may take place in the building.

Further ontological structures for the qualification of historical-cultural assets according to specific ADE (Application Domain Extensions) of the CityGML standard are elaborated in (E Costamagna & Spanò, 2012; Erik Costamagna & Spanò, 2013; Li et al., 2017; Noardo, 2018, 2017, 2016). Costamagna and Spanò 2012, 2013 (E Costamagna & Spanò, 2012; Erik Costamagna & Spanò, 2013) developed an ADE to conceptualise the elements characterising a cultural fabric according to the CityGML standard aiming at the management of a restoration project. Specifically, in (E Costamagna & Spanò, 2012), the authors focused their attention on the parametric and geometric representation of decorative components of the facade of a specific cultural architecture, according to the LOD3. In fact, the research work proposed an extension of the Building thematic module through the aggregation of the class of decorative elements (*DecorativeSuperstructure*) on vertical and horizontal surfaces (subclasses *HorizontalSuperstructure* and *VerticalSuperstructure*) to the classes of the standard BoundarySurface and Openings. Following, the same authors in (Erik Costamagna & Spanò, 2013) improved the same extension aiming at systematising and monitoring current and previous degradation phenomena of an architecture for the identification of conservation strategies. Here, the CityGML standard was extended thereby creating: i) a superclass, called *CulturalHeritageFeature*, which contains the characteristics of the a-CH featured by the same geographical information; and ii) a *CHSite* class to introduce and associate specific conservative characteristics of architectures, including the deterioration ones (abstract class *AbstractDeterioration*). The latter is functional to describe and parameterise different decay patterns on walls and window frames (*WallSurfaceDeterioration* and *OpeningFrameDeterioration* classes). Thus, the *Building* thematic module is extended through two levels of study: the first one implements the *Building* class through new attributes, and the second includes the derived data concerning the state of conservation of building facades.

Following the same goals and considering the preliminary works of Costamagna and Spanò, the research works of Noardo (Noardo, 2018, 2017, 2016) aimed at the definition, creation and application of a three-dimensional-spatial ontological structure CityGML-based, properly set up for the characterisation of the architectural heritage in compliance with the ICOMOS-Ename Charter (Silberman, 2009). In these works, the main goal is achieved by following step-by-step works, trying to solve firstly the critical issues related to the understanding and interpretation of the architectural heritage, and then the creation of technical-professional guidelines exploiting the potential of digital systems and models. This is in line with the required IT skills in managing technical knowledge within the digital environment. In particular, the works point out a thematic extension (ADE) of the standard structure for a-CH, featured by a consistent information-semantic level granularity, called "CHADE".

The ADE extends the standard within the Boundary detail class including new attributes to existing classes and new subclasses, following main types of details:

- General information about i) administrative restrictions – related to the "*AbstractCityObject*" Core class -, such as the existence and the code of constrain document (*hasCHDeclaration* and *CHDeclarationDocument* feature), ii) the physical or legal entity about the property (ownership), and iii) the identification of the supervising authority (*preservationAuthorityName*).
- General information about the architecture, adding them into the thematic class "*AbstractBuilding*"; it is the case of i) common name linked to the building ("*denomination*"), and ii) original function and codified style ("*hasAATFunction*" and

"*AATStylePeriod*"), following to the Getty Research Institute's Art & Architecture Thesaurus dictionary[2].

Moreover, the associated data were specified using detailed attributes (reference link, function, resource, denomination and period) reported in the two extension subclasses: "*BLDG AATFunction*" and "*BLDG Denomination*". The granularity and flexibility of the CHADE ontological structure are further densified through the extension of the "*AbstractBoundarySurface*" class, which enriches the informative level of the architectural building object through the "*part of*" relationship. It allows each surface of the element to be hierarchical, semantic, multi-scale and topologically improved with properties about – among the others – owner, actual use, deterioration, author, period of construction, year of dismission (*hasPatron*, *BSFunction*, *Deterioration*, *hasAuthor*, *timeOfBeginningExistence* and *timeOfEndExistence*). A second level of detail in the field of ontology applications for a single architectural heritage is identified by the ACRoofADE. It is a detailed ADE for the specific sub-systems of ceilings pointed out for their conservation and protection in valuable architectural artefacts in Chinese historical architecture (Li et al., 2017). This work aimed at highlighting the technical-constructive, material, architectural and topological characteristics which allow to distinguish them according to their cultural and historical relevance. To achieve this, the proposed ADE extends, geometrically and semantically, the "*RoofSurface*" subclass of the "*BoundarySurface*" class of the "*Building*" thematic module of the CityGML standard, introducing two main attributes related to the functional category, referring to the structural and decorative dimensions. In addition to the common need to standardise and systematise technical knowledge about these architectures, this work aims to provide experts in the conservation sector with a useful tool in the planning phase of intervention strategies, combining the parameterised model with a digital guideline for the recovery of the artefact.

The scientific works analysed up to now demonstrate the extension potential of the CityGML standard and the high importance of the conceptualisation of data and information structured according to the existing and/or new ontologies.

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[2] Getty Vocabularies, http://vocab.getty.edu/

As strengths, they highlight the opportunities to support the management of multidisciplinary information (historical-identity of places, technical-architectural) in the conservation process. Starting from such elements the scientific group of Zalamea (Zalamea et al., 2018; Zalamea & García, 2020; Zalamea Patino et al., 2018) structured and validated the BCH ontology (Built Cultural Heritage Ontology).

This ontology was properly developed to improve the interoperability of multidisciplinary information and data of the CH for the conservation and maintenance of fabrics, coherently with the principles of the preventive maintenance approach[3]. In detail, the BCH ontology is the result and the integration of three existing ontologies (Geneva CityGML, MONDIS, CIDOC-CRM), based on the CityGML-ADE model of Heras et. al. (Heras et al., 2014). The contribution provided an ontological structuring of the information derived from each phase of the conservation process, for which particular attention is paid to the semantic conceptualisation of the process.

Coherently with the cluster contents about the use of the platform, research activities of Wang et al. (Wang et al., 2018) evaluated and tested the possibility of integrating different digital systems, including virtual models and CityGML-based three-dimensional maps, for the creation of a collaborative platform multi-user for tourist use.

Starting from the approach used by Finat et al in (Finat et al., 2010), Wang et al. extended the CityGML standard by creating a Cultural Heritage ADE. This ADE imports the thematic module Building into the *Cultural Heritage* class, and extends it through new subclasses of attributes i) *History*, referred to the historical transformation; ii) *Function*, related to variations in use and function over time; iii) *Narrative stories*, which collect the historical and popular tales about the building, also thanks to the contribution of tourists and citizens.

Therefore, the research work developed a dynamic three-dimensional narrative platform for tourist use and the dissemination of knowledge using the integration of

[3] The preventive maintenance supports a periodic assessment of risks and threats for evaluating the vulnerability of the architecture. In other words, it goes beyond analysing the building only when a clear problem emerges, instead of embracing a proactive approach that involves ongoing monitoring and the management of potential risks and threats.

CityGML-based three-dimensional models and narrative systems. The developed system allows tourists and citizens to access all the information about the architecture and share it through audio, video and image documents, by exploiting the extension property of the CityGML standard.

As far as the extensions and implementations of the CityGML standard with other possible ones, a twofold scale of application was found, the urban and building ones, aiming at enhancing the final level of detail of parametric models of architectural cultural heritage to meet various requirements.

At the urban scale, the extension of the INSPIRE standard[4] was tested by integrating the Building thematic class of the CityGML standard, as well as harmonising the data of a single model according to the two standards, being one the basis of the other.

This objective was addressed within the ResCult research project (Chiabrando et al., 2018), where a European Interoperable Database (ResCult EID) was structured and developed for the analysis of the resilience of cultural buildings. In detail, the authors extended the INSPIRE data model by developing a structure that correlates cultural property with possible risks at the site scale. At the same time, they overcame the critical issues underlying the level of detail of the INSPIRE standard by modelling the Cultural Property entity according to the Building thematic class of the CityGML standard, also considering the extensions already developed in (E Costamagna & Spanò, 2012; Noardo, 2017).

While the standardisation of the CityGML-based information structure satisfies the geometric and semantic representation of heterogeneous and multidisciplinary data about cultural property, the INSPIRE standard facilitates the integration and interoperability of data stored in other national and international information and spatial systems, which are not structured for the investigated objective. As far as the building scale of standard application is concerned, the integration of the IFC and IndoorGML standards

[4] "INSPIRE" stands for "Infrastructure for Spatial Information in the European Community." It's a European Union directive that aims to create a standardized framework for sharing and accessing environmental and geographic data across European countries. The INSPIRE Directive facilitates better environmental policies and decision-making by making geographical information more accessible and interoperable.

at the semantic-geometric level stands out as a second point of discussion for the individual architectural heritage.

A first application category in testing the interoperability of IFC and CityGML-based models and standards for the geometric and semantic representation of b-CH for their conservation is recognized in Yaagoubi et al. 2019; Matrone et al. 2019, Colucci et al. 2020 and Avena et al. 2021 (Avena et al., 2021; Elisabetta Colucci et al., 2020; Matrone et al., 2019; Yaagoubi et al., 2019). Here, the papers processed protocols for the integration of BIM/CityGML-based models aimed at increasing the geometric and semantic levels of models of historic buildings (detailed technical knowledge) characterised by particular historical-architectural values. However, different applicative goals can be discussed. In Yaagoubi et al. 2019, the authors applied the SEH-SDB conceptual-semantic model, as described previously, to a case study using the GIS-BIM approach. However, starting from the photogrammetric survey data, they created a three-dimensional model combining:

- Geometric Level, modelling the geometry following the IFC standard. This means they accurately represented the shapes and dimensions of the objects in the case study. This aspect of the model is crucial for visualising and comprehending physical structures.
- Semantic Level, augmenting the geometric model with the semantic layer structured in the set-up ADE (SEH-SDB). This supplementary information allows to encompass details concerning the function, classification, and other technical and historical characteristics of the modelled objects.

This approach enables a more comprehensive and contextualized understanding of the model. The integration of a geometry with a well-defined semantic structure enhances significantly the comprehensibility and utility of the 3D model, facilitating the management and analysis of geospatial data and information related to the structures. Despite the common point of discussion about the possible interoperability of standards (IFC and CityGML), the second group of activities focused their attention on the development of three-dimensional digital archives enriched with semantics and geometric details compatible with the minimum dataset for the analysis of the damages caused by sudden events such as earthquakes, floods. In (Avena et al., 2021; Elisabetta Colucci et al., 2020; Matrone et al., 2019) the CityGML standard finds application to architectural CH for the conservative qualification of the architecture according to a defined ontological structure that is interoperable with HBIM-based parametric models at the building scale.

Similarly, in Bonora et al. 2023 (Bonora et al., 2023) the authors experimented with the integration of information collected from the technical knowledge phase of the recovery process to the Room classes of the CityGML standard (version 3.0), and CellSpace, defined in IndoorGML[5]. In detail, the study aims at representing the physical and logical aspects of spaces through the correlation and integration of both the ontological structures with the historical-architectural characteristics of Palazzo Pitti, in Florence. The work highlighted the complexity of the representation of the analysed historic fabric above all for the architectural morpho-typological characteristics of the building, the historical stratifications of physical and functional transformations, both at geometric-topological and semantic-thematic levels of the ontological structures.

The scientific articles outlined presented some common points in the solution of Cultural Heritage preservation. Several research groups have solved the conservation objective through the development of methodological approaches for intelligent and structured analysis and monitoring of the state of obsolescence and decay development as pioneered in Tekdal-Emniyeti et al. 2011; Mohd et al. 2017 (Mohd et al., 2017; Tekdal-Emniyeti et al., 2011). In detail, the studies focused on the pipeline for the transformation of laser scanning survey to CityGML-based models, combining operative tools to combine different model inputs (RGB and mapped point clouds, including decay patterns). The main goal of the works was the enhancement of the parametric 3DcityModel with the conservative-semantic level, combining the opportunities of the photogrammetry for decay monitoring (automatic fragmentation) to the digitalized architecture.

[5] IndoorGML stands for "Indoor Geography Markup Language". It is is an open standard developed by the Open Geospatial Consortium (OGC) and is designed to ensure interoperability and data exchange between different software and systems. It provides a common framework for representing indoor spatial data and introducing the “cellular space” concept.

However, both works highlighted the operative difficulty in transforming the process into an automatic one due to the necessity of a specific domain of Cultural Heritage. In parallel, the research group led by Doulamis (Doulamis et al., 2015) developed a workflow for the assessment of the state of conservation of architectural CH within the CityGML standard. Specifically, starting from image-based digital models acquired over defined periods, the variation of information was translated into a semantically coherent feature and archived in a geographic database for subsequent comparisons. This allowed the development of a method of spatio-temporal analysis of the architectures based on a predictive digitalized model. It aimed at detecting the variability of information processing the state of conservation of fabrics, the impact of environmental conditions (humidity and temperature) on materials, and the degradation phenomena generated by previous incorrect interventions.

The other class of application in the CityGML model aimed at the preservation of the architectural Cultural Heritage is related to the operative phases of the process where the operative users in the transformation activities are involved. In (Ignacio San Jose et al., 2013) a new software platform for interactive volumetric visualisation of complex architectural objects based on the CityGML standard was set up, taking advantage of previous scientific experiences in geometric and semantic modelling, and combining them with technical applications for the technical educative purposes. The paper presented how the platform can be used for teaching and training conservation interventions in architectural CH, due to the opportunity to prepare technical and operative users for the recognition and assessment of building pathologies and design proper interventions, including technical details about some case studies.

The enrichment of the CityGML-based model within its structure for the cataloguing and categorisation of architectures at the semantic levels has led scientists to overcome the representation and sharing of technical and historical knowledge, moving towards the setup of final tools based on the CityGML standard for more comprehensive goals. Obviously, the systematized knowledge passes through the described experiences and aims, but all the information was structured to determine other levels of technical details within the model.

It is the case of the damages analysis of architectural CH exposed to the earthquake combining their potential vulnerabilities and the hazard in the sites, coherently with the traditional procedures of risk assessment. It is the research activity discussed in (Chiabrando et al., 2018; E. Colucci et al., 2018). However, in Chiabrando 2018 (Chiabrando et al., 2018) the interoperability of the standard was emphasized in order to stress external tools based on syntax and languages common to all experts in the conservation sector and suitably integrated into basic ontologies (CIDOC-CRM, MONDIS) and spatial standards (INSPIRE, CityGML). Here, the main goal was the setting up of the EID Database, as a final tool to support policymakers in damage analysis. As previously discussed, the conceptual structure of the database used harmonised spatial ontologies (INSPIRE and CityGML) and integrated with i) the information reported in UNESCO documents (in particular for territorial information and the classification of natural events) and ii) the Italian directives/guidelines on the assessment of the seismic risk of CH, for the qualification of the mechanisms of deterioration and damage production. However, these quantitative results were discussed and presented by Colucci et al. 2018 (E. Colucci et al., 2018), as applicative work of the same research activity, highlighting the potentialities of the structured system of decision support included in the EID database.

4.3.2. Historic District

The second category of b-CH recognized in the review process comprises historic districts, including both systemic architectures and the places within such urban areas. Here, buildings are analysed according to their cultural and landscape significance, transcending the individuality of singular structures; the historic built environment is observed and considered in order to highlight the practices about the management of their technical knowledge towards their conservation and preservation. As results have highlighted, major applications of the CityGML standard in this context pertain to the semantic structuring for managing the historic built environment, the management of risk, the monitoring and qualification of fabrics for their preservation, the energy efficiency and the effect of climate change on the heritage. Here, the use of the CityGML standard is optimised due to its inherent features in representing, sharing and managing data in urban 3D models. The broad application of the standard on such CH category is ascribed to the inherent dimension of a 3D city model. On the other hand, the horizontal rules at the basis of the geometric and semantic representation of buildings in a specific urban sub-part allow the management of data and their processing for the conservation and preservation of b-CH, including the landscape dimension at the basis of cultural relevance of such places. These aspects are thoroughly discussed in Costamagna and Spanò 2011 (E Costamagna & Spanò, 2011). Here, the authors highlighted the contact points of discussion between the required multiscale approach in solving the preservation/management of historic districts and the integration of various digital tools centred on CityGML-based models to support all the required activities - survey, modelling, use of the model and data -. This is motivated by the criticalities related to the scarce homogeneity data to be collected, and the difficulty of finding and cataloguing them which are common points of slowness in active and administrative practices using traditional procedures and methods for the setup of recovery plans.

As discussed for single architectures (§4.3.1), the CityGML standard finds applications in the dimension of ontology modelling, standard applicability and interoperability for urban historic districts. These districts consist of a system of buildings and paths located in a defined urban area and joined by common and systemic characteristics. However, this category benefits from the outcomes of standard extensions for single architectures, highlighting the needs related to extended built heritage.

In the context of the preservation of the existing built heritage in historic districts, the authors in (Margherita Lasorella & Cantatore, 2023) experimented with the application of the CityGML standard for the qualification of historic districts, useful for its management in digital recovery plans. In detail, the research study investigated and analysed the individual architectural and urban entities within three levels of depth (descriptors, primary and secondary factors), according to a logical-relational scheme of i) taxonomies defined by the glossaries of stone material degradation, ii) existing ontologies for the geometric-spatial and thematic-semantic representation of architectural artefacts, iii) regulations of the building systems and restoration sector and iv) established approaches in the field of conservation.

Consequently, the theoretical notions converged in logical-mathematical relations that allow the correlation of information and properties in quantitative and qualitative data for the processing of derived factors (primary and secondary). Therefore, on the basis of the organic structuring of technical knowledge, a decision-making system implemented on the CityGMl-based digital three-dimensional model was structured.

More recent studies about the same issue are the works of Kokla et al. and Cecchini C. (Cristina Cecchini, 2019; Kokla et al., 2019) which pointed out workflows and methodological approaches for addressing and overcoming the critical issues related to the setting up of recovery plans for historic districts, exploiting systems and models characterised by:

- scalarity, concerning the geometric data and the information levels enabling the utilisation of data at the building scale within an urban model.
- multi-user management regarding the types of stakeholder classes (citizens, administrations, expert technicians), allowing simultaneous access to several users.
- interoperability, in relation to the type of data at IT and thematic-semantic levels.
- a defined semantic syntax, encompassing geometric-topological and semantic-typological data structured within a hierarchical and relational framework.
- specific standards to be shared at the international scale which support the data open.

Starting from the analysis of the notions reported in UNESCO and ICOMOS legislative documents, definition of vocabularies (Getty Vocabularies), existing ontologies in the Cultural Heritage field (CIDOC-CRM, CRMgeo) and spatial-geometric scale - both at an urban (CityGM) and building (IFC) scale -, directives and guidelines in the superordinate plans (landscape plans), Kokla et al. (Kokla et al., 2019) conceptualised the information related to and required for the representation of architectural and urban entities in Historic Centres.

Due to the variety of semantic and spatial levels, the authors emphasised the necessity of creating a granular ontological structure that describes historical architectural heritage from both a semantic and geometric perspective.

This aspect is also explored in Cecchini C. (Cristina Cecchini, 2019), which outlined the possible methods for implementing a three-dimensional geographic digital archive of a historic district, through the integration of the IFC and CityGML standards in a single digital model. The historical-architectural feature is extended on a semantic level through the application of the ADE-CHADE, structured by Noardo and discussed in the previous section (§4.3.1). The parametric model, developed at different levels of detail, facilitates the use of all types of information related to individual buildings while ensuring control at the district scale. Following these results, Cecchini et al 2020 (C Cecchini et al., 2020) extended their semantic representation of historic buildings towards an energy-oriented one. In detail, the developed ADE, called ADE-ER (Energy Refurbishment Application Domain Extension) combined two existing ones for a single scope (energy and Cultural Heritage) for monitoring and simulating energy performances of historic buildings following the UNI EN 15603:2008 standard. The ADE-ER linked to the Building thematic module of CityGML standard all the issues related to the preservation of historic districts and the energy characteristics, towards their classification according to the Italian Energy Performance Certificate. In detail, the ADE-ER consists of such following attributes: i) *CHDeclarationDocument*, *hasCHDeclaration*, *ownership* and *preservationAuthorityName*, related to the CityObject class; ii) *demonination*, *AATStylePeriod*, *heatedArea*, *heatedVolume*, *annualTermalEnergy*, *annualElectricalEnergy*, *hasEpc*, *epcClass*, referring to the *AbstractBuilding* class; iii) *BSArea*, *BSThickness*, *hasAuthor*, *timeOfBeginningExistence*, *timeOfEndingExistence*, *ifcElementType*, *deterioration*, *isThermalBoundary, transmittanceU*, *emissivityE*, *absorptionCocientA*, *aFin*, *aHor*, *aOv*, *boundaryCondition*, *exposition*, related to the *BoundarySourface* class; and iv) *solarFactorG*, related to class *Opening*.

More recent works about CityGML standard applied to historic districts focuses on the elaboration of methodological approaches based on the translation (IFC to

CityGML, CityGML to IFC) of standards at different scales and/or on the integration of different ontological models (IndoorGML, CityJSON), also through the aid of the semantic web.

The first study about the interoperability of BIM models and CityGML standards for historic districts is the work of (Dore & Murphy, 2012). In detail, the work presented the operational workflow to reproduce the details of historic buildings in the 3D model of the city using data from image/range-based acquisitions, with IFC as the predominant standard to be compared with CityGML. The main aim of their research was to create a three-dimensional model of cultural sites that could meet several needs:

- *Semantic classification*. The model had to be able to assign semantic classifications to all architectural and urban elements present on the site.
- *Linkage with External Data*. It was necessary to establish a link between the model and external databases containing specific information on site attributes. This would allow the model to be enriched with additional data of historical relevance.
- *Web accessibility*. The three-dimensional model needed to be made available for web use, both geometrically and semantically. In other words, it had to be accessible online to allow a wider audience to explore the site.

To achieve these objectives, the authors followed a methodological approach that included: i) the mapping of IFC Semantic Classes, by mapping the semantic classes of the IFC (Industry Foundation Classes) format, commonly used for modelling buildings and constructions, to the specific thematic classes of the CityGML standard.

This step allowed the translation of data from one format to another, while preserving the semantic meaning and geometric modelling; ii) the implementation of additional information, the CityGML-based model was implemented in the semantic part with additional historical, archival and documentary information, stored in web portals and external information systems. This in-depth data was aimed at improving the technical understanding of the cultural site. The methodological approach was tested by the authors on a part of the selected historic district, demonstrating its applicability and usefulness in the systematisation of technical knowledge, considering several objects/parts of the built environment (roads, facades, decorative elements).

The application on a historical site provides the opportunities for a semi-automatic processing of large-scale-built environments taking advantage of high levels of details in 3D modelling determined by the scan-to-BIM techniques and all the recurrent features and criticalities about the historical sites that could be managed into a single model. On the other hand, the authors remarked how the potentialities of the workflow find some operative criticalities when the transformation of IFC to CityGML standards runs on historical buildings, due to the absence (in 2012) of specific ADE or ontology extension about Cultural Heritage.

Subsequently, the experiences of (La Russa, 2023; E.S. Malinverni et al., 2022; Vaienti et al., 2022) tested the highest degree of interoperability of the parametric model applying it for the maintenance of b-CH. In detail, the authors checked and validated operative pipelines to support the goal from the process of conversion and/or creation of a structured information system for the determination of features and their relationships within the ontological structures towards the setting up of a final CityGML-based model. With this aim, in (E.S. Malinverni et al., 2022) the authors defined an ontological structure that integrates CityGML-based and IndoorGML-based models, to obtain and share the ontological model in a semantic web environment. In detail, the IndoorGML standard was used to connect buildings to the urban context (streets, squares, open spaces), and the semantic web as a tool for integrating these two standards. Consequently, the methodological approach was developed for the creation of a single standardised urban model useful to sector experts in various application fields, such as i) the restoration of historic facades, for the definition of the occupation of public land; and ii) the viability, for traffic analysis and emergency management. A similar multi-scalar data integration approach was tested by La Russa (La Russa, 2023) with the help of the CityGML standard coding.

The authors elaborated a semantic workflow using CityJSON-based models, for the systematisation of technical knowledge data of the historical centre of Catania.

Moreover, in (Vaienti et al., 2022) a workflow was developed according to the CityGML Json coding scheme, the CityJson, which allows the automatic and dynamic updating of the semantic component for the creation of diachronic urban models.

The key aspect of this coding scheme is the inclusion of temporal coding within the parametric model. In particular, the authors proposed the structure, called historicalCityJSON, for the setup of the urban models, which included two-dimensional data (map and historical cartographies) and attributes, also related to the historical/temporal dimension of real assets. Specifically for the latter, three sub-categories of semantic attributes were determined, establishing also the relationship types: i) *Synchronic link* when the temporal variation refers to the geometry; ii) *Diachronic link*, which connects conceptual model to the geometric one and its transformations over the time (e.g., modification of some parts of the building or total reconstruction of the building) and iii) *Methodological link*, when temporal-semantic attributes refer to the variation of building morphology. Therefore, for each object, the time attribute was defined using three sub-attributes referred to the hypothetical/possible date of construction, historical data documented by archival sources and the demolition date of the building.

During the same period, and in consequence of resolving ontological details, a specific research was conducted to test the CityGML standard in managing the historic district for their conservation (E Colucci et al., 2021; Hidalgo-Sánchez et al., 2022; M Lasorella & Cantatore, 2023; I. Prieto et al., 2018; Suwardhi et al., 2022).

In (M Lasorella & Cantatore, 2023), CityGML-based model and point clouds are inserted into a pipeline to define an automatic process for the cataloguing of buildings in historic districts according to their state of conservation. Specifically, the tested pipeline focused on the use of points clouds of facades and roofs, the automatic recognition and segmentation of each decay pattern – as defined in the UNI 8290 -, their geometric (extension) and qualitative assessment (Seriousness, Intensity), following the rules of the UNI CEN TS 17385:2019. In this case, the work did not enrich the standard but referred to the extension tested in (Margherita Lasorella & Cantatore, 2023) and enhanced it with the potentialities of the photogrammetric techniques.

In Hidalgo-Sánchez et al. (Hidalgo-Sánchez et al., 2022), the authors elaborated a digital recovery plan according to the CityGML standard for the ancient core of the City of Seville.

They developed a three-dimensional geographic information system useful for the collection and archiving of multidisciplinary information deriving from the phases of analysis and technical knowledge. This system was based on an informative structure organized into four macro-categories (identification, documentation, diagnosis, intervention strategies) and twelve disciplinary sectors (general information, protection, sources and bibliography, archaeology, conservation, maintenance, space management, training, networks, projects, sponsorship and creative industries). In particular, following the pre-diagnosis phase, a semi-automatic procedure was defined for the geometric elaboration of architectural entities relating to the qualified and systematized features and information in the informative and geographical structure. The methodological approach developed by the authors follows the traditional phases of the conservation process but exploits digital systems.

In Prieto et al., 2018 and Suwardhi et al., 2022 (I. Prieto et al., 2018; Suwardhi et al., 2022) the authors developed a web-based platform accessible by technicians and citizens during the setup of a recovery plan. The platform was configured to be: collaborative, allowing its use to different types of users; and interoperable, in coherence with the multidisciplinary and multiscalar information which requires improvements. However, starting from the CityGML-based urban model, technical information about single buildings was imported using the HBIM approach.

In (E Colucci et al., 2021), the authors started from the intrinsic definition of the Historic Centre, the consolidated ontologies in the field of Cultural Heritage (CIDOC-CRM), the standard of urban representation (CityGML), the existing vocabularies (Getty AAT) for the elaboration of a methodological approach for the conceptualisation and the representation of Historic Centres through a top-down approach. In detail, the semantic enrichment of historical urban models consists of the implementation of semantic data referring to historical identity values (external formal values of buildings and urban morphological configuration) and the normative-legislative sphere (urban planning, technical implementation standards, regulation construction) of the historic district, according to the semantic and ontological rules.

The CityGML standard finds application also in the critical reading of the landscape significance of urban historic districts. This is the case of Rubinowicz e Czyńska (Rubinowicz & Czyńska, 2015), where the research used geographic parameter models for the evaluation of the panoramic points in cities, identifying the shaded parts along the landscape sight line by the highly densified areas. Despite the final identification of conservation strategies, the study was based on city simulation methods for the creation of urban plans and urban growth.

As in single architectural Heritage cases (§4.3.1), some studies use CityGML parametric models for risk assessment and multi-risk scenarios applied to historic districts. Specifically, in Gandini et al. (Gandini et al., 2020) and in Büyüksalıh et al. (Büyüksalıh et al., 2019), the authors developed specific holistic and multi-scale approaches for the analysis and management of physical vulnerability of the extended heritage exposed to hydrogeological risk. The approaches also provided support to the decision-making process in choosing mitigative strategies and adaptive solutions for the conservation of such existing built environment from a resilient point of view. In detail, the approach identified by the authors in (Gandini et al., 2020) was focused on the operative phases of risk assessment (i.e., qualification of the historic district, vulnerability assessment, derivation of risk index, determination of intervention priorities), using geometric factors, spatial properties and semantic data properly consistent with the standard. Among the elements of particular interest, it is useful to highlight how the study supports the use of the "recurring type" to determine the survey model and the characters of comparison to determine priorities for intervention, coherently with the traditional methods in setting up recovery plans for historic districts.

However, in the work, the required properties were also used to structure specific relations among general data and constructive features and these ones were linked to risk determinants and used for the overall risk assessment. For instance, the year of construction was used to ascertain construction techniques, the presence of basements, and the type of roof to evaluate a building's vulnerability and define intervention priorities.

Similarly, the existence of constraints, the number of housing units, and the socio-economic status of resident families were considered for assessing the type of intervention needed.

Such operative activities in elaborating risk maps resulted from the application of detailed DSS structures, even if following different flows. In Büyüksalıh et al. 2019 (Büyüksalıh et al., 2019), the risk was related to single buildings starting from the land vulnerability to the hydrogeological phenomena, extending natural and anthropic details in a single geometric-parametric model. On the other hand, in Gandini 2020 (Gandini et al., 2020), the DSS for the risk assessment and mapping was based on the MIVES (Integrated Value Model for Sustainable Assessment), a multi-criteria approach for providing object parameters, such as vulnerability, risk and indices of intervention priorities. Specifically, the approach combines the physical details of buildings and the geological quality and rainfall levels of the sites.

The CityGML standard applied to urban historic districts finds relevance also to energy-resilient assessment (Cantatore et al., 2021; C Cecchini et al., 2020; Egusquiza et al., 2018; Mutani et al., 2019). As a common point, the authors developed methodological approaches for qualifying historic districts and assessing their energy consumption. They used urban parametric models for archiving and managing information aligning them with a consolidated, interoperable, and multiscale structure.

Moreover, all the information was structured in order to be shared with policymakers to support urban sustainable development.

In this scenario, Cecchini et al. (Cecchini et al., 2020) developed a methodological approach which integrates parametric (IFC and CityGML) and energy models, for the generation of a three-dimensional one and associated database for the evaluation of the energy behaviour of single buildings within historic districts.

As described for the historic district, the structure of the setup energetic ADE collected and related physical parameters, and these were used to determine the performance of single buildings within the historic districts.

These were thus systematized and combined with historical details of buildings and shared in a web-based platform in order to equip all the various users, including public administrations, with a virtual tool for the management of complex historical assets characterised by safeguarding regulations.

In Egusquiza et al. (Egusquiza et al., 2018), the authors extended the CityGML standard through the energetic, Cultural Heritage, indicators and dynamic domain extensions, as the prevalent application of the EFFESUS method (structured by the same authors in (Egusquiza et al., 2022)) for the energy recovery, fast assessment and selection of retrofit measures for buildings in historic districts. Coherently with traditional approaches for their recovery, the process of historic district qualification in the paper used the recurrent building types to describe prevalent features, performance and deficiencies, while still following the hierarchy of CityGML attributes. In particular, the considered parameters were referred to the sub-component scale, combining and assessing their geometric features and performances (e.g., the inner dimension to calculate the heated volume of buildings or the number of facades to determine the dispersant areas and their main cardinal exposures), and historical-semantic properties at the building level (i.e., year of construction to derive construction techniques and materials for assessment of thermal characteristics, and level of safeguarding to define the historical significance and the suitability the intervention strategies). All the detailed features, assessed at sub-component scale, were thus related in order to determine the energy effect of specific strategies also at the building scale, as has resulted from the calculation of thematic normative (ISO 13790:2008). With the same approach, Cantatore et al. (Cantatore et al., 2021) structured a methodological approach for the creation of digital energy-resilient plans of CityGML-based Historic Centres, albeit with the aim of developing a 3DCity Model that can be used via the web by technical users and administrative operators, as an equivalent recovery plan to be easily shared and updated in a digital way.

Starting from previous results, the research group of Egusquiza showed the potentialities of the CityGML-based model for the communication of multi-layer and multi-scale sharing of technical knowledge within web-based tools. However, they extended their applications providing a technical tool available for the policymakers and technicians to support their operative activities. Specifically, Prieto et al. 2017 and Egusquiza et al. 2016 (Egusquiza et al., 2016; Iñaki Prieto et al., 2017) used the CityGML model with the energy results and shared it in a web tool, aiming at determining the priority of intervention at the historic district scale with a focus on the blocks. Specifically, the model was implemented with a DSS system which helps technicians in the calculation of the vulnerability maps at buildings and block scales considering 5 main parameters: the main use, the number of facades, the year of construction, the protection degrees, the energy performance, the possible interventions already suffered, the state of conditions. These data were qualified into a proper scale of values and then were combined to calculate specific total scores; these were also classified in terms of ranges for the determination of classes of vulnerability to be combined with the exposure value – density of occupancy at the block level -. No specific external relations ruled the calculations that were determined in terms of specific ranges, laying the ground for the most structured work in recent activity discussed in Egusquiza et al. 2020 (Egusquiza et al., 2020). This was achieved to support technicians, in the early-stage process, in selecting the so-called Energy Conservation Measures. Specifically, in (Egusquiza et al., 2020), the CityGML extension took advantage of multi-criteria results of the EFFESUS project – in turn based on an AHP process - by combining the traditional theories about the recovery process of historic districts to the guidelines of ICOMOS about the Heritage impact assessment, and considering specific ranges of energy savings, calculated according to energy requirements, and costs of the simulated interventions; these were thus applied to two different case studies in order to test and validate the method.

Similarly, in Mutani et al. (Mutani et al., 2019), the research aimed at developing methods and tools for performing energy analyses within a single digital system. Here, the authors discussed and analysed platforms, integrating statistical energy models with CityGML-based urban ones. Moreover, the platform took advantage of the interoperability of specific management tools, suitably calibrated for the energy, and conservation semantic properties, combining building and micro-urban scale modelling tools (CitySim).

A further application on the energy issue is the work of Buyuksalih et al. 2013 (Buyuksalih et al., 2013), even though the CityGML standard was applied to evaluate the energy potential from renewable sources, such as photovoltaics. However, the CityGML-based urban model was used to test the interoperability of the parametric model with a dynamic solar software game engine. This enables the creation of parametric models for evaluating the solar incidence of renewable energy systems installed on building envelopes.

The last application typology on historic districts related to their management for the identification of priority of intervention based on the district-level distribution of buildings in the urban ancient cores is found in Lasorella and Cantatore 2023 (M Lasorella & Cantatore, 2023). The authors outlined a potential workflow for the semi-automated preparation of qualification criteria for intervention classes and their associated priority levels. Even though the improvement of semantic quality of the CityGML-based model for conservation was achieved through the photogrammetric techniques, these outputs were included in a large-scale model CityGML-based in order to relate such properties among all the buildings in the selected case study.

Due to the inherent interoperability already experimented with previous scientific work, the authors took advantage of web viewers of the 3D City databases to share the parametric and semantic models within a collaborative platform useful for all the experts involved in the recovery plan design and activities. Here, the outcomes were determined for equivalent levels of state of conservation at the single building scale derived from the setup of a Technical Decision-Support System (T-DSS) based on the UNI 11182, UNI/CEN TS 17385:2019, and Italian Consolidated Building Law.

This is in line with the national scale of interest in the work which also required considering the national listing procedure and the predetermined classes of interventions.

4.3.3. Other Classes

In this section, all other classes of built/architecture Cultural Heritage are discussed, as singularities from historic districts and single architectures. In detail, the review has highlighted other three types: the systemic architectures, scattered in the territory and characterised by recurring features (e.g., morpho-typological, constructive, material, original function); archaeological sites and industrial heritage. For them, some common aims are recognised and discussed in applying the CityGML-based model, such as the geographical distribution of architecture/ruins in the territory or the site, historical cataloguing, and technical construction features.

The research groups of Colucci et al. 2021 and Malinverni et al. (Elisabetta Colucci et al., 2021; Eva S. Malinverni et al., 2018) elaborated specific CityGML-based parametric models. In particular, in Colucci et al. (2021) (Elisabetta Colucci et al., 2021) the authors proposed an ontological structure applied and validated for fortified structures, such as castles. These models combined range-based digital survey techniques, the segmentation and classification of textured point clouds, thematic vocabularies, glossaries (such as the Getty Art and Architecture Thesaurus), existing ontologies for the semantic representation of Cultural Heritage (CIDOC-CRM), and parametric models at both the city-scale (CityGML) and building-scale (IFC). Furthermore, Malinverni et al. 2018 (Eva S. Malinverni et al., 2018) applied the CityGML modelling to disused military sites, applying the standard for their semantic and geometric qualification and extending the ontological structure with information about materials and the state of conservation of individual architectural artefacts. Here, the information, featured by a cognitive-technical nature and thematic maps of the state of conservation, was linked to the individual portions of the architectural building object of analysis and archived in the three-dimensional geographic information database.

Another level of detail, highlighted in the elaboration of CityGML-based ontological structures, refers to specific classes of Cultural Heritage, such as archaeological sites, to support sector experts in the historical and stratigraphic reconstruction analysis phases of the sites (Felicetti et al., 2010; Lorenzini, 2009).

In detail, Felicetti et al. 2010 (Felicetti et al., 2010) proposed a semantic structure for the analysis of such sites integrating and extending the CityGML standard with the CIDOC-CRM ontology; particular attention was paid to the temporal information of entities which is essential for the representation of such classes of entities, combining their geographical distribution in the sites. In (Lorenzini, 2009), the author used the classes and attributes of the Building module of the CityGML standard at the semantic-thematic level and integrated the CityGML-based parametric model through three-dimensional models derived from the topographic surveys. This approach aimed at managing information included in 3D models of reconstructed fabrics and elements in archaeological sites.

Similarly, the critical assessment of the construction transformations, related both to the physical evolution (historical-architectural transformations) and formal aspect (juridical-normative evolution), finds applications in the research of (Chagnaud et al., 2016; Périnaud et al., 2015; Samuel et al., 2016) for industrial heritage. In (Chagnaud et al., 2016; Samuel et al., 2016), an ADE specification of the CityGML standard was developed to support the planning of the existing building stock. The extension of the standard proposed by the authors aimed at correlating documents and graphic representations to the geometric model according to historical dating. In parallel, within the ALARIC project (Incremental Urban Change Research Project), Clémentine Périnaud et al. (Périnaud et al., 2015) elaborated a city model according to the CityGML standard starting from historical documents in order to understand the historical evolutionary processes, as well as the previous urban planning strategies of the industrial cities in the Lyon-Saint-Etienne region.

Among the studies classified, the works of Delgado et al (Delgado et al., 2010) and Finat et al (Finat et al., 2010) aimed at solving the critical issues related to the interoperability among different tools and users involved in the conservation process by developing a collaborative platform called GIRAPIM.

In such works, the technical knowledge integrated details about single historical architectures spatially distributed within the urban land but related among them for common details (systemic architectures); thus, such information was managed within the geometric and parametric model properly implemented with a logical-relational structure where also diagnostic information - deriving from non-/ semi-destructive and multi-sensor monitoring and tracking data – were associated. Therefore, the authors extended the CityGML standard through the creation of a "*PATRAC*" CityGML extension, importing the attributes of the Building thematic module into the Cultural Heritage class, and extending it through the classes "*Pathology*" (the attributes referred to conservation and accessibility of the fabric) and "*Intervention*" (conservation strategies and solutions aimed at solving critical issues about building accessibility).

So, being structured according to the CityGML standard, the GIRAPIM application, , was functionally prepared for the management of systemic architectures through:

i) the integration of semantic data into the geometric models, which allows the understanding of the meaning and function of the elements within the urban or architectural context. This integration also fosters collaboration and interaction between different platforms and users.
ii) the geolocalisation of models, whose geographic and spatial data ensure precise localisation and georeferencing of objects and information within the model. This is fundamental for the efficient management of architecturally similar assets scattered across the territory, as well as for interoperability with other information systems outside the model.
iii) the development of a systemic network of architectures in a web-based environment. This promotes the creation of a network of web services based on common standards, such as CityGML. These services enable people, experts in the field (engineers, architects) and local administrators to share, access and use data in a collaborative and consistent manner. This facilitates cooperation between different actors and the shared management of information.

PART 2 THEORETICAL AND METHODOLOGICAL INSIGHT

The 3D Semantical Historic District Systematic Code

5. METHODS AND TOOLS FOR THE 3D SEMANTICAL HISTORIC DISTRICT SYSTEMATIC CODE

In the initial chapter, the recovery process of historic districts is presented as a complex undertaking necessitating a comprehensive analysis and evaluation across various disciplines and scales. This involves the collaboration of numerous experts and the engagement of diverse technical and administrative stakeholders. The recovery process encompasses a range of operational, conceptual, and instrumental activities designed to identify intrinsic aspects such as morpho-typologies, materials, construction techniques, and architectural significance. Additionally, it addresses extrinsic factors such as transformations, social dynamics, cultural values, and economic considerations. The assessment includes evaluating these factors in terms of performance and conformity with norms, while also recognizing their importance in shaping local identity. By linking the development of digital tools to the classic phases of the conservation process, it is possible to highlight that there are inherent weaknesses associated with: i) heterogeneity of acquired data, in terms of the nature of the data (.ply, .las, .collada, .ifc, . gml, . jpeg, .html, .pdf); ii) multidisciplinary nature of collected data, information encompasses documentary, historical, architectural, and diagnostic aspects, making it diverse and complex; iii) interoperability of data, ensuring seamless interoperability is crucial for conducting various analyses effectively, as well as iv) quantity of the data, in quantitative and computerised terms. Addressing these critical issues underscores the necessity to formulate a digital code of practice that adheres to traditional conservation phases. The approach to elaborate such a code is: i) multi-scalar, considering geometric data and information at different levels; ii) multi-disciplinary, accounting for the diverse nature of IT and thematic-semantic data, and iii) multi-user, tailoring the code to accommodate various user types (administrative/technical, professionals) and numbers. This multi-faceted digital code of practice acknowledges the complexity of conservation processes, emphasizing adaptability and inclusivity across scales, disciplines, and user categories.

To address the challenges inherent in the traditional conservation process-specifically, the fragmentation and disjointedness of information in terms of integrating documents and results across phases, as well as fostering collaboration among diverse experts such as engineers, architects, restorers, historians, and archaeologists - a comprehensive digital code of practice has been developed and structured. This code, named the 3D Semantical Historic District Systematic Code (3shD-SystematiCode), aims to overcome these issues by providing a systematic framework for the entire conservation process. It follows the traditional phases of the conservation process: i) technical knowledge, aimed at the historical, architectural, material analysis, and evolution of the architectural-structural and functional transformations and the state of conservation to which the asset has been subjected over time; ii) pre-diagnosis, consisting in the cataloguing and structuring of the information gathered in the previous phase, with the aim of identifying initial hypotheses, also through phenomenological modelling supported by error or diagnostic trees, which will contribute to the planning of subsequent types of diagnostic analysis; and iii) diagnosis, in which the information gathered is developed for the determination of recovery interventions. By following these well-defined phases, the 3shD-SystematiCode aims to streamline, in operational terms, the conservation process, fostering a more cohesive and collaborative approach among experts and ensuring a comprehensive understanding of the historical and architectural aspects of the asset.

5.1. Tools

The section shows the main steps and necessary tools of the Digital Code of Practice useful for the elaboration of CityGML-based parametric models integrated with a Technical-Decision Support System (T-DSS). Specifically, the workflow is structured for the conservative analysis of historic districts, as well as to support technical users (engineers, architects) during the final phases of recovery and managment plans: management of the conservation levels and the subsequent identification and selection of intervention classes. In detail, the proposed workflow takes advantage of six main tools:

i) **GIS tools**. The GIS software tools are indispensable for the collection and geographic localisation of fabric information. Prominent GIS software, including Esri's ArcGIS and the open-source software QGIS, play a crucial role in facilitating data management, analysis, visualisation, and geoprocessing. These leading GIS tools empower users to efficiently handle geographical data, offering advanced functionalities that span from organizing and analyzing spatial information to creating visually informative maps. Esri's ArcGIS, known for its robust capabilities, and QGIS, as an open-source alternative, provide a comprehensive suite of tools for professionals engaged in diverse fields such as urban planning, environmental management, and infrastructure development.

ii) **VR Tools**, the available software aimed at the creation of virtual tours is evolutions of the Krpano program, the first application conceived by the Austrian programmer K. Reinfield. It had not a graphical interface and it was implementable exclusively in .xml language. Over time, several commercial applications have been developed for the purpose of creating virtual tours. Notable among these are Tourweaver©, 3D Vista Virtual Tour©, Panotour©, My 360©, Real Estate Virtual Tours Creator©, and VirtualTourEasy©, which are widely recognized and utilized for the described purpose (Cardaci & Versaci, 2013).

iii) **FME** (Feature Manipulation Engine) is a Spatial ETL (Extract Transform Load) software used for the conversation of main data (spatial and semantic information) according to the CityGML standard. It is a software platform developed by Safe Software for extracting, transforming, and loading data (ETL) between different formats and systems. It is based on a graphical interface that allows a simplified conversion of data based on specific categories of functions. This tool enables users to automate data workflows, conduct data quality control, and execute intricate spatial data transformations. The platform facilitates the seamless movement of data across diverse formats and systems, providing a powerful solution for automating and streamlining complex data processes. Users can leverage this tool to ensure the accuracy and reliability of data, conduct quality checks, and execute sophisticated spatial transformations, thereby enhancing efficiency and precision in data management. (SAFE SOFTWARE, n.d.).

iv) **3DCityDatabase** is the geographic informative system CityGML-based useful for the analysis and management of data in the parametric 3D model. The architecture of the database supports both the ORACLE Spatial and PostgreSQL/PostGIS relations and it is based on the CityGML v.2.0 for LODs up to 4. The 3DCity database is equipped with the 3DCityDB Import/Exporter tool, useful for the creation of semantic relations between the starting database and the CityGML standards, including geometric and semantic features. Moreover, the software allows to import and export KML/COLLADA/glTF data, to integrate and manage data through external Spreadsheets and manage additional ADE structures (Yao et al., 2018).

v) **3DCityDatabase Web Map Client** is the web-based viewer of three-dimensional maps useful in supporting the digital fruition of semantic data of architectural entities. The 3DCityDB Web-Map-Client is a viewer based on a web-browser based on APACHE, structured as an extension of Virtual Globe CesiumJS WebGL. The Web-Map-Client aims at the visualisation of the virtualized city models and properties in the webpage, importing them following the CityGML standards. The easily use help users in interacting with the Digital Models showing the structured details. It is fully compatible with KML/glTF files exported from the 3DCityDB Import/Exporter tool. The upload of model databases can be available for two classes of users: end-users that can just upload and visualize the data and overarched-users able to manage the contents of databases. It is possible thanks to the management of thematic features by means of external sheets (i.e. Spreadsheet Google API or PostgreSQL REST API) (Chaturvedi et al., 2015), restricting accesses to a limited number of users.

5.2. The 3D Semantical Historic District Systematic Code

5.2.1. Semantic structuring of data in a Historic District

In the current scenario, the management of the existing architectural heritage is regulated on a national and regional scale, identifying the principles for their conservation on the basis of previous “Restoration Charters”. In Italy, the regulatory binding framework of the landscape heritage is entrusted to the regions, declining within the "Landscape Plans" (in compliance with Legislative Decree no. 42 of 2004) tools and guidelines useful for the identification of the system of values associated with the complex built district system, regardless of specific features at the building scale. For this, the conceptualisation of digital recovery plans CityGML-based with Technical Decision Support System, both at geometric and semantic levels, requires three key aims, as the main goal of this section: i) find and categorize the regulations and previous experiences to identify geometric and semantic data, coherently identified for terminology and requirements; ii) determine the correct relations and the logical scheme of the identified data; iii) organize data in databases structured according to the CityGML ontology. Currently, the recovery of such heritage should include specific issues, such as:

- The recognition of environmental, historic and cultural values following national and regional regulations. In this class of data, all material and immaterial elements to be preserved can be associated, from the friezes to construction techniques and building morphologies.
- The identification and qualification of obsolescence of building function, mostly related to static, energetic, and hygienic performances of fabric and components. Here, constructive, technological, and material features of components (walls, windows, roofs, HVAC system, …), and geometric characters of inner spaces (number of floors, presence of windows, geometry of rooms), constitute the main data to focus on.
- The identification of buildings decays. This is associated to the analysis of physical and technological obsolescence of materials and system technologies that cannot directly affect the function of buildings but may alter the building

uses. This is the case of data describing the state of conservation of non-structural elements of components (decay of plasters or the presence of stone alterations in unplastered walls) and systems (connection to the grid, maintenance of systems).

- The administrative compliance of architectures, such as cadastral information of buildings, the previous intervention of transformations (uses, raisings, demolitions, superfetation), etc.
- The use of “Building Types” as models of architecture, featured by the recurrent combination of morpho-typological, construction, and material characters, as well as extension and height. This is useful for the description of extended heritage featured by various combinations of simple properties, uses and state of conservation to be assessed for criticalities and potentialities and investigated for intervention required.

All these data require to be firstly elaborated, understanding the elements of the built environment to characterize and the properties to enrich the model, and then interrelated within the CityGML database. As briefly introduced before, data to be collected and managed for the recovery plan of historic districts can be classified according to three informative dimensions: the normative frame [N] – prevalently distinguished at national levels-, approved ontologies [O] and scientific ontologies [SO] just proposed and tested in literature, and previous experiences [PE] in setting up recovery plans. Specifically for each category and in the details of the Italian case, Table 1 summarizes the main references about. In detail, as far as the Italian normative frame [N] is concerned, specific relevance is on the concept of “habitability” for residential spaces, as the prevalent uses of systemic fabrics in historic districts. Habitability of dwellings is determined as a set of minimum requirements which must guarantee safety and security in living residential spaces (statical and hygienic requirements). Besides the detail of uses, national regulation considers the qualification of fabrics according to cultural and historic relevance; it is the case of the Italian Code on Cultural Heritage and Landscape.

Finally, the last regulations concern urban land uses and management which identify the administrative details of fabrics and the allowed actions (transformations, permissions (Testo A, 2001)). Considering previous approaches [PE] details, major references are related to the experiences in creating recovery plans. Here, the derived elements are not related to the normative constraints but to the methods applied. Among the major experiences, the recovery plans for the cities of Bologna and Palermo, and of Abruzzo and Sardegna regions that are mainly identified as “recovery manuals”. As the categories of information relates to ontologies [O], the digitalisation process of a real case study according to specific rules usually generates the setting up of some properties or data which are consistent with the standard but independent to the other necessities. Considering the regulated and approved ones, CityGML and CIDOC CRM (Doerr, 2003) are the most common ontologies applied in the creation of digital and parametric models of large urban areas and/or fabrics or elements featured by cultural relevance. However, for the paper purposes, the attention is on the CityGML standard (Gröger et al., 2012). As inherent requirements for it, some geometric data and geographic properties are introduced in the system of parameters in order to generate the 3D model.

In addition, the scientific experiences in studying and extending ontologies have produced a set of scientific ontologies [SO] that are not approved by the related standard but that find their application and test in real case studies. In this case, factors are highlighted due to the similarity in approach or subject matter. Specifically, two main references are detailed: the CHADE (Cultural Heritage Application Domain Extension), as specific ontology CityGML-based for the description of Cultural Heritage (Noardo, 2018) and the SEH-SDB (Semantically enriched historical spatial database) which conceptualize historical, architectural, and cultural information of Cultural Heritage (Yaagoubi et al., 2019). Following the research's aim, all the collected classes of data are categorised into three types: i) Descriptors (Ds) that can be directly obtained by means of direct in-situ inspection or documental acquisition (period of construction, buildings permission, uses, state of maintenance of walls, roofs); ii) Primary Factors (PFs), the first level of derived data, that offer a higher and technical level of knowledge about the descriptors as combinations of derived factors (nD); iii) Secondary factors (SFs), the most complex level of derived data, as the combination among primary ones (nPF), primary and descriptors (nPF + nD). Then, all of them are classified for thematic similarities:

- General data include the administrative information of buildings, street assets and district. The cadastral data may be used to identify them (identified as building ID in order to ensure their unambiguous lecture.
- Historical-archival information gathers all the collectable data by means of documental sources and refers to the historical information of elements of the built environment.
- Technical knowledge data refers to the practical information acquired by in-situ inspections and measurements.
- Normative regulation includes notes about the regulatory framework, such as the type of regulations and constraints.
- Architectural emergencies refer to the features and elements with cultural, constructive and historical relevance.
- The conservation level collects details on the state of maintenance of building components (walls, roofs) and systems.
- The derived data collects all the information associated with simple data for the evaluation of the built environment, such as the qualification of performances and interventions and the identification of priority levels of interventions.

Table 3 - Codes of Normative [N], Previous experiences [PE], Ontologies [O] and Scientific Ontologies [SO] involved in the qualification of parameters for the recovery process

Code	Name	Reference
NORMATIVE [N]		
N1	Code on Cultural Heritage and Landscape	(Legislative Decree no. 42 of 22 January 2004, 2004)
N2	Height and hygienic requirements for residential spaces	(Modifications to the Ministerial Instructions of 20 June 1986, Concerning the Minimum Height and Main Sanitary and Hygienic Requirements of Dwellings, 1975)
N3	Technical Standards for Construction	(Decree of 17 January 2018 'Technical Standards for Construction,' 2018)
N4	The European Standard - Guidelines for a condition survey of Built Cultural Heritage	(UNI EN 16096:2012)
N5	Method for codition assessment of immobile constructed assets	(UNI/CEN TS 17385:2019)
N6	Urban land uses and management at urban scale	(Presidential Decree no. 380 of 6 June 2001, 2001)
PREVIOUS EXPERIENCES [PE]		
PE1	Manuals for the recovery of urban ancient core	(Adorante et al., 2011; Atzeni & Manias, 2006; Cannarozzo, 2007; P L Cervellati & Miliari, 1977; Pier Luigi Cervellati & Scannavini, 1973)
ONTOLOGIES [O]		
O1	CityGML	(Gröger et al., 2012)
SCIENTIFIC REFERENCES OF ONTOLOGIES [SO]		
SO1	CHADE - Cultural Heritage Application Domain Extension	(Noardo, 2018)
SO2	SEH-SDB - Semantically enriched historical spatial database	(Yaagoubi et al., 2019)

Finally, the semantic data are codified and described in order to have an unambiguous reading of information, discussing the level of the data type and the associated CityGML classes. In particular, data are related to semantics already presented in "*Building*" (B) and "*Transportation*" (T) classes; when specific ones are not conceptualised in the CityGML standard, they have been implemented by the Generic Attribute class. In this way, the semantic digital model has been extended by applying the characterisation of the existing architectural heritage, underlining the potentialities and the multi-scale approach of data computing. Thus, for each specific thematic section, the tables (Table 4, Table 5, Table 6, Table 7, Table 8, Table 9, Table 10, Table 11) show the details of parameters, introducing codification, name, description, and informative data, following the thematic classification and highlighting the relations with the categories of informative dimensions and the CityGML associated "Class".

Table 4 - System of data involved in the technical knowledge of historic districts, codified and classified in terms of associated CityGML "Class" (B Building, T Transportation, * when the class is implemented with generic attribute) for their modelling, and related reference ("Ref") according to the categorisation in Table 3- General Info and Historical-archivial Sections

Section	Code	Name	Description	Ref	Class
1. Gen. Info	ID_C	Cadastral Data	Sheet, parcel and subalterns	-	B*
	ID_U	Urban Data	Urban class in the plan	N4	B*
	ID_T	Toponomastics	Avenue, Street, Square, … house number	O1	B
2. Historical-archival data	B_Cl	Building Class	Building Type (castle, building, church, …)	O1	B
	B_Fct	Building Function	Original use (residential, strategic, etc.)	O1	B
	B_Use	Building Use	Current use (commercial, residential, etc.)	O1	B
	B_CP	Construction period	Construction period of building	N3	B
	B_DP	Demolition Period	Demolition period of building	PE1	B
	B_Ow	Building ownership	Public/Private building	SO1	B*
	B_St	Building State	Current condition (abandoned, partially used, …)	PE1	B*
	B_Tl	Building Title	First and latest building permissions	PE1	B*
	B_PI	Presence of intervention carried out	Alteration of the original fabric	N3	B*
	B_TPI	Type of building intervention carried out	Building renovation, Static recovery, Raising, Conservative restoration, etc.	N3	B*
	B_PPL	Year of intervention carried out	Reference period relating to the execution of previous intervention	N3	B*
	U_Cl	Urban Class	Classification of element (Street, square, …)	O1	T
	U_Fct	Urban Function	Original use type of the urban element	O1	T
	U_Use	Urban Use	Actual use type of the urban element	O1	T

	U_St	Urban State	Current surface decay of urban element	PE1	T*
	U_PI	Previous interventions of urban element	Identification of transformations carried out	PE1	T*
	U_TPI	Type of urban intervention carried out	Urban restructuring urban redevelopment	PE1	T*
	U_PPI	Period/year of urban Intervention carried out	Reference period relating to the execution of past urban interventions	PE1	T*

Table 5 – According to the Table 4 the Section 3 – Technical knowledge data

Subsection	Code	Name	Description	Ref	Class
3.1. Geometric	B_nFa	Storeys above ground	Total number of storeys above ground	O1	B
	B_nFb	Storeys below ground	Total number of storeys below ground	O1	B
	B_H	Measured Building Height	Maximum building height above the ground evaluated at the eaves	O1	B
	B_SH	Storey heights above and below ground level	List of storey heights calculated between the floor level and floor extrados height (ground to top)	O1	B
	B_A	Floor area	Commercial area of the building	N2	B*
	B_Pwi	Presence of windows	Presence and relative location of windows	N2	B*
	B_nR	Number of rooms	Total number of rooms in the building	N2	B*
	B_WiA	Window area	Total extension of window in each room	N2	B*
	B_WD	Wall dimension	Thickness of wall	N3	B*
	B_WiAw	Window Area wall	Total extension of windows assessed in the wall	N3	B*
	B_WA	Wall area	Total extension of the wall	N3	B*
	B_Arf	Roof area	Total extension of the roof	N3	B*
	B_RA	Room area with window	Area of room with a window	N2	B*
3.2. Morpho-types, architect..-constr.	B_Typ	Building Type	Morpho-typology (palace, simplex, …)	PE1	B*
	B_Str	Structural typology	Type of building structure (masonry, vaults, mixed building, etc.)	N3	B*
	B_WT	Wall Type	Description of construction technique of wall and elements + materials of elements (e.g.,	SO2	B*

			compound wall with squared stone blocks)		
	B_RT	Roof Type	Description of construction technique for roof and elements + material of elements (e.g., vault in squared tuff blocks)	SO2	B
	B_VCT	Vertical Connection Type	Description of construction technique + material of stairs (e.g., concrete stair, cantilever stone stair)	SO2	B*
	B_WiT	Windows Type	Physical-material features of window elements (e.g., E-low double glass and wooden frame)	SO2	B*
	B_FiT	Type of building finishing layers	Description of materials for wall and roof finishing (e.g., mortar plaster walls; external bituminous finishing of roof)	SO2	B*
	B_MQ	Mortar Qualification	Qualification of mortar in classes (good, medium, bad)	N3	B*
	B_QJ	Quality of vertical and horizontal joints	Presence and quality of joints floor-to-walls, and wall-to-wall in classes (good, low, bad)	N3	B*
	U_PT	Element type of urban paving	Surface finishing and material (e.g., paving in irregular cobblestones)	PE1	T*
3.3. Technolog. Systems	B_TS	Technological system	Presence of any technological system in the building (water; sewage; heating; …)	N2	B*
	B_TST	Technological system type	Type of technological system in the building (water; sewage; heating; …)	N2	B*
	U_PU	Primary urbanisation	Presence of any primary urbanisation	N2	T*
	U_TPU	Primary urbanisation type	Type of primary urbanisation (water, sewerage, electricity, gas, telephone, …)	N2	T*

Table 6 - According to the Table 4 the Section 4 – Legislative references

Code	Name	Description	Ref	Class
B_ChC	Cultural Heritage Code	Constraints defined by the Cultural Heritage and Landscape Code	N2	B*
B_LsR	Landscape restriction	Constraints defined by regional landscape regulation	SO1	B*
B_MR	Municipal constraints	Constraints defined by municipal policies	SO1	B*

Table 7 - According to the Table 4 the Section 5 – Architectural emergencies

Code	Name	Description	Ref	Class
B_EV	Elements of value	Presence of elements with historical and cultural value (portal, epigraph, decorations, friezes, …)	SO1	B*
B_HR	Historical relevance	Distinctive cultural, historical and identity features	SO1	B*

Table 8 – According to the Table 4 the Section 6 – Condition survey

Code	Name	Description	Ref	Class
B_BM	Building mechanical qualification	Mechanical qualification of building (good=0, medium=1, low=3)	N3	B*
B_CC	Condition Class of building	Presence of cracking, damp, and decays	N4	B*
U_CC	Condition Class of Urban Element	Presence of cracking and decays	N4	T*

Table 9 – According to the Table 4 the Section 7 - Qualification of decays

Code	Name	Description	Ref	Class
B_Td	Type of decay	Assessment of cracking, damp, and decays	N5	B*
B_S	Seriousnes s	Severity of degradation	N5	B*
B_In	Intensity	Level of decay	N5	B*
B_Ex	Extension	Extension of the decay area	N5	B*

Table 10 – According to the Table 4 the Section 8 - Aggregate data

Code	Name	Description	Ref	Class
D	Extension of decay	Aggregate extension of decay area	N5	B*
Fc	Corrective factor	Corrective factor assessed according to the class of condition of the single decay	N5	B*
Ad	Extension of decay	Extension of the i-th decay, in percentage	N5	B*
Ccd	Condition for single decay	Class of condition for single decay	N5	B*

Table 11 – According to the Table 4 the Section 9 - Derived Data

Code	Name	Description	Ref	Class
B_CS W	Conservative state of wall	Qualification of the conservative state of wall	N5	B*
B_CS R	Conservative state of roof	Qualification of the conservative state of roof	N5	B*
B_CS Wi	Conservative state of windows	Qualification of the conservative state of windows	N5	B*
B_BT	Recurrent Building type	Type of building identified as combination of recurrent characters	PE1	B*
B_CS	Global Conservation state of building	State of conservation of building, considering all the components	PE1	B*
B_HS P	Hygienic and sanitary parameters	Compliance with hygiene and sanitary parameters for every residential building (yes=0, no=1)	N2	B*
B_IC	Building Intervention Class	Class of required intervention (ordinary maintenance, static recovery, …)	N6	B*
B_IPr	Building Intervention Priority Index	Prioritisation of intervention considering value range of Building Intervention Class and building type	PE1 /N4-5-6	B*
U_AT	Urban Asset Type	Typical urban element identified as combination of recurrent characters	PE1	T*
U_CS	Conservative class of urban element	Surface decay and physical lacks in paving	N4	T*
U_IC	Urban Intervention Class	Class of required intervention (urban maintenance, regeneration)	PE1 /N6	T*
U_IPr	Urban Intervention Priority Index	Prioritisation of intervention considering the value range of intervention class and type of urban element	PE1 /N4-6	T*

Following, Table 12 details the relations among Descriptors and Factors for each Primary and Secondary ones as determined by the scientific and normative review.

Table 12 - List of Primary (PF) and Secondary Factors (SF) and codes of combined descriptors and factors

Code	Name	Data Type	Combined Descriptors
B_BT	Recurrent Building type	PF	B_Typ; Cl; CP; TS; Fct; Use; nFa; PW; WiA; Str; WT; RT; VCT; WiT; TST
B_Ccd	Class of condition for single decay	PF	B_Td; S; In_Ex
B_Di	Aggregate extension of decay	PF	B_Ccd; Fc; Ad
B_DiW	Total Aggregate extension of Wall decay	PF	B_Di
B_DiR	Total Aggregate extension of Roof decay	PF	B_Di
B_DiWi	Total Aggregate extension of Windows decay	PF	B_Di
B_CSW	Conservative state of wall	PF	B_DiW; WA
B_CSR	Conservative state of roof	PF	B_DiR; RArf
B_CSWi	Conservative state of windows	PF	B_DiWi; WiA
B_CS	Global Conservation State of building	SF	B_CSW; CSR; CSWi
B_HP	Hygienic parameter	PF	B_WiA; RA; Use
B_HSP	Hygienic and sanitary parameters	SF	B_nR; TS; TTS; HP
B_IC	Building Intervention Class	SF	B_BT; CS
B_IPr	Building Intervention Priority Index	SF	B_ IC
U_AT	Urban Asset Type	PF	U_Cl; Fct; Use; ST
U_CS	Conservative class of urban element	PF	U_CC
U_IC	Urban Intervention Class	SF	U_AT; CS
U_IPr	Urban Intervention Priority Index	SF	U_IC

5.2.2. The conceptual normative structure of T-DSS

Coherently with the rule of a standard, all the information required for the conservation process needs to be structured according to consolidated relations. In that sense, the use of descriptors and primary and secondary factors allows the identification of relations between simple and derived data. Descriptors are determined by survey or archival activities mainly aimed at the description of basic information, while factors result from logical and mathematical relations between simple (descriptors) or complex (descriptors and primary factors) information.

This section is structured in order to show the translation process of normative relations in the Technical- Decision Support System (T-DSS) as the over-ordered phase of the practical workflow, described in section 5.2.1.

The process of analysis and assessment of the existing built and urban heritage is standardised with respect to the main standards in the sector, including:

i) UNI EN 16096: 2012, for the survey of the qualitative conditions of buildings and urban elements (streets, squares, open spaces);
ii) UNI 11182, for the identification of the forms of deterioration of stone materials,
iii) UNI 8290, for the categorisation of elements and sub-components that characterise the technological units of the building system,
iv) UNI/CEN TS 17385:2019, for the assessment of the conditions of architectural artefacts;
v) Presidential Decree no. 380 of 6 June 2001, for the definition of intervention classes at urban and building scale.

In detail, an initial qualitative reconnaissance analysis on an urban and building scale is carried out using UNI EN 16096:2012. Each urban and building entity is qualified according to the descriptors in Table 13.

Table 13 - Qualitative classification of the state of preservation of physical entities according to EN 16096:2012

CONSERVATION CLASS B/U_CC	**SYMPTOMS**
CC0	NO SYMPTOMS
CC1	LIEVE SYMPTOMS
CC2	SYMPTOMS OF MEDIUM INTENSITY
CC3	SEVERE SYMPTOMS

Consequently, the type and priority of intervention on an urban scale is derived according to the conservation class of the urban element (Table 14) and the primary factor Urban Asset Type.

Table 14 - Relations between classes and priority of intervention to the values of Global conservation state of urban element

U_CS	**Condition**	**U_IC**		**U_Ipr**
		U_AT with historical value	U_AT without Historical Value	
0	Excellent	Urban restoration	Ordinary maintenance	2
1	Good			
2	Fairly good		Urban renovation	1
3	Low			

Specifically, for the building environment, according to Table 13, if:

$0 \leq [B\_CC] \leq 1$;

the classes of intervention (B_IC) is the Ordinary maintenance, without priority.

Contrary, a second level of in-depth quantitative analysis is required.

For this, the factors involved in the identification and characterisation of the state of conservation of buildings and their sub-components in historic districts correspond to an adjunctive semantic information (Table 15).

Table 15: Descriptors for the qualification of single decays, to be associated to sub-components

Code	**Name**	**Class**	**Normative Reference**
B_Td	Type of decay	B/GA	UNI 11182
B_S	Seriousness	B/GA	UNI CEN TS
B_In	Intensity	B/GA	UNI CEN TS
B_Ex	Extension	B/GA	UNI CEN TS
D	Extension of decay	B/GA	UNI CEN TS
Fc	Corrective factor	B/GA	UNI CEN TS
Ad	Extension of decay	B/GA	UNI CEN TS
Ccd	Class of condition for single decay	B/GA	UNI CEN TS

Specifically, Table 15 shows descriptors identified for the qualification of type of decays for single sub-components, and the levels of seriousness and intensity and global extension. Such descriptors are determined from the assessment of:

- UNI 11182:2006 (UNI 11182) identifies, in an unambiguous way, the typologies of decay. Here, defects caused by humidity or environmental conditions (i.e., erosion, alveolation), and cracks are included (B_Td);

- UNI CEN TS 17385:2019 (UNI CEN TS) which evaluates the level of conservation of architectures and sub-components, according to the seriousness (B_S), level of intensity (B_in) and extension (B_Ex) of the identified defect/s. In detail, qualitative and quantitative indicators are identified for the descriptors (B_s, B_In, B_Ex) according to the technician's expertise and objective values (Table 16), in order to have a unique indicator (a value from 1 to 6 called Class of condition) for each type of decays;

All the descriptors are associated to single sub-components of single fabrics according to their technical classification identified in UNI 8290.

Table 16: Values of Classes of conditions (Ccd) (1 – 6) as the combination of Seriousness, Intensity and Extension descriptors

Seriousness	Intensity	Extension: Minimal (≤2%)	Extension: Inconsistent (>2%, ≤10%)	Extension: Consistent (>10%, ≤30%)	Extension: Significant (>30%, ≤70%)	Extension: Widespread (>70%)
Minor	Low	1	1	1	1	2
	Medium	1	1	1	2	3
	High	1	1	2	3	4
Serious	Low	1	1	1	2	3
	Medium	1	1	2	3	4
	High	1	2	3	4	5
Critical	Low	1	1	2	3	4
	Medium	1	2	3	4	5
	High	2	3	4	5	6

As far as the contents in Table 16 are concerned, the conservative states of single sub-components (wall, roof and window) are thus introduced in the semantic structure as primary factors, due to the relations and the quantification of the associated simple descriptors. When single levels of conservation are combined towards a unique factor of the global state of fabrics, the Global Conservation state of building [B_CS] is determined as a Secondary factor.

While, for the identification of the unique conservative state of sub-components when multiple types of decays are present, UNI CEN TS suggests the grouping method.

Table 17: Factors for the qualification of the conservative state of building sub-components (walls, roof, windows) – primary factors -, and global index for buildings – secondary factor -.

Code	Name	Class	Normative Reference
B_CSW	Conservative state of wall	B/GA	UNI CEN TS
B_CSR	Conservative state of roof	B/GA	UNI CEN TS
B_CSWi	Conservative state of windows	B/GA	UNI CEN TS
B_CS	Global conservative state of building	B/GA	UNI CEN TS

For each decay class [B_Td], the defect is assessed in terms of aggregate extension [D] considering the associated class of condition [Ccd], a specific corrective factor [Fc] is linked to the real extension in order to have a weighted extension of the defect (see Table 18, Equation 1 and Equation 2).

$$Di= Fci*Adi \ (i=1\ldots n) \qquad (1)$$

where Di= i-th aggregate extension of decay.

Fci= i-th corrective factor assessed according to the class of condition of the i-th decay (Table 18).

Adi= extension of the i-th decay, in percentage.

Thus, the total extension of the defected area (Dtot) results as the sum of the i-th aggregated extension of decays (Di):

$$Dtot= \Sigma Di \ (i=1\ldots n) \qquad (2)$$

Table 18: Corrective factors for each class of conditions

Class of condition for single decay [Ccd]	Corrective factor [Fc]
1	1
2	1.02
3	1.10
4	1.30
5	1.70
6	2

Finally, the primary factor of “conservative state” for each sub-component [B_CSx] is determined according to Equation 3, and qualitatively described according to the aggregated condition class defined in Table 19.

$$B\_CSx = Dtot/Ac \qquad (3)$$

where Ac= extension of sub-component, in percentage

Table 19: Tange of values of Dtot/Ac and associated values for the aggregated class of conditions

Dtot/Ac	Aggregated class of condition
$x \leq 1.01$	1
$1.01 < x \leq 1.04$	2
$1.04 < x \leq 1.15$	3
$1.15 < x \leq 1.40$	4
$1.40 < x \leq 1.78$	5
$x > 1.78$	6

As far as the assessment of the secondary factor, the Global conservation state of building [B_CS] is calculated according to the notes of UNI CEN TS 17385:2019.

This is the result of the weighted average of decays and related sub-component extensions as described in Equation 4:

$$B\_CS = \Sigma\ (CSW^{*}\ WA + CSR^{*}RA + CSWi^{*}WiA/WA + RA + WiA) \qquad (4)$$

where B_CS= Global Conservation State of building
B_CSW = Conservative state of Walls
WA = Area of Walls
B_CSR= Conservative state of Roofs
B_RA= Area of Roofs
CSWi= Conservative state of windows
WiA= Area of Windows

As far as the relation among classes and priority of intervention with the global state of conservation is concerned, Table 20 summarized the rules. Specifically:

- The classes of intervention are determined according to the preservation strategies identified the Italian Consolidated Law on Building (D.P.R. Decree of the President of the Republic no. 380/2001). In concordance with the regulation, differences exist both for the state of conservation and direct cultural or historical restriction of single buildings. In fact, conservative restoration is the only possible class of intervention, while for historical fabrics, ordinary, extraordinary maintenance and building rehabilitation are recognized as possible classes of intervention associated to the global conservation level.
- The priority of intervention is introduced as a global index of intervention class. It is a numeric feature (1 to 3) associated to the inverse seriousness of intervention classes.

Table 20: Relations between classes and priority of intervention to the values of Global conservation state of building. The intervention classes are: Ordinary Maintenance (OM), Straordinary Maintenance (SM), Building Renovation (BR) and Building restoration (BR*). The priorities of intervention are: green – low priority, yellow – medium priority and orange – high priority.

<table>
<tr><th rowspan="2">B_CS</th><th rowspan="2">Condition</th><th colspan="2">B_IC</th><th rowspan="2">B_Ipr</th></tr>
<tr><th>Listed</th><th>Not Listed</th></tr>
<tr><td>1</td><td>Excellent</td><td rowspan="6">Building restoration</td><td rowspan="2">Ordinary maintenance</td><td rowspan="2">3</td></tr>
<tr><td>2</td><td>Good</td></tr>
<tr><td>3</td><td>Fairly good</td><td rowspan="2">Straordinary maintenance</td><td rowspan="2">2</td></tr>
<tr><td>4</td><td>Low</td></tr>
<tr><td>5</td><td>Bad</td><td rowspan="2">Building renovation</td><td rowspan="2">1</td></tr>
<tr><td>6</td><td>Very Bad</td></tr>
</table>

5.2.3. The conceptualisation of 3shD-SystematiCode

The section introduces the 3D Semantical Historic District Systematic Code (3shD-Systematic Code) to support the technical knowledge of historic districts; it results from the combination of the traditional process involved for Cultural Heritage recovery and the potentialities of disruptive three-dimensional CityGML-based models, with the help of: spatial information systems, relational databases and decision support systems, as well as digital tools based on photogrammetry and virtual reality.

The main macro phases that constitute the 3shD-Systematic Code are (Figure 22):

Ph 1 – Knowledge analysis;

ph 1.1 Data Collection;

ph 1.2 The structuring of technical knowledge;

ph 1.3 Spherical-image survey;

Ph 2 – Creation of systems and digital models;

ph 2.1 Shape file processing;

ph 2.2 Setting up of the relational-Database;

ph 2.3 Creation of the Virtual Model ;

Ph_3 - Qualitative surveys in situ and/or on-desk;

Ph 4 - Quantitative analysis of the state of preservation on a building scale;

ph 4.1 Image-based survey;

ph 4.2 Thematic mapping for conservation assessment;

Ph 5 - Implementation of the parametric model according to the CityGML standard;

ph 5.1 Setting up of the CityGML-based Model;

ph 5.2 Model storage in 3DCityDB;

Ph 6 - Elaboration of the model for technical use.

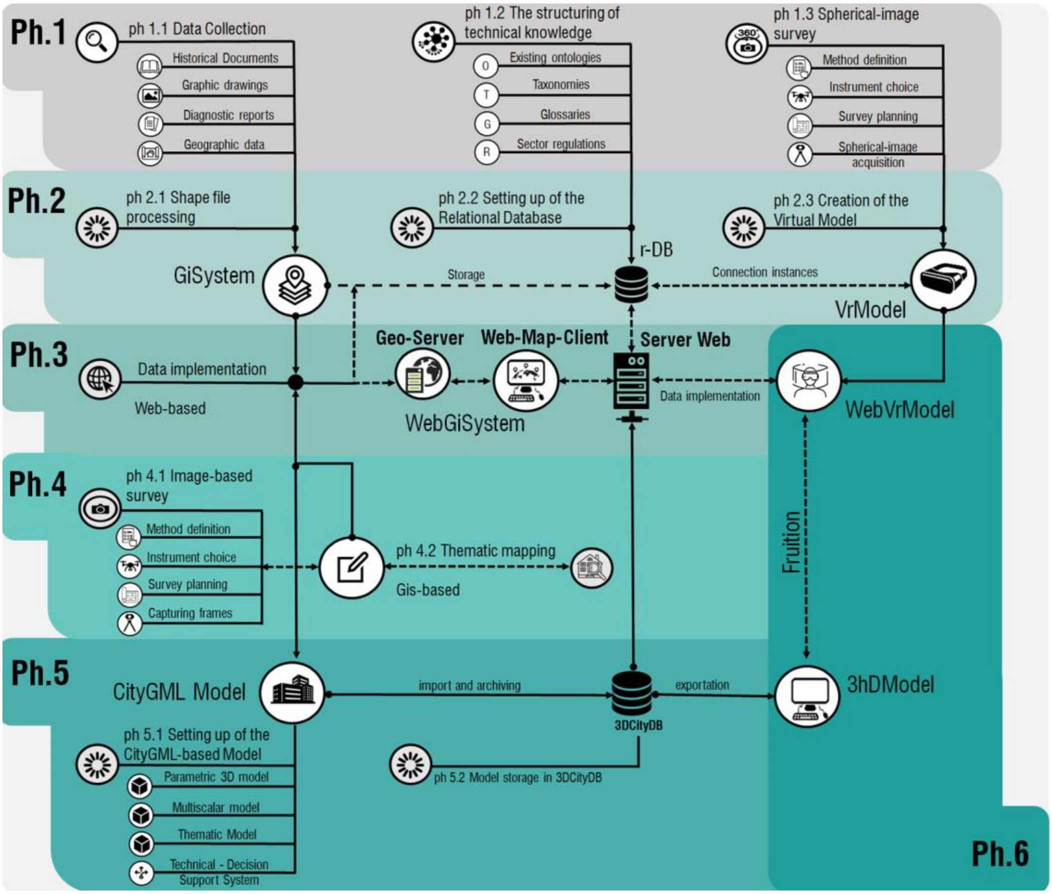

Figure 22 - Phases and sub-phases involved in the digital code of practice

Specifically, the digital code of practice delves into technical knowledge on several levels:

1. Information Level - It provides insights into the nature and type of data encoded within it;
2. Thematic Level - It focuses on different types of historical heritage entities, placing a particular emphasis on the built environment, encompassing residential and special buildings, as well as urban spaces such as squares, streets, and open areas;
3. Disciplinary Level - The code of practice contributes to different fields of investigation, including structural, architectural, and historical aspects;

4. Definitional Level - It establishes a multi-scalar approach, which involves the qualification of heritage analyses at the aggregate scale (macro) the geometric-spatial information and at the building/urban space scale (micro) the semantic/technical cognitive information.

The code aims to enhance technical understanding by providing detailed information at these four levels, thereby contributing to a comprehensive comprehension of heritage analysis and preservation, particularly in the context of the built environment and urban spaces.

5.2.3.1. Knowledge analysis

Phase 1 involves in collection of both quantitative and qualitative data and information relevant to the analysis and interpretation of the area under investigation. Quantitative data includes historical design drawings, diagnostic reports, monitoring analyses, and geographical data. On the other hand, qualitative data encompasses historical documentation, historical photographs, iconographies, and archival data.

Therefore, this phase is conducted on a dual scale of investigation: micro (architectural artifact, urban entity/space) and macro (urban aggregate, historic district).

Here, three sub-phases are required:

ph 1.1 – Data collection

The cognitive process consists of a preliminary sub-phase.

At macro scale requires:

i) Historical-documentary-archival investigation, for studying the diachronic evolution of architectural artifacts and related urban transformations;
ii) Morpho-typological and architectural analysis of the urban fabric, useful for defining building types (terraced houses, tower houses, houses in a line) and urban types (paths, streets, squares, open spaces);
iii) Analysis of the site's morphology, for defining the orographic/morphological course of the ground, as well as extrapolating plani-altimetric data;
iv) Identification of primary urbanisation systems (water, sewerage, electricity, gas).

Additionally, during this phase, information on a territorial scale (orthophoto and regional technical maps, digital terrain and surface models) is analyzed and acquired. This information is useful for the subsequent geolocation (ph_2.1) and elaboration of three-dimensional models of individual building artifacts (ph_5.1).

At the micro scale, the intrinsic characteristics of the artifacts are investigated, including:

i) Identification of construction techniques (load-bearing masonry, mixed building).
ii) Determination of the material characteristics of building components and sub-components (horizontal and vertical closures).
iii) Assessment of the conservation status of individual building elements.
iv) Identification of technological systems installed in the building (water, sewage, electrical, thermal systems).
v) Exploration of past and current uses.

In detail, it should be noted that the types of information collected in this phase and sub-phase derive from bibliographic, archival, and documentary analyses. This involves the collection and cataloging of information preserved in public and/or private bodies such as state archives, libraries, and professional offices.

This, to gather comprehensive information regarding the evolutionary, morphological, and material-constructive aspects of the site.

ph 1.2 - The structuring of technical knowledge

The conceptualisation of a defined logical-relational scheme in which taxonomies defined by glossaries of stone material degradation, existing ontologies on the spatial and semantic representation of Cultural Heritage, regulations in the field of building systems and restoration, and established approaches in the field converge.

This subphase consists of coding the multitude of information collected for proper storage and management, in compliance with the principles and rules for the diagnosis of historical heritage. In particular, three types of parameters outlined in §5.2.1 and shown in Tables 4 – 5 -6 -7 -8 -9 -10 -11 were identified.

As outlined in § 5.2.2, the logical-mathematical relations underlying the ontological structuring are designed to support a T-DSS. They are based on mathematical algorithms that enable the processing of unstructured problems through the correlation of quantitative and qualitative data, overcoming the previous conception of an optimal solution with respect to unambiguous parameters. However, ontology structuring allows for the qualification of the existing historical heritage at different granularities of investigation, which is also useful for the subsequent definition of intervention strategies.

ph. 1.3 – Spherical-image survey

The investigated area is digitally acquired by carrying out a speditive survey using the spherical-image approach. This subphase requires the definition of the survey plan, a pre-operative phase for the digitalisation of architecture. Starting from the tecnichal collected data, expert users should plan the photographic survey activities and procedures. Firstly, the expert can structure the image acquisition plan by means of the spherical head, defining their position and the total amount of photographs, according to the information about the morphological features of the urban environment. This activity is useful to ensure a proper overlap between spheres, as well as the widest acquisition level. In addition, it is possible to link two operative approaches for the shooting activities: using i) tripods or ii) robot or Unmanned Aerial Vehicles (UAVs).

Consequently, the spherical image-based survey is carried out as the operational step for the digital acquisition of architecture. The acquisition of spherical images (Sph_RGB) in the real environment is executed according to the planned activities and strategies.

5.2.3.2. Creation of digital systems and models

Phase 2 consists in the processing of the geographic and relational information system, and virtual model. Here, three sub-phases are required:

ph 2.1- Shape file processing. Each architectural entity and its associated geometric properties are accurately geolocated in the reference system. Specifically, the shape file is processed using available territorial information system data (e.g., regional technical map, digital surface and terrain model) for the representation of fabrics. The GiSystem is correlated with the relational-Database (r-DB).

ph 2.2 – Setting up of the relational-Database (r-DB). The r-DB is structured in order to allow the filling and systematization of semantic data required for the goal (descriptors in Table 4, Table 5, Table 6, Table 7, Table 8 and Table 9), resulting from the first information collection. Specifically, the database is structured following the conceptual structure defined in Ph. 1.2.

However, the structure set up for this purpose consists of 7 sections:

S1. General information (Section_Gen.Info), in which all information of a general data is collected, as toponomastic (municipality, street) and cadastral (sheet and parcel) data;

S2. Historical-archival information (Section_Historical_archival_data), in which historical (period of construction, historical nomenclature of the property) and architectural (type of construction, building type, number of floors, height of the building, function and state of use) data are collected;

S3. Technical knowledge data (Section_Technical Knowledge data), in which information is provided on the technical-constructive and material characteristics of each element (vertical and horizontal closures) of the building system;

S4. Legislative references (Section_Ref.Legislation), in which the binding information of the individual architectural assets is reported;

S5. Architectural elements (Section_Archit.Emerg), reports the main historical-architectural features of particular cultural and identity value;

S6. Survey status (Section_Cond.Survey), this section reports the qualitative conservative level of the buildings and urban elements, for which a visual survey of the state of degradation can be carried out..

S7. Conservative status (Section_Qualification_decay), concerning the second in-depth quantitative analysis of the buildings. In detail, the section is articulated by analyzing the main surface alterations of: natural and artificial stone materials (stone, brick), and cement conglomerates of architectural artefacts, as well as related to geometric parameters.

For this purpose, the informative and relational database is structured on PostgreSQL, with the PostGIS extension, using the pgAdmin interface.

Due to the multidisciplinary classes of data - caused by various application fields involved in the process (historical, architectural, diagnostic)- and their heterogeneity (drawings, images, documents), all the data have to be collected and properly encoded using alphanumeric values. In detail, the r-DB is linked to the GiSystem and establishes correlations for all the information according to detailed relations. Starting from the unique ID code assigned to each digitalized virtual model, the database is structured following the interconnections (n to many) for all the data.

Therefore, all data are linked to the associated architectural entity (vector polygon) in GiSystem (ph 2.1), as well as in VrModel by a specific hotspot (ph 2.3).

ph 2.3 – Creation of the Virtual Model (VrModel) represents the digitalisation step of urban historic district (Sph_joining). Specifically, VrModels are structured as Virtual Tours, based on spherical images, properly related among them and to specific levels of information. These are useful for the creation of real-based digital copies about architectures and urban entities and their technical enhancement according to the required level of knowledge involved in the recovery process. The VrModel is a unique digital model constituted in the Virtual Environment (VE) and enhanced with different levels of information (Figure 23). In detail, VE is the digital and visible model of the architecture resulting from the structured organisation of the collected spherical panoramas in ph 1.3 according to their distribution planning. In addition, the VMs are linked to a relational Database (r-DB) to store and codify the contents, according to the levels of information and a proper relational structure to support the second level of conservation analysis (Ph_4). In detail, in each virtual environment (Shp_RGB) specific Hotspots are located in correspondence with the individual buildings and/or urban entities, named according to a unique ID of them, which correlates the VrModel to the sections of the r-DB. In fact, the VrModel and r-DB are designed as a tool to support the technical user, organizing the information collected in a structured manner in compliance with ph 1.2.

Consequently, this systems (GiSystem, r-DB and VrModel) are prepared for the subsequent phase (Ph_3) of historical heritage recognition through Web-based integration in a single platform accessible from a web browser (Figure 23). The main system is made up of the WebGiSystem which contains the WebVrModel within it. Finally, the WebGiSystem system is made accessible via the web via Geo-server and related Web-Map-Client, both connected to the relevant web-server.

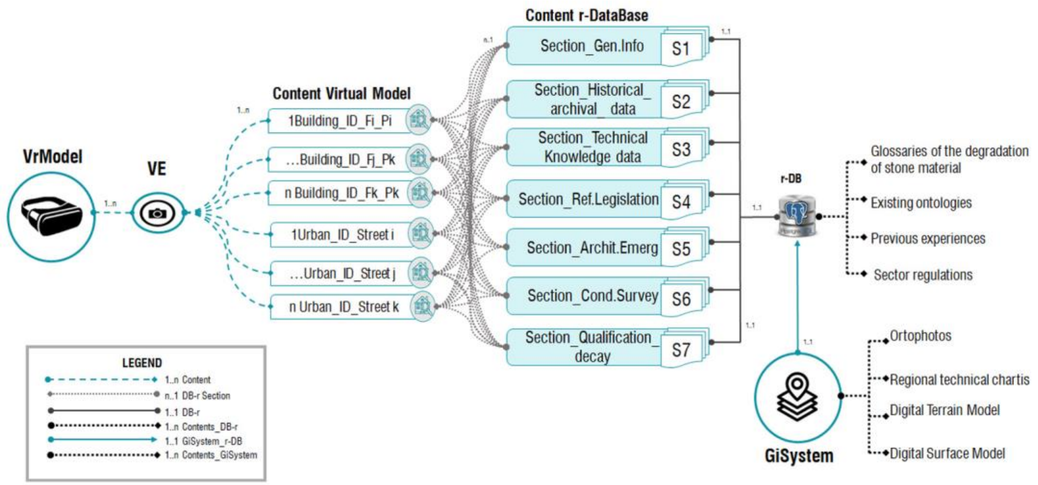

Figure 23 - Conceptual structure for connecting the VR Model with the GiSystem through the r-DB

5.2.3.3. *Qualitative surveys in situ and/or on-desk*

Phase 3 consists of the qualitative analysis of the urban and built environment of the historic district, by technical expert users (professional technicians). The operative process may vary considering the survey type: a) in situ using portable devices, i.e., tablets or b) remotely using on desk applications. Therefore, the implementation of the information system takes place: i) in-situ, where the expert user has the possibility of entering the data directly into the r-DB; or ii) on-desk, in which case the user has the possibility of implementing the data through a remote visual inspection using the Web-GiSystem/VrModel (Figure 24).

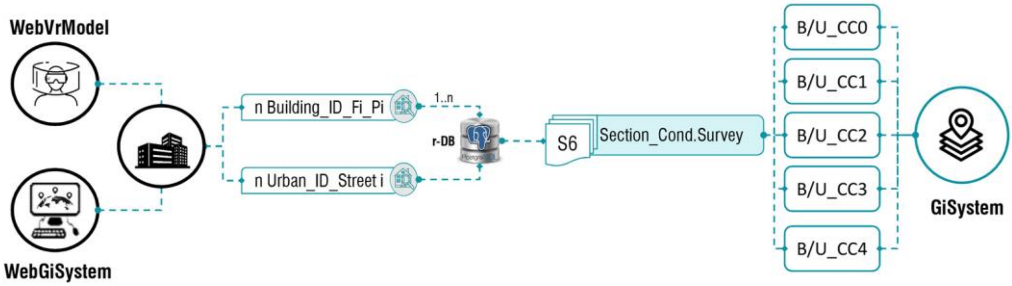

Figure 24 - Conceptual structure for implementing the data in r-DB and GiSystem via web

5.2.3.4. *Quantitative analysis of the state of preservation on a building scale*

Phase 4 According to the rule of T-DSS (§5.2.2), only for buildings with a low condition class, qualitatively assessed by the technical expert who carried out the in situ/on desk survey (Phase 3), is a second level of analysis required.

In detail, two sub-phases are required:

ph 4.1 – Image-based survey, comprising the Close Range Photogrammetry acquisition, based on SfM (Structure from Motion) procedures, in order to obtain RGB point clouds and, eventually, texturized polygonal meshes and ortophotos.

The elaboration of the RGBCloud has resulted from a preliminary analysis of the fabrics (ph 1.1) useful for the definition of the type of survey (aerial and/or terrestrial) and the planning of the photogrammetric acquisition. Consequently, the images acquired on site were pre-processed, using photo editing software in order to decrease and/or eliminate the presence of noise resulting from the low environmental conditions during the frame acquisition (i.e., low light).

ph 4.2 Thematic mapping for conservation assessment. Aiming at the qualification of the main building components (walls, roofs and windows), this sub-phase points out the identification and selection of classes of decay and the required qualitative and quantitative indicators (Table 9). Specifically, the decays (B_Td) require to be detailed according to the UNI 11182:2006, and then Seriousness, Intensity and Extension (B_S, B_In, B_Ex) can be filled for each type of decay (Figure 25). Each digitalized architecture is imported into the GIS environment and codified with its ID in order to determine a unique code for its identification. The levels of details about required specific indicators are associated to each architectural entity (vector polygon). This information is included in the GiSystem and correlated r-DB as sub-properties of the identified ID and properly coded.

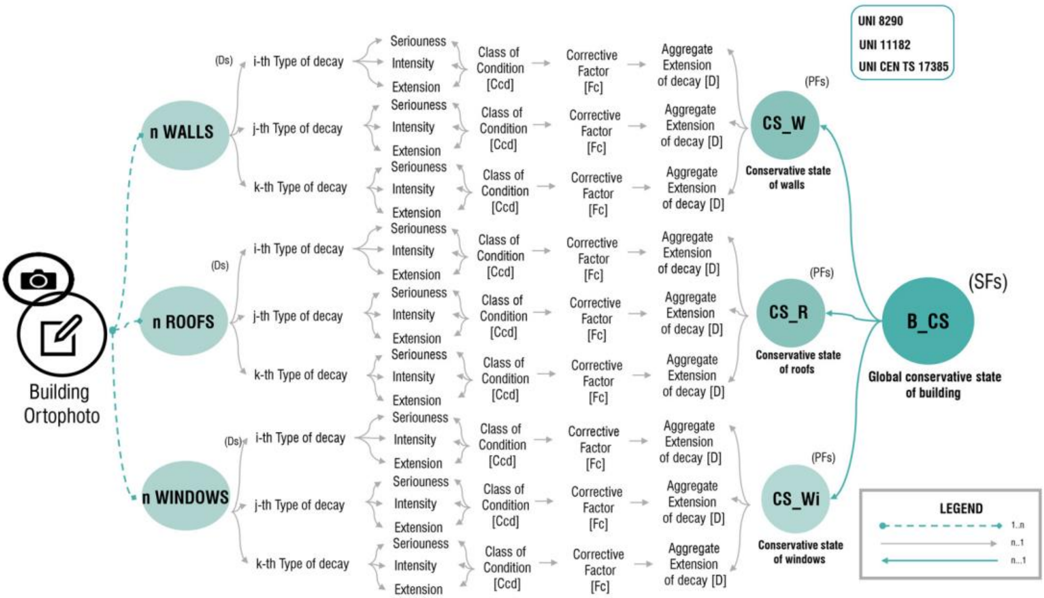

Figure 25 - Conceptual structure of the evaluation of the conservative state of building components according to the T-DSS rules

5.2.3.5. Implementation of the parametric model according to the CityGML standard

Phase 5 focuses on the creation of the urban parametric model according to the CityGML standard. For this, three sub-phases are required:

ph 5.1 Setting up of the CityGML-based Model. This phase concerns in the development of the parametric model starting from the geometric and geolocated data included in the shape file (ph 2.1), general semantic information organized in the ph.2.2 and features derived from the mapping processing in ph 4.3.

All the collected data in GiSystem (.shp file) and r-DB, concerning geometric and sematic features, are translated according to the CityGML standard (.gml file). The process follows the specific workflow ETL in FME in order to create the system of (vertical) relations between single city objects to attributes, as well as (horizontal) relations among them (Figure 26). In detail, the specific workbenches of the FME visual platform used for the aim are described as follows:

- Importing and reading the .shp files for the model of the built and urban environment, in which the attributes were identified as catalogued in the GIS environment, and the raster file for the digital terrain model (*transformer: Read*);
- Processing of the digital terrain model (TIN), through the transformation of the raster data into an irregular triangular mesh, consequently transformed according to the CityGML standard, useful for the subsequent superimposition of subsequent geometric-thematic models (*transformer: TINGenerator*);
- Creation of the geometric model (LOD1), of the built and urban environment by draping the previously elaborated ground surface and extruding the footprint area of buildings, streets, squares and open spaces according to their heights. The realisation of the geometric model in LOD1 was carried out by extruding the collected heights included in the relative DSM, as well as the projections of the floors of each building, starting from the technical information reported in the starting .shp file (*transformer: SurfaceDraper and Extruder*);
- Codification of buildings according to the Cadastral information, and of streets, squares and open spaces, according to toponymic data.

All the buildings and urban entity are associated to a specific alphanumeric ID that includes data according to specific codes, with the aim of supporting the final search activities and visualisation of objects and data (transformer: *UUIDGenerator and String Concatenator*);

- Implementation of the T-DSS, through the structuring of logical relationships with respect to the outlined rules. Here, the logical-relational structure is defined according to the T-DSS (§5.2.2). So, specific classes of attributes are set up according to the standard in order to introduce primary and secondary factors related to the conservation levels of sub-components and buildings (Table 11, U_CS, B_CSW, B_CSR, B_CSWi, B_CS), as well as the secondary factors associated to the classes and priority of intervention of each building (Table 11, U_IC, U_IPr, B_IC, B_Ipr). Secondarily, the generation of CityGML attributes, where all the .shp features are translated in the CityGML standard, through the creation of specific CityGML attributes into which the results of the T-DSS flow, with respect to the implemented data (*script: AttributeCreator*);
- Identification of relations between geometric object (building, street, square and open space) and attributes, aimed at defining the type and role of the geometry (CityGML LOD Name: Lod1MultiSurface; FeatureRole: cityObjectMember) (*transformer: CityGMLGeometrySetter*);
- Creation of CityGML model and concordance with thematic classes; here, all the data are related to the features of "*Building*" and "*Transportation*" classes, when already structured with the CityGML standard, or to the "*_genericAttribute*" and "*ExternalReferences*" as a conclusive semantic enrichment. Specifically, an ExternalReference defines a hyperlink from a _CityObject to a corresponding object in another information system. Each of them includes the name of the external information system, represented by a URI, and the reference of the external object, given either by a string or by a URI.

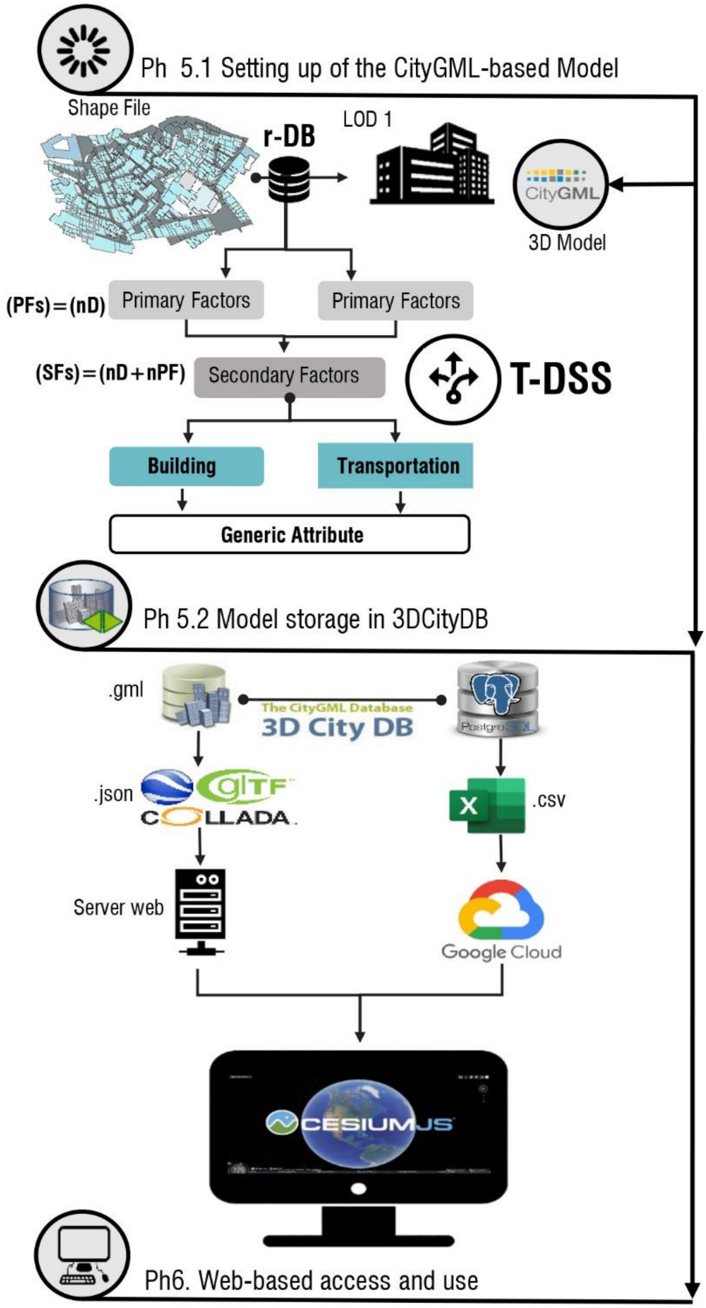

Figure 26 - Conceptual structure relating to the phases and tools for the development of the parametric model CityGml-based

During this phase, the outcomes of scientific and technical expertise resulting from the district analysis come together to address three key aspects:

i) The effective management of semantic data originating from external calculations is a crucial component;
ii) A meticulous examination of building properties, encompassing site surveys and external measurements, is conducted with a critical perspective;
iii) Integration of the legal framework pertaining to the preservation of the historic aggregate is a vital consideration.

Furthermore, geo-topological data, which includes building and transportation classes and cadastral identification, is introduced. This is complemented by functional data such as ownership and use, all organized systematically to address the administrative dimension of knowledge.

Simultaneously, both admissible intervention strategies and their execution priorities are stored in the 3DDatabase, automatically derived from the implemented data, are stored in the database. These serve as attributes of specific fields for the actual buildings, providing valuable support for professionals and technical experties involved in the process.

ph 5.2 Model storage in 3DCityDB - The parametric model is incorporated into the 3DCityDatabase for the archival and administration of CityGML data (Figure 26). The CityGML-based Model is imported in the 3DCityBD using the relational database based in PostgreSQL/PostGIS that can be readable by means of a specific graphical interface (PgAdmin). The process requires a medium-high level of IT support (expertise) due to the programming procedure. In this phase the database is also prepared for the management of data between final users (administrative and technical). In that sense, .csv files can be created from the database to be shared with different levels of accessibility in the Google Cloud Platform by means of Google sheets API. This facilitates the ongoing management of the parametric model, enabling different users within the sector to interact with it over time, thanks to the implementation of suitable usage coding. Additionally, the system allows for the export of semantic-thematic and geometric-topological data, which can be visualized in a web environment. This process involves reworking and refining the data to ensure its optimal presentation and accessibility in the online context.

5.2.3.6. Elaboration of the model for technical use

Phase 6 involves the use of the CityGMLModel and the VrModel through a web-based approach that allows them to be imported into a platform designed to host the two models (Figure 26). This phase concerns the visualisation and interaction of the three-dimensional CityGML-based model through the 3DCityDB Web-Map-Client.

Here, all the final users may interact with the model, and read all the semantic information at the fabric scale, by means of an easy web browser. Specifically, the phase is conceived to allow the ease access of class and priority of interventions at the district scale by all the final users involved in the practical activities of building recovery. Particularly, the model is queryable for cadastral information of buildings and all the related semantic data are shown in the specific pop-windows.

The importing process for the visualisation by the authorized users requires both .json file and data, organized in sheets in the previous phase. The use of Google sheets allows the visualisation of thematic data, while only administrative ones are authorized to modify and manage the contents.

At the same time, a connection to the WebVrModel is allowed from the pop-windows, which increases the level of perception of the investigated environment, where in this case the hotspots of the virtual model only allow the visualisation of the data.

PART 3 APPLICATION AND VALIDATION TO PILOT CASES

6. VALIDATION OF THE CODE TO PILOT CASES

This section of the thesis discusses the implementation and validation of a digital code of practice developed for the preservation and management of existing architectural heritage. This involves leveraging rapid methodologies rooted in virtual reality and utilizing a multi-scale, multidisciplinary digital information system for thorough analysis, modeling, and cataloging of selected investigation areas.

Specifically, the validation of the digital code was undertaken on three specific pilot cases, addressing essential challenges associated with the physical and regulatory obsolescence of buildings. These challenges encompass aspects such as the quantity and dimensions of rooms, inadequacy of services and urbanisation systems, and the absence of maintenance or rehabilitation interventions for activities within the buildings.

6.1. CASE 1 – Historic District of Carovigno, Brindisi, Italia

This paragraph outlines the qualification of the built environment in Historic Districts according to the CityGML standard, appropriately prepared in accordance with phases 1-2-5 of the digital code of practice.

The Figure 27 shows the 3D Semantical Historic District Systematic Code phases validated and applied to the Historic Centre of Carovigno.

6.1.1. Historical information

Carovigno is a town in the Apulian region, situated 8 km away from the Adriatic coast and 28 km from Brindisi (Figure 28). Its ancient core has its roots in Messapic origins, subsequently expanded and fortified during the Middle Ages. Today, it is encircled by ancient defensive walls and four prominent towers. The significance of Carovigno's old core for the study application is linked to inherent challenges in terms of physical and normative obsolescence of buildings. These challenges encompass issues such as the number and size of rooms, the inadequacy of services and urbanisation systems, unchecked alterations of the built-up area, and the scarcity of activities for maintenance and recovery interventions. These factors have presented external challenges for local public bodies in handling abandoned buildings and families facing a high unemployment rate.

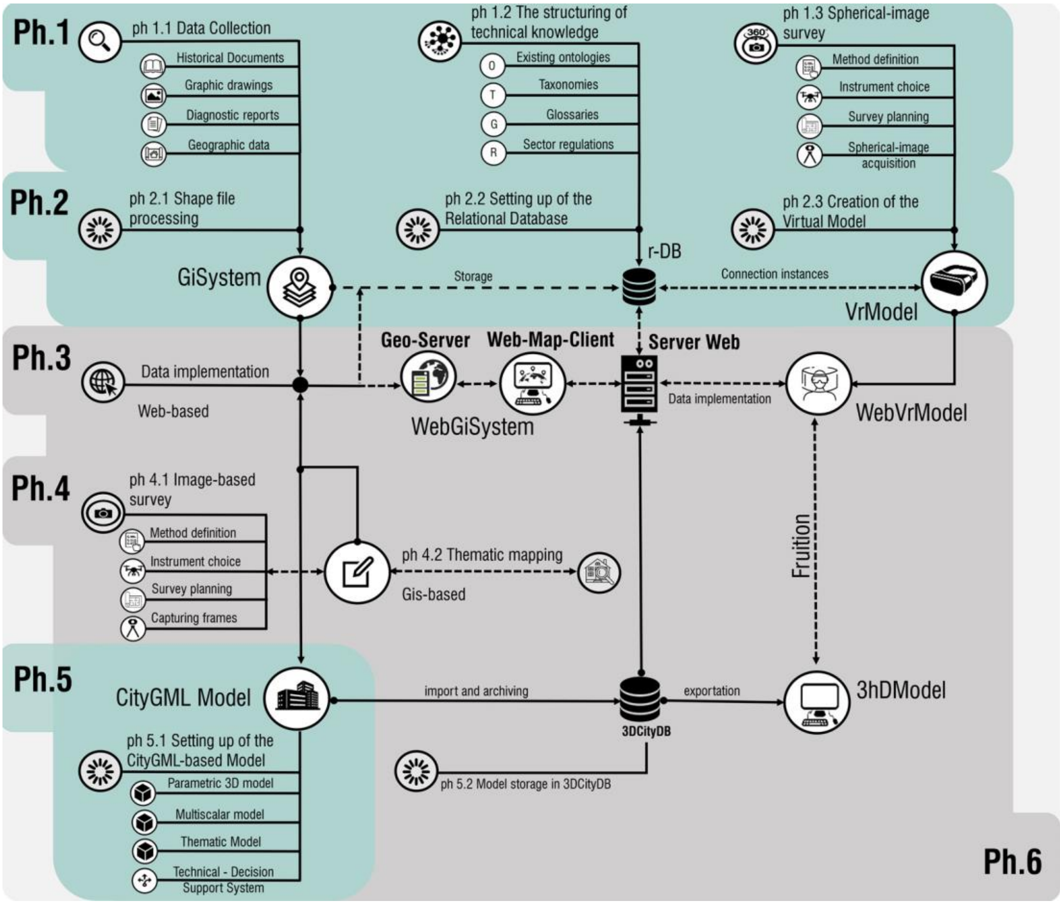

Figure 27 - Phases of the digital code of practice applied and validated for the pilot case of the Historic Centre of Carovigno. In light blue the phases applied

Conversely, these features have prompted various urban regeneration activities aimed at enhancing and adjusting existing urbanisation services. However, these efforts have resulted in thematic archival and documentary analyses that are not adequately consolidated in a detailed Recovery Plan. This has given rise to a complex system of historical and technical information, encompassing original characteristics, uncontrolled and controlled transformations, and the current state of structures, necessitating a comprehensive reorganisation. The establishment of a CityGML-based 3D urban model provides an opportunity to bridge this gap. However, coherently to the3shD-SystematiCode, only the re-organisation of technical knowledge has been done. Moreover, the application highlights the interoperability between GIS-based informative systems (ph 2.1), usually open to technicians and public administration, and thus, the higher level of compatibility between not-structured knowledge and ontology-based models (ph 1.2).

Figure 28 - (Left to right) location of Carovigno (BR) in Italy, perimetration of the historic centre in the city land, Castle of Carovigno as part of ancient walls

6.1.2. Technical qualification of the Historic District of Carovigno

The technical cognitive process of the historic center of Carovigno has specifically concentrated on its most ancient area (Figure 29). The investigative activities commenced with the studies conducted by the Municipal Authority. Therefore, the thorough analysis enables the identification of all necessary characteristics for a comprehensive understanding of the ancient core from a technical perspective.

The primary feature defining the Old Core on a broader scale is the curvilinear layout of pathways, thoughtfully arranged in narrow passages. This distinctive characteristic holds significant historical and cultural relevance, stemming from both defensive requirements and the unique topography of the Carovigno region. It is essential to consider this aspect in conjunction with the use of large calcarenitic blocks for paving. Nevertheless, over time, this original character has been largely modified, particularly in most pathways, which have been substituted with asphalt. The most notable instances of this transformation can be observed in the vicinity of the Castle of Carovigno and various churches, serving as prominent examples of architectural alterations over time. Regarding the initial urban development, the historic core is furnished with electrical, sewage, and water systems.

However, certain areas lack gas supplies, leading to increased reliance on electricity for heating and cooking. Nevertheless, the electrical and sewage pipelines seem insufficient for their intended purposes and external conditions, resulting in numerous disruptions in functionality.

Figure 29 - Significant parts of the historical buildings in the Historic Centre of Carovigno

In terms of the morpho-typology of architectures, the ancient core of Carovigno is characterised by four primary building types (Tn) (Figure 30):

T1. "Terraced House," with both single-cell (a) and double-cell (b) configurations exhibiting vertical and horizontal dwelling development, represents the most prevalent types. The distinction lies in the historical evolution, involving the amalgamation of single-cell dwellings where functions are vertically distributed through a private stair. In the case of merged terraced houses, residential uses evolve horizontally, and stairs connect different private residences. The single cell (a), featuring a single façade, comprises 1-3 rooms vertically connected. Windows are present only in the living area, while bedrooms lack openings, leading to ventilation challenges. In the double-cell (b), the living room and bedrooms are oriented towards the streets, addressing hygienic deficiencies.

T2. "In-line House" is a multi-family building type distinguished by an articulated plan morphology and a substantial extension of living space on the first floor, featuring two or more balconies or overlooks. The ground floor typically served as storage space, while vertical distribution is facilitated by a private stair.

T3. "Palace" type shares similar dimensions and distribution characteristics with Type 2 but also incorporates significant architectural and decorative elements. This morpho-type is the outcome of more recent architectural developments, particularly from the early 1900s.

T4. "Corner or End Houses" is a building that lacks consistent features but represents a variation of previous types designed to address the corners of district blocks.

The predominant constructional and material features include the use of masonry and vaults made from *Leccese* tuff, serving as the primary technological elements. The incorporation of small rooms facilitated the creation of sturdy floors, designed with barrel, cloister, and star-shaped vaults. The utilisation of local materials and the distinctive *Leccese* tuff represent intrinsic values of the region. The masonry may be composed or in a single layer, primarily constructed with unplastered *Leccese* tuff.

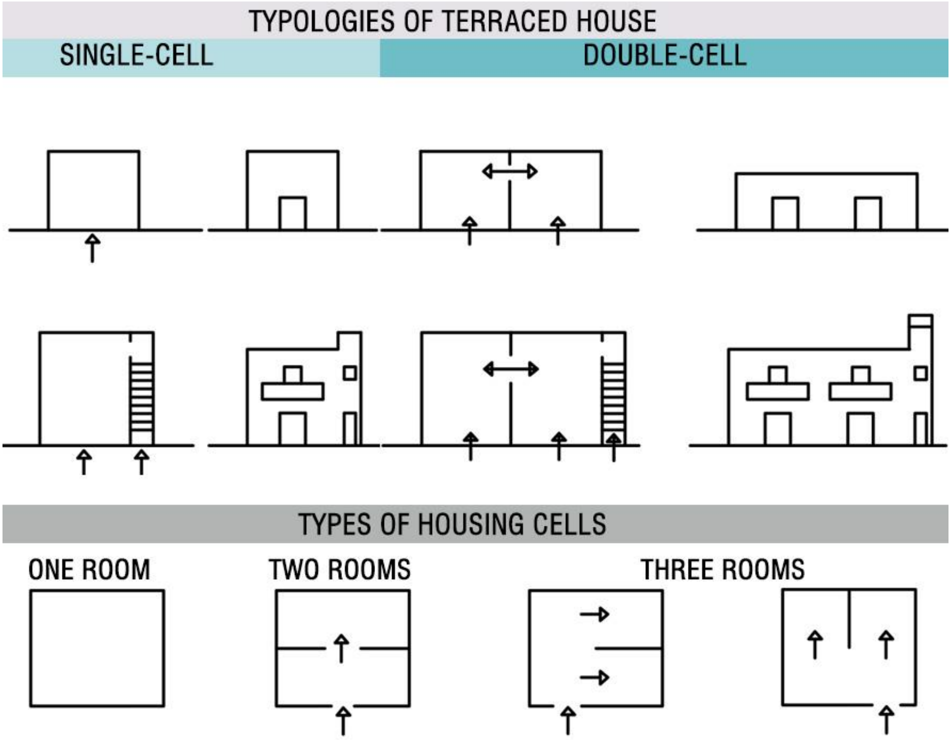

Figure 30 - Details of plan distribution of terraced house, for single and double cells (image created starting from details available in the general land management regulation of Carovigno city)

Furthermore, the state of preservation in this area holds significant importance. The combination of functional and normative obsolescence has led to a gradual abandonment of dwellings, resulting in a present-day high level of decay, evident through vegetation growth, biological colonisation, and crust formation.

Additionally, the absence of a protective layer of tuff and the presence of thrust roofs have led to static deficiencies, manifesting as cracks, mortar deterioration, and damp issues.

6.1.3. The CityGML Model setting-up

In the initial phase, a meticulous collection and analysis of theoretical notions, practical experiences, and previous scientific and regulatory studies of the historical area of Carovigno were undertaken (ph 1.1). The technical knowledge acquired in this phase facilitated the codification of the collected data according to the ontological structure (ph 1.2). The conceptualisation of simple parameters (Descriptors), as outlined in Table 4, Table 5, Table 6 and Table 7, enabled the structured qualification of the environment based on a preliminary evaluation level.

In detail, the creation of the CityGML Model for the case study involved two main steps (Ph. 2 and 5) based on the nature of the data, initially processed in a GIS environment (ph 2.1). The geometric level, encompassing ground elevation, building height, and the extension of building and urban elements, was resolved using the Digital Terrain Model (DTM) and the Regional Technical Map available on the SIT of the Puglia Region web site (ph 1.1) (Figure 31).

Following this, as the first stage of digital systematization of the data, the multidisciplinary and heterogeneous alphanumeric information was organized in the relational database (r-DB) (ph 2.2), which was preliminarily prepared according to the defined conceptual structure (ph 1.2) and linked to georeferenced geometric features (ph 2.1) (Figure 32). Consequently, all the described information was implemented in the GiSystem by means of a .shp file and it constitutes the main system of features to transform in the CityGML attribute.

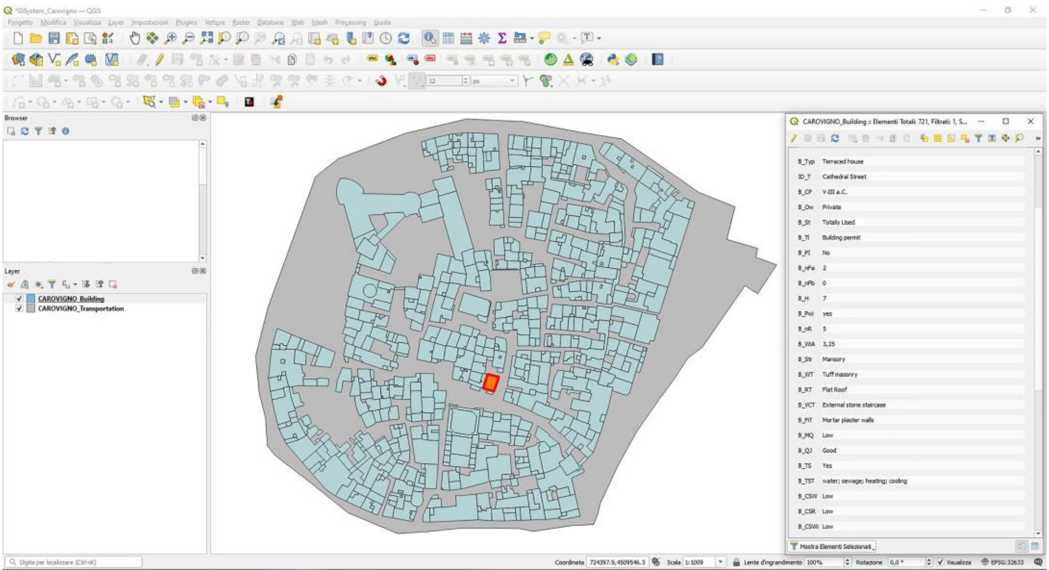

Figure 31 - GiSystem of the Historic Centre of Carovigno. On the right the information window showing the descriptors implemented in the r-DB for the selected building.

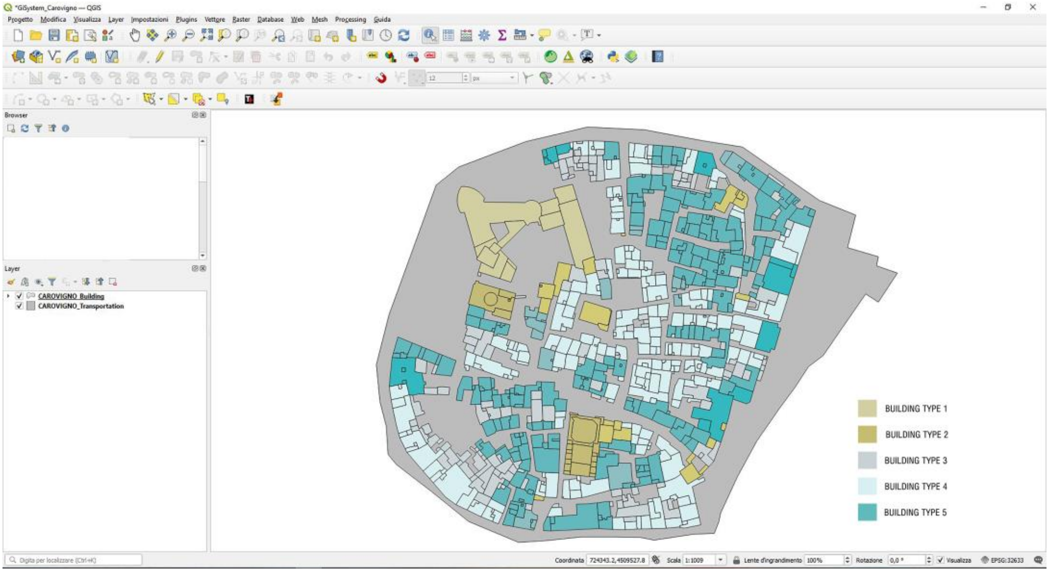

Figure 32 - GiSystem of the Historic Centre of Carovigno showing recurring architectural types

This preparation was done for the subsequent translation of the data in accordance with the CityGML standard, utilizing the Safe FME visual programming platform (ph 5.1). In this context, i) geometric data was translated into a three-dimensional digital model as a system of entities (building and urban elements) in LOD 1, ii) semantic and geometric data were translated following the CityGML standard, and iii) logical functions were implemented for the automatic processing of primary and derived factors, proving beneficial for the subsequent qualitative and quantitative analysis phase of the historic building.

In the parametrization process, each entity is distinctly identified through an alphanumeric code, utilizing cadastral data for architectural entities and toponymic information for urban elements. This facilitated the formulation of specific queries and their utilisation in the digital model. At the semantic-thematic level, all gathered information underwent filtering for attribute creation, adhering to the CityGML standard. Special attention was given to establishing relationships between each datatype entity and specific attributes, as well as among attributes.

To achieve this, close observation of the properties of source information was conducted, considering both the intrinsic nature of the data and the vertical relationships among subject classes, along with horizontal relationships among individual attributes of the specific CityGML class. As a result, architectural entities populated the "*Building*" class, and urban elements were assigned to the "Transportation" class. Additional attributes were translated based on the CityGML datatype, using the Generic Attribute class.

Ultimately, the geometric and thematic-semantic model was transformed into the CityGML standard, serving as the semantic digital model for the ancient core of Carovigno. All the semantic and geometric information of the model was imported into the open-source software tool FZKViewer, providing the ability to query the model at both geometric and semantic levels, focusing on specific attributes and/or entities (Figure 33).

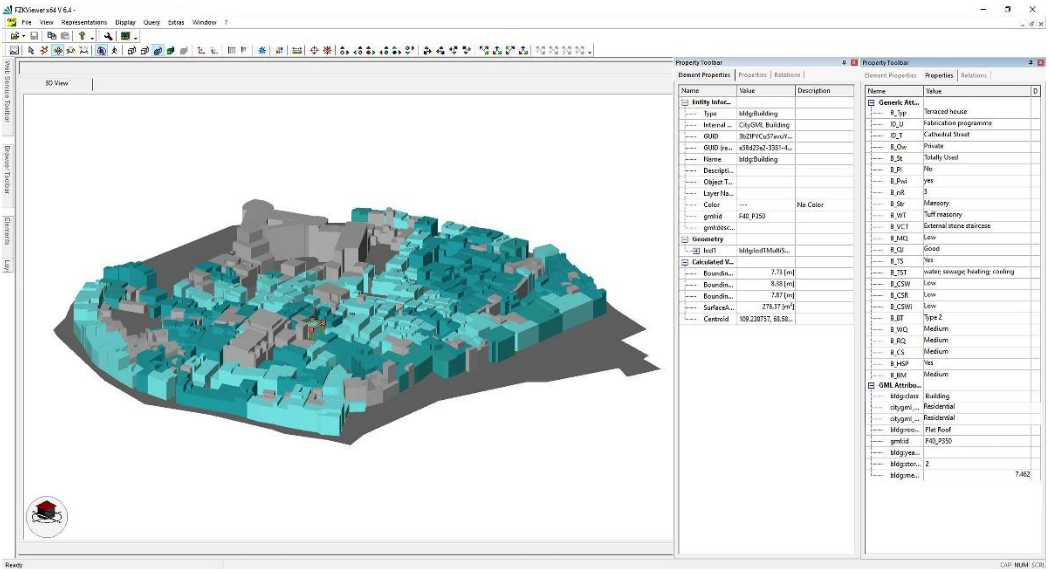

Figure 33 - Visualisation in the FZKViewer of architectural entities classified for morpho-typologies. On the right, semantic details about the queried entity

This development of the semantic digital model not only aids users involved in the preservation process but also facilitates the analysis of the historic built environment. The organisation of technical knowledge into coordinated parameters and factors within a structured database, along with established relations, supports the elaboration of subsequent conservation strategies and enables the appropriate reuse of buildings. This can include enhancing existing functions or introducing new social functions such as cultural, managerial, or commercial activities.

6.2. CASE 2 – El Cabanyal, Valencia, Spagna

In line with the research aim, specific phases of the 3shD-Systematic Code have been implemented in a historical area of Valencia's El Cabanyal neighbourhood (Spain) (Figure 34).

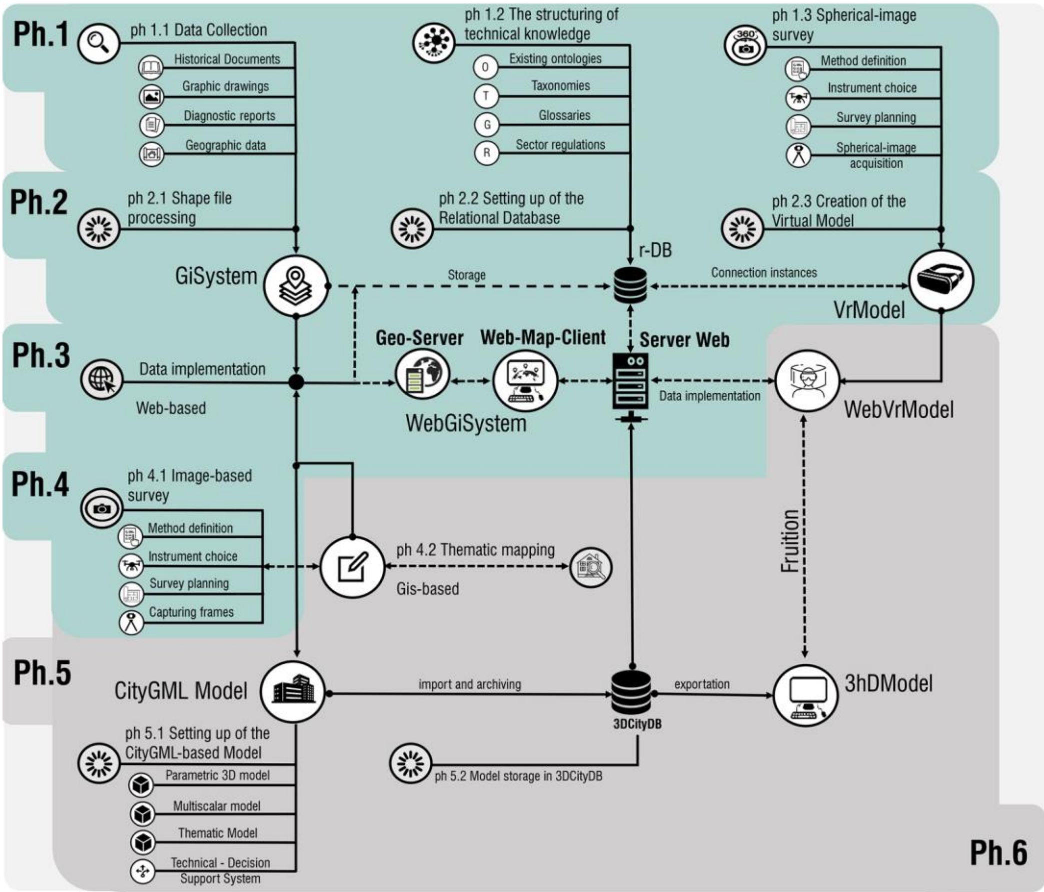

Figure 34 - Phases of the digital code of practice applied and validated for the pilot case of the historic neighbourhood of El Cabanyal (Spain). In light blue the phases applied

However, given the large amount of data required to create the database and results, it was considered useful to apply Phases 1 -2 -3 of the digital code of practice to a specific study area to validate the acquisition of technical knowledge information remotely using Virtual Reality techniques.

The selection of the study area was specifically determined through a preliminary documentary-archival knowledge analysis. This analysis facilitated the identification of a historical area encompassed by the Cabanyal-Canyamelar Special Plan (Pla Especial del Cabanyal-Canyamelar - PEC), falling under the protection regime of the Property of Cultural Interest (BIC-CH Original core of the El Cabanyal expansion) (Figure 35), and part of the protected historic complex Grao-Cabanyal according to current planning (Figure 36). In this area, the majority of buildings (i) date back to pre-1936 (Figure 37) as their construction period, (ii) were in a state of low preservation in 2013 (Figure 38), and (iii) are privately owned (Figure 39).

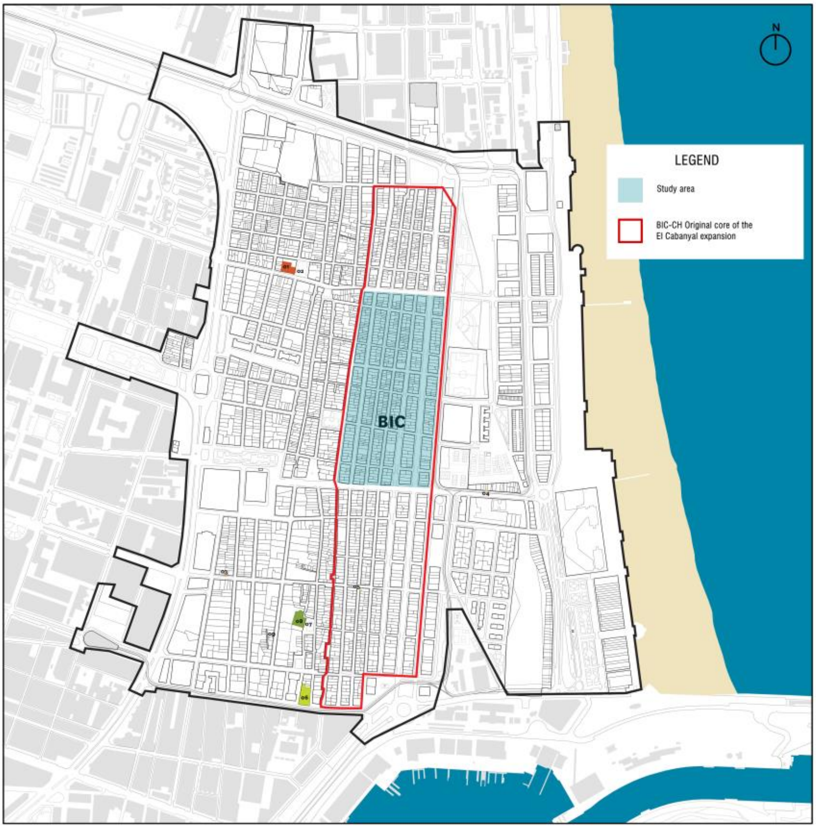

Figure 35 - The technical document of the the Cabanyal-Canyamelar Special Plan plan showing the perimeter of the BIC-CH core of the El Cabanyal expansion and the study area (image created starting from details available on the Valencia City Council website)

Figure 36 - The technical document of the the Cabanyal-Canyamelar Special Plan showing the area of the Protected Historical Complex Grao-Cabanyal and the study area (image created starting from details available on the Valencia City Council website)

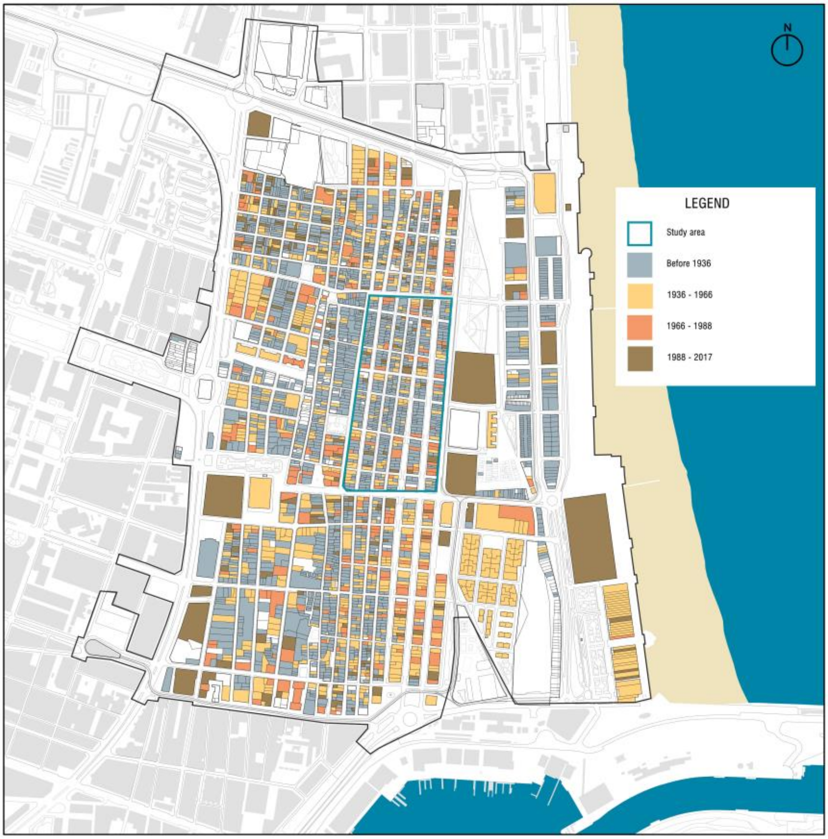

Figure 37 - The technical document of the the Cabanyal-Canyamelar Special Plan showing the construction period of the buildings and the study area (image created starting from details available on the Valencia City Council website)

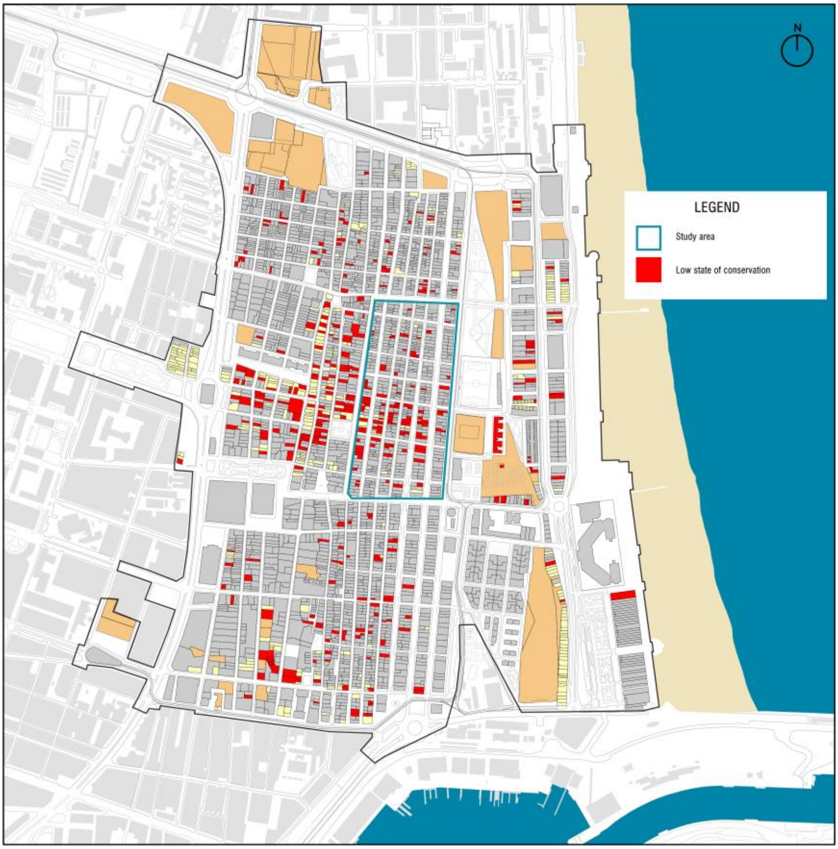

Figure 38 - The technical document of the the Cabanyal-Canyamelar Special Plan plan highlights the low state of conservation of the buildings and the study area (image created starting from details available on the Valencia City Council website)

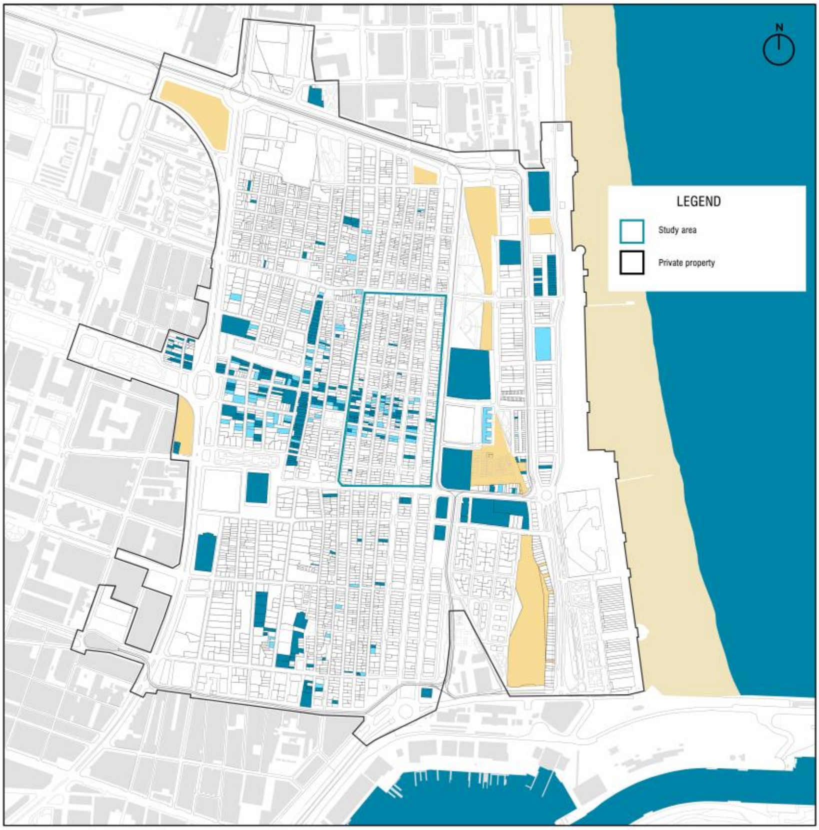

Figure 39 - The technical document of the the Cabanyal-Canyamelar Special Plan plan highlights the ownership of buildings and the study area (image created starting from details available on the Valencia City Council website)

6.2.1. Historical background

El Cabanyal is a maritime district of Valencia (Spain), with a history dating back to the 13th century, coinciding with the construction of Vila Nova Maris, now known as El Grau. During that period, a sandy strip north of the city walls extended, separating the land from the sea. In the 18th century, inhabitants began to settle informally on these lands, which were originally part of the Real Patrimonio.

The resulting village became primarily populated by fishermen residing in *barracas*. Towards the end of the 18th century, informal settlements were consolidated, giving shape to the El Cabanyal district as a distinctive maritime village.

Throughout the 19th century, El Cabanyal experienced continued growth and development, evolving into a significant centre for fishermen and the local community. This expansion faced an initial obstacle with the construction of the railway network. The barriers to the east of the historic quarter initially impeded urban growth, restricting the expansion of the urban grid. However, once these barriers were overcome, thanks to a new retreat of the coastline, a second noteworthy expansion of the urban fabric unfolded (Terol, 2014).

Simultaneously, increasing demographic pressure served as a catalyst for urban development, prompting a redefinition of the urban grid. This marked the beginning of a phase of suburban colonisation to the west of the historic district. The urban grid expanded its boundaries, initially progressing westwards and subsequently reaching, and even surpassing, the railway routes to Castellón.

This shift in the direction of growth has not only addressed demographic needs but has also played a vital role in transforming and enhancing the overall urban structure of the city. Moreover, this dynamic adaptation of the urban grid not only surmounted initial barriers but also showcased resilience and the ability to evolve in response to changing community needs and urban dynamics. The expansion beyond the railway tracks towards Castellón signifies a significant milestone in the city's growth.

Analysing the Figure 40, the evolution of the urban texture of the El Cabanyal neighbourhood is clearly visible. The distinctive grid, derived from the previous alignments of the old barracas, extends from the beach to the railway tracks to

Castellón. However, currently the continuity of the urban plot is hindered and interrupted in some areas. The peculiar reticular urban texture derives from the alignments of the old barracas that were later transformed into the current social housing.

The Geometrical Plan of 1796 is an technical document that offers a detailed analysis of the state of construction in the original core of Valencia's historic neighbourhood El Cabanyal. This map reflects the urban configuration of the time with great accuracy.

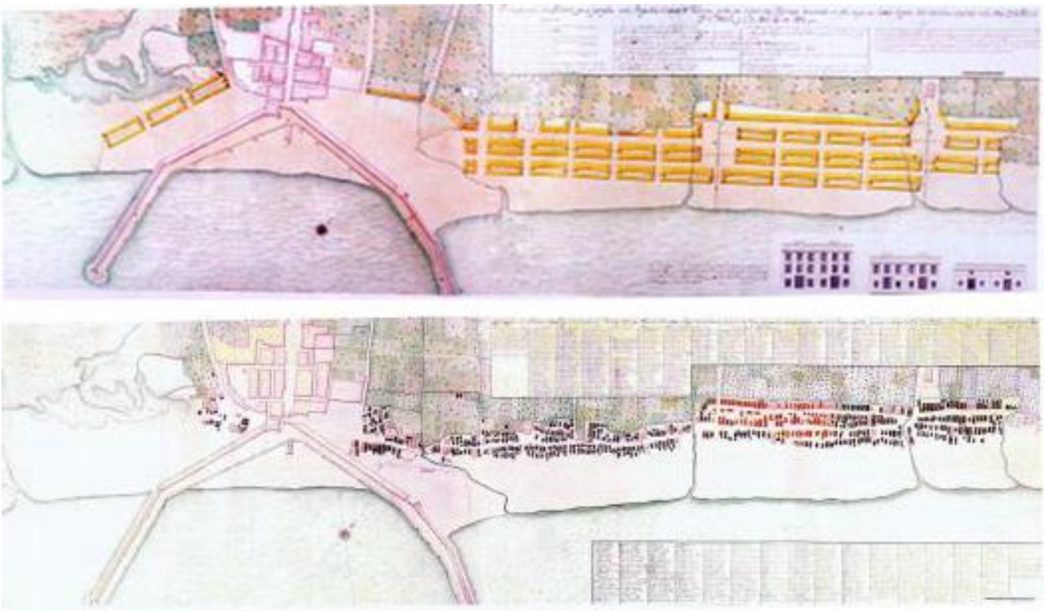

Figure 40 - The Geometrical Plan of 1796 (image created starting from details available on the Valencia City Council website)

The plan (Figure 40) provides a detailed insight into the composition of the dwellings and the early stages of the architectural transformation that defined the neighbourhood's unique character throughout its history. In the part of the Cañamelar, identified as the Cañamelar lot, the census showed the presence of 180 barracas and 22 houses. In the sector known as del Cabañal, there were 181 barracas and 24 houses, while in the Cavo de Francia area, in the lot of the same name, there were 79 barracas and 5 houses. In total, the Geometric Plan recorded 491 buildings, of which only 51 were considered constructions, such as houses.

The gradual process of transforming barracas into houses gained significant momentum after the fire of 1796, during which the reconstruction of barracas was prohibited. This prohibition marked a pivotal moment in the district's history, accelerating the transition from the temporary and lightweight constructions of the barracas to more solid and durable houses. It represented the initial step towards the existing architectural structure (Figure 41).

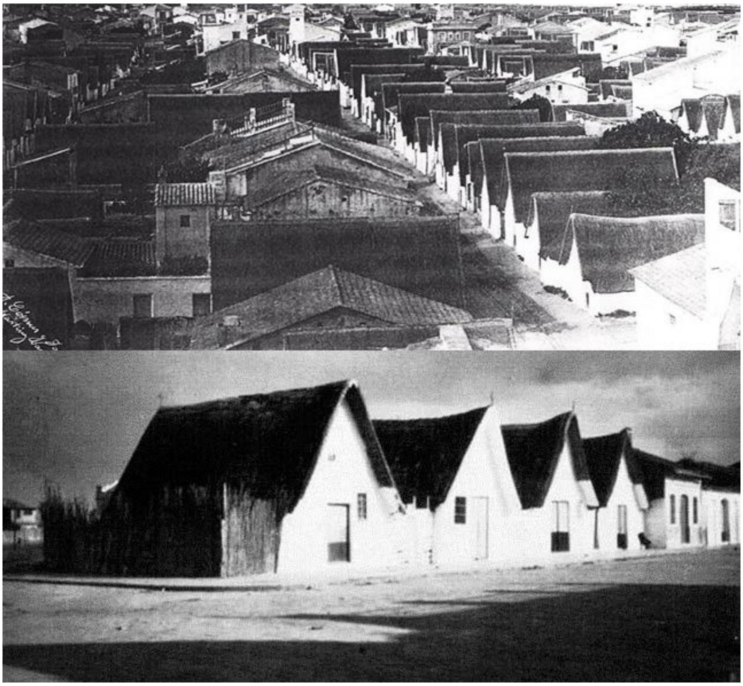

Figure 41 - Historical photo of the neighbourhood of Valencia showing the historical land use and building type of the Barracas. Source (Gosálvez Gómez, 1998)

In the years since the 20th century, the district has encountered numerous challenges, primarily linked to urban development projects that jeopardised its historical character. The preservation of the neighbourhood and its traditions became a contentious issue, sparking protests and discussions regarding its cultural and architectural identity.

6.2.2. The Current qualification of the urban and built environment

The process of acquiring technical knowledge about the Historic District of El Cabanyal commenced with the investigations conducted by the Municipal Authority during the formulation of the urban regeneration plans for the historic area (*Plan Especial de Protección y Reforma Integral del Cabanyal-Canyamelar - PEPRI 2001 and the Plan Especial de Protección del Cabanyal-Canyamelar- PEC 2023*).

This process was enriched by previous studies conducted by researchers (Basset-Salom & Guardiola-Víllora, 2021; Kazimierczak & Wrona, 2019). Particular emphasis was placed on the analysis of the identified primeval area, thereby contributing to a deeper understanding of the historical and technical characteristics of the district. Consequently, an in-depth analysis of descriptors summarizes in Table 4, Table 5, Table 6, Table 7 and Table 8, such as architectural-constructive-material characteristics, morpho-typological features of the historic built environment, and the morphology of the urban space in the Historic District, was undertaken. The urban environment of the El Cabanyal district is structured around a system of freely accessible public spaces, originally designed with a primitive street layout adapted to the natural geography of the area. The distinct maritime character of the district is evident in the arrangement of the streets, which run parallel to the sea in a north-south direction. The urban layout facilitates optimal access to the dwellings, designed in a way that allows the façades to receive sunlight at specific times during the day, while the pavements benefit from periods of shade. These streets harmoniously integrate with the routes, promoting permeability between the city and the neighbourhood, and between the latter and the sea. The road layout has been strategically planned, incorporating crossings that create open spaces in the part nearest to the sea. This design facilitates convenient access to the beach, a crucial location for the local fishing industry and, during the summer, also for tourist use. West of the district, paths and roads lead towards the city centre. The priority in urban planning is devoted to fostering a connection with the sea. The symbiosis between the urban fabric and the natural environment, particularly the sea, is a distinctive element of the district. Indeed, the daily lives of El Cabanyal residents are closely intertwined with the sea, with the streets reflecting their connection to maritime activities, ranging from the fishing industry to the enjoyment of the beach during the summer months.

The built environment of the El Cabanyal district derives from its architectural-urban transformation. As shown in Figure 42, the neighbourhood was initially characterised by the typical profile of barracas, with alignments of fronts separated by private spaces known as *escalas*.

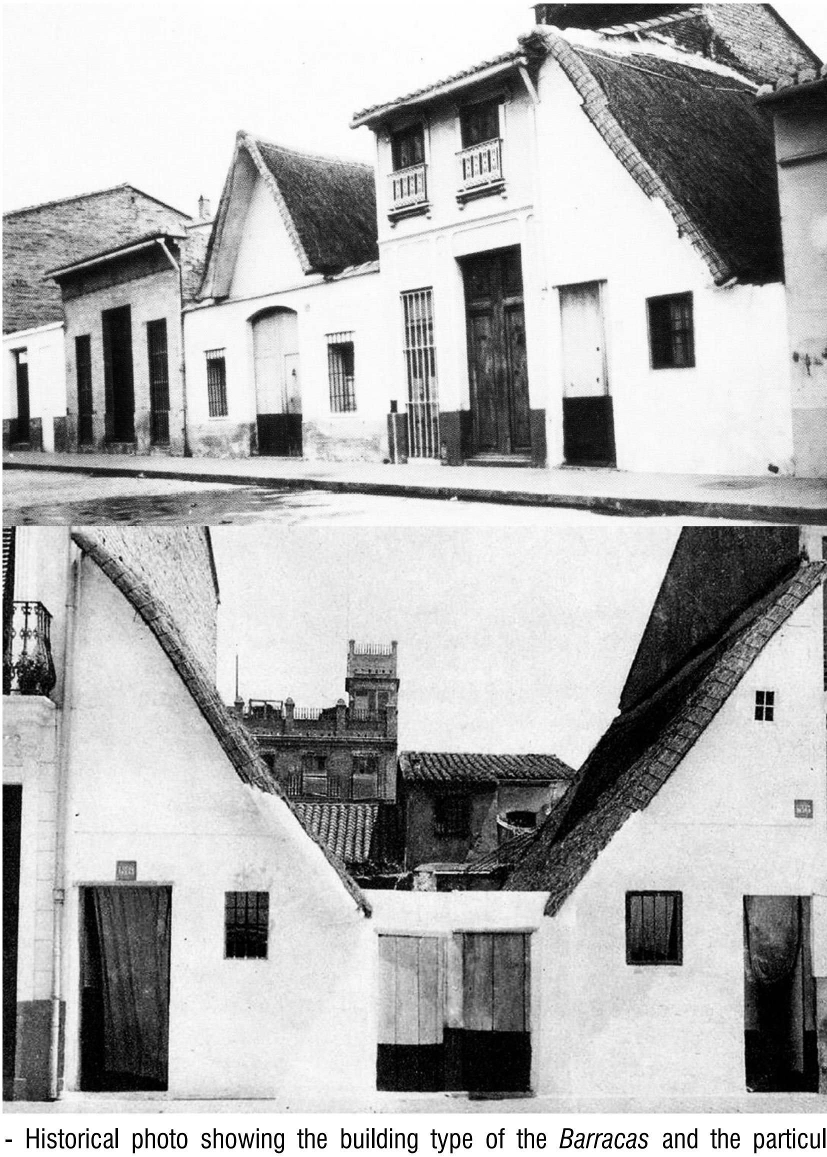

Figure 42 - Historical photo showing the building type of the *Barracas* and the particular building component of the *Escalas.* Source (Gosálvez Gómez, 1998)

However, after the fire of 1865, which led to the destruction of approximately 250 *barracas*, the municipal administration prohibited the construction of new barracas precisely due to their typological, constructive, and material characteristics, which conferred a high vulnerability to the risk of fire. This resulted in the replacement of wood with brick and thatch roofing with clay materials. On a morpho-typological level, the process of replacing barracks with masonry buildings represented a significant change in the urban layout of the historic neighborhood (Figure 43).

In detail, a *barracas* was built on an area of approximately 6.40 m x 10.50 m, within which the only sizes that could change were the width of the barrack front and/or the "*Escalas*". Currently, the most common building front widths are 6.40/7.08 m and 7.08/7.76 m. Thus, starting from the building type of the *barracas*, the typological process of buildings presents a series of evolutionary phases.

Figure 43 - Current urban façade of the El cabanyal neighbourhood

Initially, the basic type was the single-storey terraced house. It underwent duplication at both planimetric and elevation levels. As the process progressed, the single-family terraced house evolved into a multi-family terraced house, through the duplication of the base cell and the use of cell overlap in height. This evolution led to the creation of a house with two dwellings per floor. This diversity has resulted in a range of architectural styles and details that mirror individual preferences on one hand and the cultural influences of the construction period on the other (Figure 44).

Figure 44 - Significant parts of the historical buildings in the historic area of El Cabanyal neighbourhood

The coexistence of styles, materials, and architectural details contributes to bestowing upon El Cabanyal a unique identity and historical appearance. Amidst the architectural complexity of El Cabanyal, a consistent element inherited from the village endures: the direct connection of buildings to the street, without common intermediate elements. This direct link reflects a tradition of proximity and social interaction dating back to the days of the barracas when community life predominantly unfolded outdoors.

This dynamic has persevered and evolved over time, influencing how the neighbourhood's inhabitants interact with their built environment. Lastly, the dwellings maintain the tradition of a direct relationship with the street, without the interposition of common elements such as entrances or condominium staircases.

6.2.2.1. Morpho-typological building analysis

In the evolution process of the district, the persistence of the terraced house building type is clearly observed. In detail, sub-types can be inferred in relation to the number of floors and housing units:

T1 - single-family terraced house (Figure 45), characterised by a front with a width of between 3.20 m and 7.76 m, a building height of 1 or 2 storeys, and an internal distribution of rooms that varies depending on the position of the corridor. The single-family terraced building typology has three subcategories:

T1.1 - one-storey terraced house. The layout is characterised by a lateral and/or central distributor space. The main access space to the dwelling consists of a single room lit by the presence of two openings on the main façade: the access door and a narrow longitudinal window. The corridor starts from the side or centre of this room through which one enters the bedrooms, which are generally two in number, to the last room, the dining room. From the dining room/kitchen there is access to the inner courtyard of the building. The bathroom, consisting only of the latrine, is located in the inner courtyard.

T1.2 - one-storey terraced house with attic. This is a building type consisting of the same planimetric characteristics as type T1.1, to which a room is added on the upper floor, corresponding to the attic or terrace. Access to the attic is provided by a stairwell, the position of which may change in plan.

T1.3 - single-family terraced house with a height of two storeys or more. This is a building type with the same planimetric characteristics as type T1.1, to which a second floor is added. In detail, the presence of a second floor introduces the architectural element of the balcony and its railing.

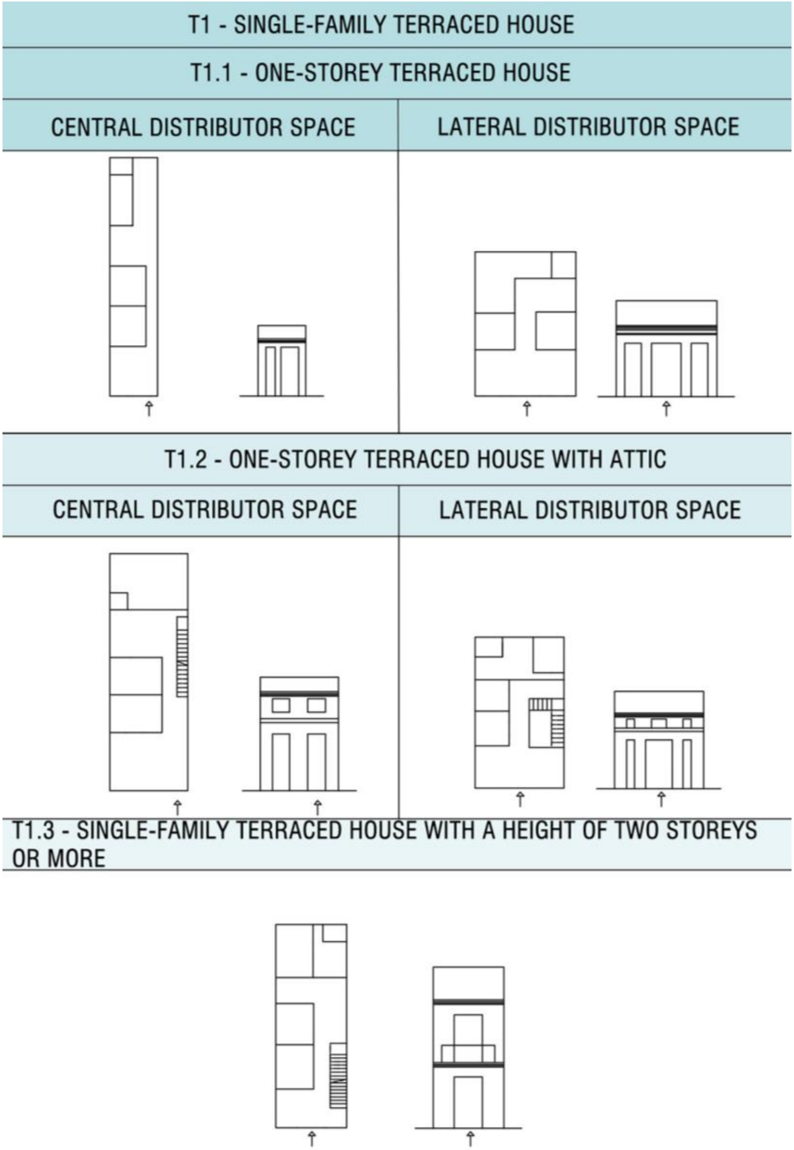

Figure 45 - Details of plan distribution of terraced house, for single cell (image created starting from details available on the Valencia City Council website and in (Pastor Villa R., 2011))

T2 - terraced multi-family house (Figure 46), building type consisting of a stairwell serving one dwelling unit per floor.

The planimetric distribution of the interior rooms follows that of T1. The T2 building type has two subcategories in relation to the size of the main front and the number of floors:

T2.1 - a building with a façade width of between 3.20 m and 9.12 m and a height of two or three storeys. Type T 2.1 can have a planimetric layout consisting of a lateral linear staircase and a lateral or central distributor shaft.

T2.2 -building with a façade width greater than 9.12 m and a number of storeys greater than 2 and a stairwell of two or more flights, on which the internal distribution of rooms depends.

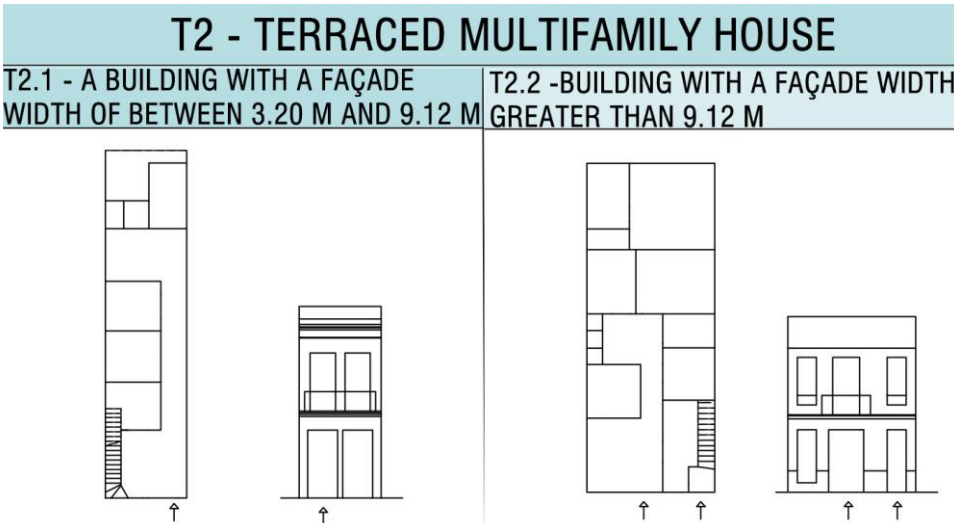

Figure 46 - Details of plan distribution of terraced multifamily house (image created starting from details available on the Valencia City Council website and in (Pastor Villa R., 2011))

T 3 - Terraced multi-family houses (Figure 47), a building type consisting of a stairwell serving at least two residential units per floor. The layout distribution varies according to the type (one or more flights) and the position of the stairwell (central or side). Therefore, the subcategories are:

T3.1 - Terraced multi-family house with linear, central staircase and side corridor. The internal room distribution follows type T1.1;

T3.2 - Terraced multi-family house with linear and central staircase and distribution space.

T 3.3 - Terraced multi-family house with two-flight staircase and side corridor.

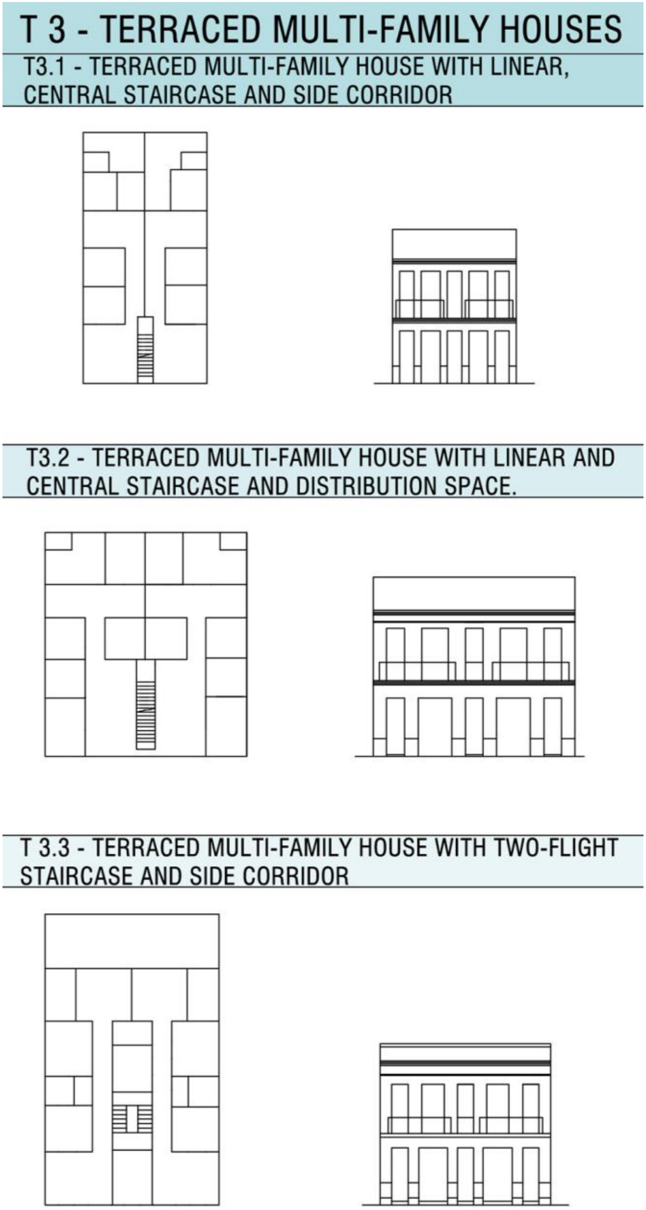

Figure 47 - Details of plan distribution of terraced multifamily house consisting of a stairwell serving at least two residential units per floor (image created starting from details available on the Valencia City Council website and in (Pastor Villa R., 2011))

The current configuration of the buildings, respecting the inherited subdivision, has adapted their heights to changing regulations and the needs of the owners. This adaptation has led to a variety of heights between the buildings.

Additionally, the buildings have inner courtyards that provide double exposure of the interior spaces, and represent a substantial change in the concept of privacy and organisation of space. This feature, resulting from the presence of street frontages and rear courtyards, facilitates effective ventilation of the rooms.

Taking advantage of the regime of sea breezes from east to west, this arrangement favours air exchange and contributes to living comfort. The façades of the houses are finished according to the owners' taste.

6.2.2.2. Qualitative analysis of the built environment

Phases 1-2-3 of the digital code of practice outlined in chapter 5 have been applied and validated on the study area of the historic neighbourhood El Cabanyal in Valencia (Spain). Specifically, particular attention was paid to the Sperichal-image survey phase (ph 1.3) and on-desk data acquisition using the WebGiSystem and WebVrModel (Ph 3). Consequently, with respect to the first phase of the digital code of practice, an in-depth knowledge of the property under study was conducted (ph 1.1) through the consultation of historical documentation (manuscripts, miscellanies, books), iconographic representations, graphic works (maps, cartographies and drawings) and historical photographs, from different periods. Additionally, during this phase, information on a territorial scale (orthophoto, regional technical maps, general and detailed urban planning instruments) useful for the subsequent geolocation and processing of the GiSystem is analysed and acquired.

From the historical/archival research, and specifically on the basis of the large-scale design drawings, the spherical photo acquisition procedure was defined, as well as the relevant survey plan with n survey points. In detail, the spherical photos were acquired consecutively with a constant step in the plan, according to the acquisition scheme.

Once the survey plan was defined, the acquisition of the equirectangular photos was performed in situ using a spherical head (Theta 360) and a tripod (ph 1.3). Subsequently to the characterisation of the built and urban environment, the acquired data were implemented in the GiSystem prepared according to the defined logical-relational schema (ph 1.2). In parallel, the relational information system PostgreSQL (r-DB) with PostGIS extension was structured via the pigAdmin graphic interface. The latter was connected to the GiSystem environment in order to implement in it the technical knowledge acquired in ph 1.1. Here, each building was, therefore, geolocalised according to the WGS84 global reference system, and the spatial information level was increased thanks to the populating of the alphanumeric information, useful for the subsequent translation of the data according to the CityGML standard. Therefore, the data and information from the historical-architectural analysis were systematised in the GIS environment according to the sections and descriptors defined in Table 4, Table 5, Table 6, Table 7 and Table 8.

Figure 48 - Representative equirectangular images

Having acquired all the information and data on the historical building and urban element, the VrModel of the study area was created (ph.2.3). In particular, the VrModel was obtained by connecting the 568 spheres acquired according to the plane (ph 1.3) (Figure 48). Given the number of scenes and the complexity of the area (in relation to the morphological similarity of the blocks) an interactive orientation map was implemented to support the use of the VrModel which, thanks to the presence of specific hotspots, allows the user to choose the environment to be viewed (Figure 49).

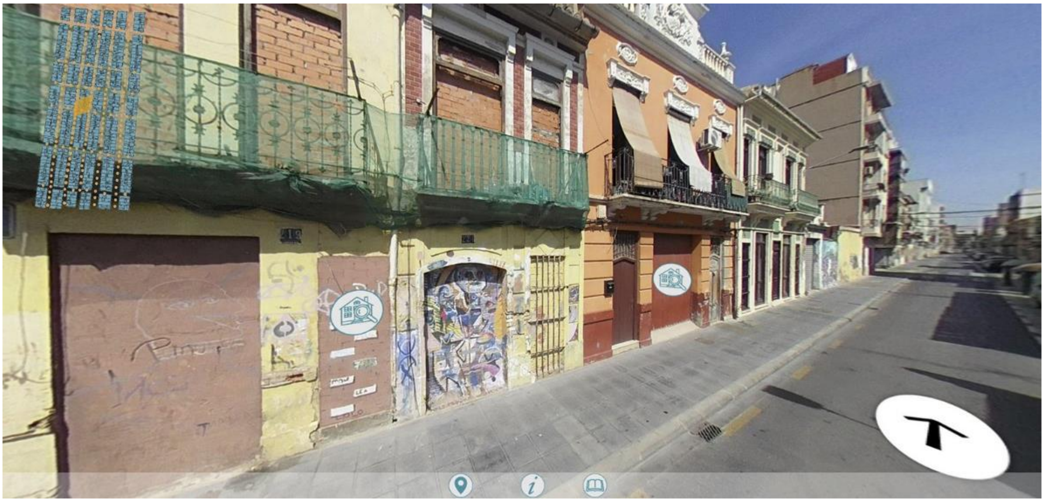

Figure 49 - VrModel home screen

In addition, a specific hotspot was placed at each spherical that allows connection to the WebGiSystem. Finally, a hotspot was inserted at each building that allows connection to the specific section of the r-DB (Figure 50).

The generated VrModel was then prepared to be used via the web in a semi-immersive (on-desk) way. Prior to web sharing, the hyperlink of the WebVrModel was implemented in the r-DB sections. Subsequently, the web-sharing of the GiSystem was prepared with the aid of the QGIS geo-server and the Apache web-server, enabling the use of the technical knowledge information via web browser (Figure 50).

By means of the WebGiSystem and WebVrModel, additional technical knowledge data that was not present was implemented in the r-DB, as well as all the information regarding the state of conservation of each building necessary for the reconnaissance analysis of the study area.

Figure 50 - Home screen of the Web-GiSystem showing the query of an architectural entity. The information window allows the connection to the Web-VrModel, as well as the implementation of further data, remotely on-desk, in the r-DB.

Consistently of the T-DSS rules, buildings characterised by a low level of conservation were identified, for which the subsequent quantitative conservation analysis followed (Ph. 4). In accordance with phase 4 of the digital code of practice, the photogrammetric survey was carried out. Specifically, the digital survey was conducted through the use of passive terrestrial digital technologies, i.e. camera (Canon EOS 100D) mounted on the tripod/telescopic, useful for the acquisition of portions positioned at high heights. Considering the recurring morphotypological and architectural characteristics of the buildings, the acquisition process followed the same scheme for all the buildings identified. Consequently, the frames were processed using SFM software (Agisoft Metashape©), obtaining three-dimensional elements in textured point clouds (Figure 51).

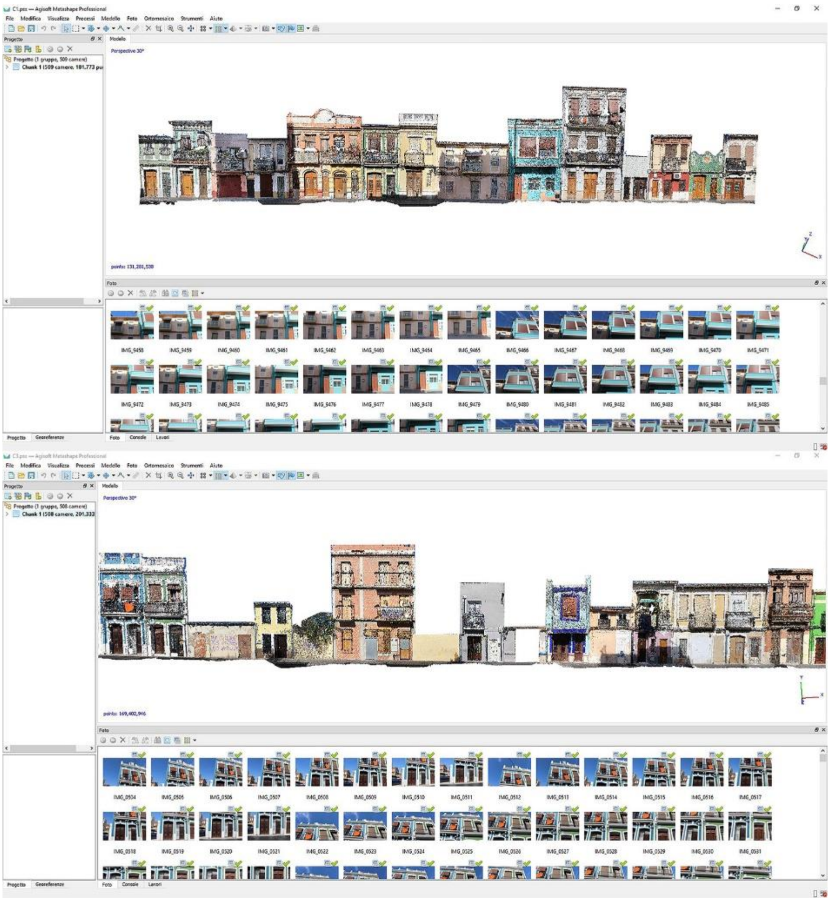

Figure 51 - Processing of point clouds of urban fronts using SFM software

At the end of the elaboration of the three-dimensional models, scale orthophotos (Figure 52) were elaborated of the perspective backdrops of the buildings useful for the subsequent (gis-based) mapping of degradation through the identification of degradation themes.

Figure 52 - Orthophoto of an urban front

The approach of acquiring descriptors with the aid of virtual reality techniques was useful in order to collect large amounts of data in a geographic database (GIS, .shp), which in fact constitutes the organic system of information to be translated into the CityGML environment.

6.3. CASE 3 – Historic District of Ascoli Satriano, Foggia, Italia

The complete workflow of the code of practice outlined in Chapter 5 (Figure 53) has been implemented and validated in an emblematic historic district of the Puglia Region. Specifically, this process was carried out in the historic district of Ascoli Satriano, a small municipality in the province of Foggia (Figure 54). This pilot case has been selected it due to its various historical and architectural characteristics that set it apart.

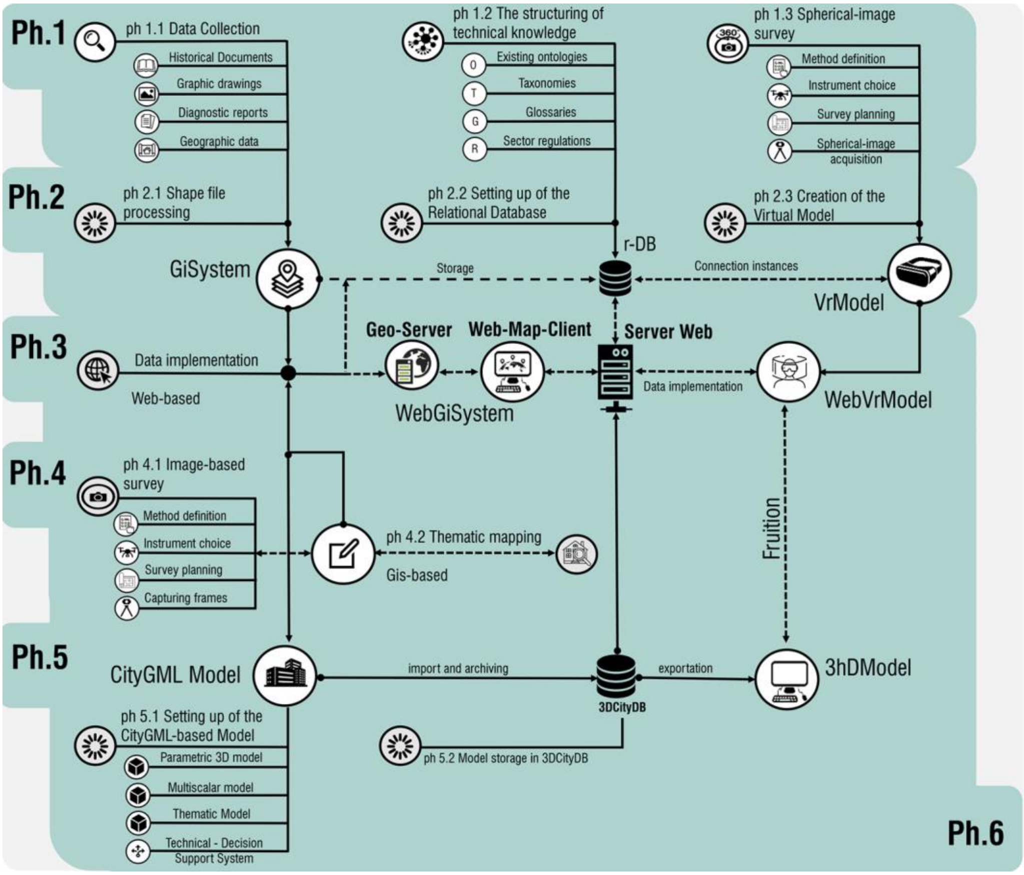

Figure 53 - Phases of the digital code of practice applied and validated for the pilot case of the Historic Centre of Ascoli Satriano. In light blue the phases applied

6.3.1. A comprehensive Arrchitectural-Urban analysis

The Historic Centre of Ascoli Satriano is in the highest part of the city promontory, also known as "Castle Hill". The prevalent features of the urban fabric in the Historic Centre are associated to various dimensions and distribution of street dimensions in the plan and single cell units with vertical development or terraced houses with horizontal development. 90% of buildings have residential use. Its current morphological-architectural configuration is the result of historical violent seismic events (in 1343 and 1361) and the subsequent slow process of reconstruction, caused by the absence of an urban planning regulation for the historic district.

Figure 54 - (Left to right) location of Ascoli Satriano (FG) in Italy, perimetration of the Historic Centre in the city land

Main suffered transformations relate roofs, partially collapsed which has generated the co-presence of various constructive and material combinations. In fact, roofs, originally characterised by pitched wooden structures, have been replaced with flat slabs (iron beams and brick vaults or reinforced concrete).

Figure 55 - Significant urban parts of historic buildings in the historical centre of Ascoli Satriano

On the contrary, walls have preserved the original multi-layered features, showing the combined use of stone and solid brick blocks, plastered both along the external and internal sides.

Finally, the transparent building sub-components (windows and doors) have different frames to the original ones (wood) and are featured by a widespread low state of conservation. Currently, they consist of aluminium frames with simple and clear double-glazed technology, commonly introduced in the last twenty years of the last century.

Concerning building types, three primary recurring morphological typologies have been identified (Figure 56):

T1 Single-cell or two-cell building, exhibiting a vertical planimetric development in relation to the street front. The structure comprises one floor, featuring a vaulted ceiling in the basement and a flat or vaulted ceiling on the upper floor. Certain buildings of this type may include a second floor, added subsequently to the ground floor.

T2 A multi-cell building formed by merging several Type 1 building cells, characterised by horizontal planimetric development in relation to the street front. The structure comprises a basement floor utilized for non-residential purposes and a ground and first floor designated for residential use.

T3 A single or semi-palace house, featuring horizontal planimetric development along the street front and comprising multiple residential units. The defining characteristic of this building type is the existence of a shared central stairwell serving the housing units on the upper floors, along with distinctive architectural elements on the main facade. The basement and ground floor are designated for non-residential purposes, while the upper floors are allocated for residential use.

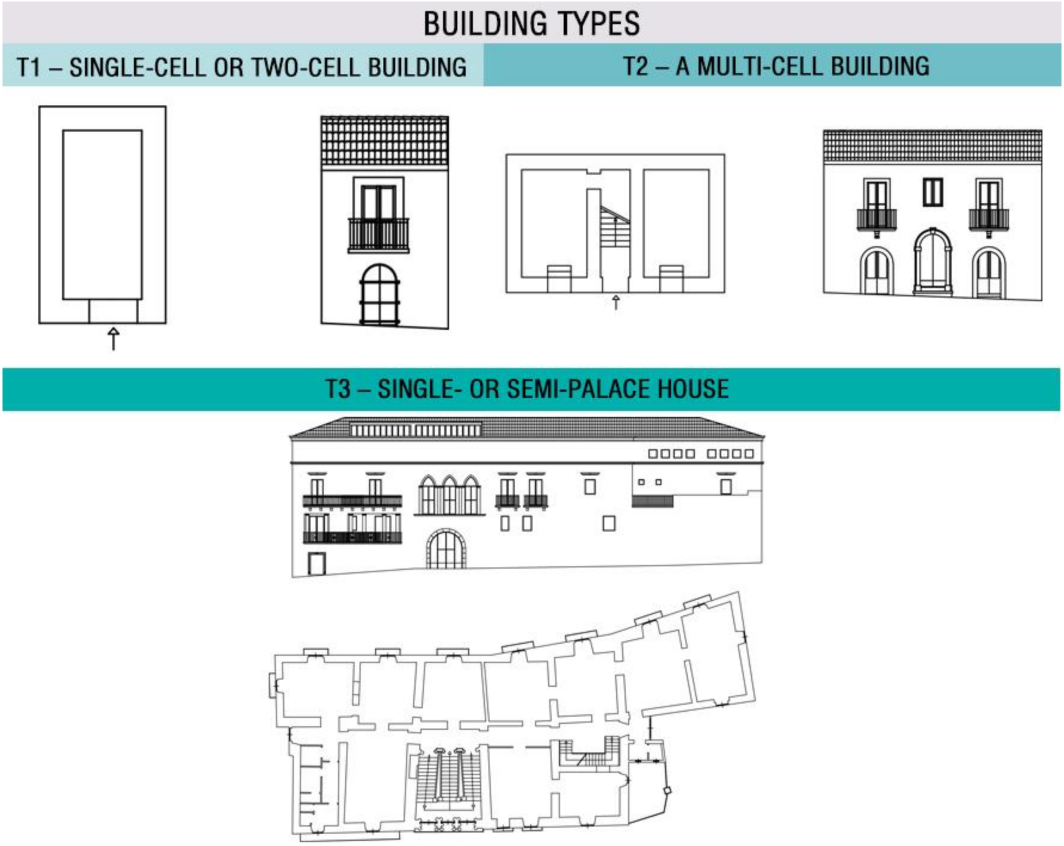

Figure 56 - Details of plan distribution of building type (image created starting from details available on the Ascoli Satriano Council website)

6.3.2. Validation of 3shD-SystematiCode to Historic District of Ascoli Satriano, Foggia, Italy

Firstly, the data required for the basic knowledge of buildings (Table 4, Table 5, Table 6 and Table 7) have been collected and properly systematized according to the ontological structure (ph 1.2), as well as archived in r-DB (ph 2.2) connecetd to the GiSystem (ph. 2.1). In the detail of data and activities in ph 1.1, geometric and geographical information of buildings are extracted from the Regional Technical Charter (SIT Apulia Region), while morpho-typological, constructive and architectural features have been collected starting from in situ surveys and previous studies and technical activities. These are thus used to set up the basic geographic information system of the historic district (Figure 57). Here, the architectural entities have been represented with vector polygons in the global reference system (WGS84-UTM 33N) and the r-DB has been structured through attribute tables (ph1.2).

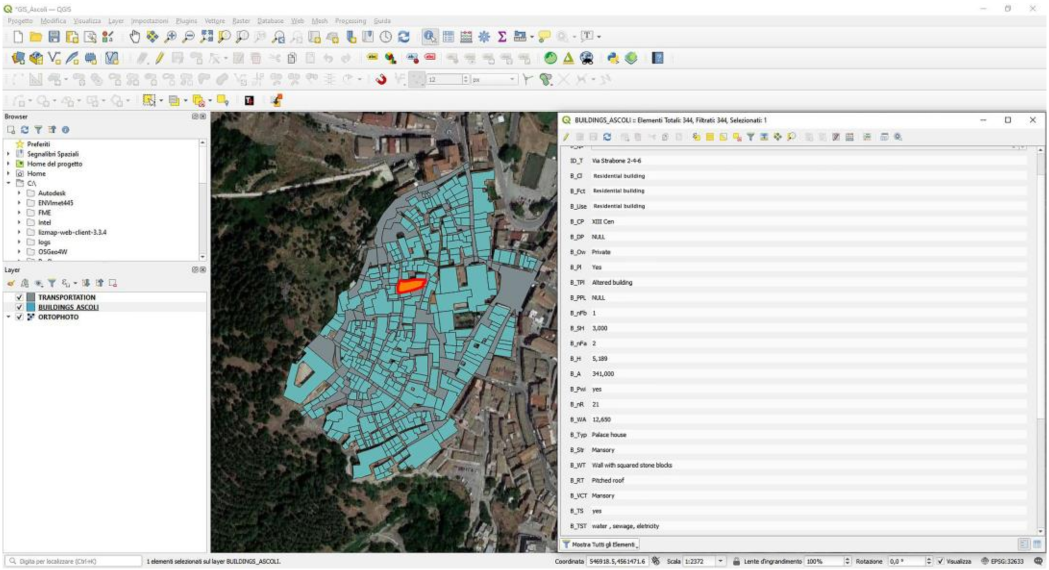

Figure 57 - GiSystem of the Historic Centre of Ascoli Satriano. On the right the information window showing the descriptors implemented in the r-DB for the selected building.

In particular, a specific attribute table has been created for each section of the r-DB, structured to support: i) the historic-archival information (Ph 1); ii) the data acquired on-desk (Ph 3); and iii) the conservation level by thematic mapping (Ph 4). Simultaneously, the spherical image survey (ph 1.3) was conducted in accordance with the prescribed acquisition plan (Figure 58), where 558 points were captured at a consistent interval in the planimetry.

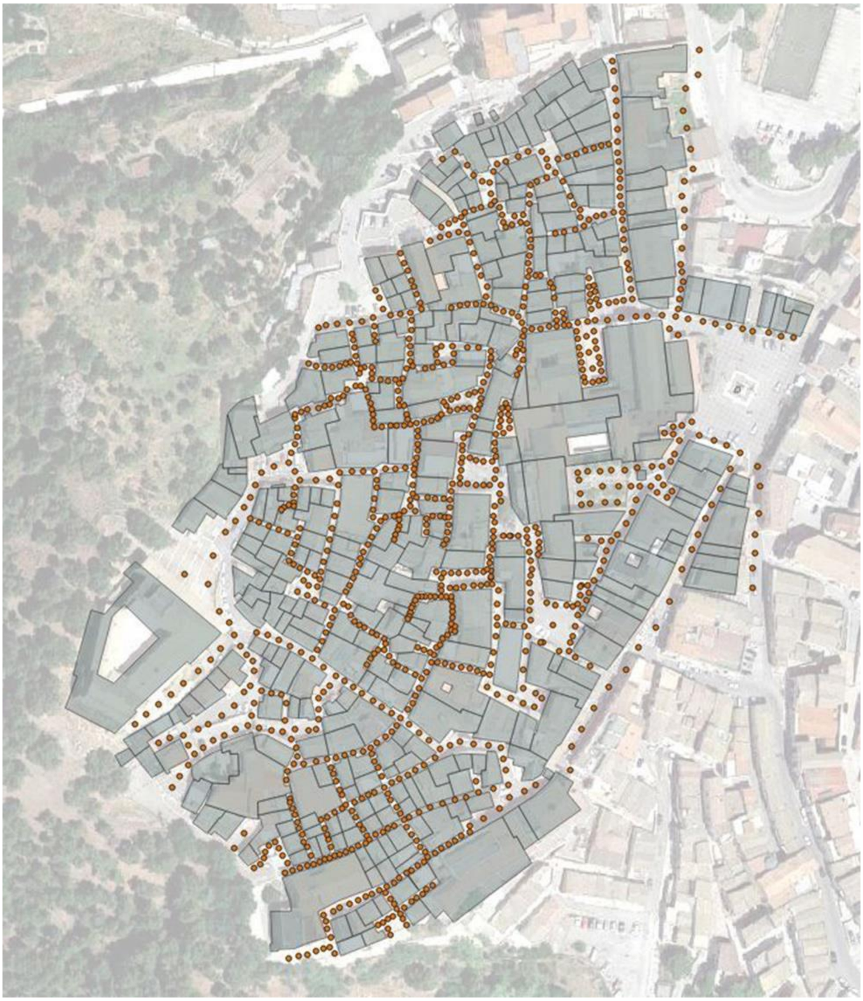

Figure 58 – The Spherical-Image survey acquisition plan

Specifically, the equirectangular photos were acquired on-site with the assistance of a spherical head (Samsung GEAR 360 camera) and a tripod. Following this, the VrModel was generated by interconnecting the captured images into ph. 1.3. Moreover, a dynamic orientation map has been incorporated in each scene, enabling the user to navigate through the scene and ascertain its planimetric localisation.

The orientation map also facilitates the viewing of the n acquisition points on the site, enabling users to navigate within the virtual model. Additionally, each scene includes a hotspot connecting to the WebGiSystem for its utilisation (Figure 59).

Particularly for the VrModel, specific hotspots have been incorporated for each building and urban element, allowing a connection to the r-DB. Consequently, both the GiSystem and the VrModel have been adapted for web-based usage (Ph3).

Figure 59 - Home screen of the Web-GiSystem showing the query of an architectural entity and the link to the Web-VrModel. The Web-VrModel screen shows the implementation of additional data in the r-DB remotely on-desk

Hence, all the technical knowledge and information pertaining to the reconnaissance analysis of the conservative state of the historic building were acquired in a semi-immersive, web-based manner at the desk. In this process, the r-DB was established with all the pertinent information necessary for identifying buildings and urban elements requiring a more detailed examination (Ph. 4), in alignment with the rules of the T-DSS. As far as the latter is concerned (Ph4), the qualification and assessment of decays for the selected buildings have been processed in GIS environments by means of their ortho-images. Specifically, the image-based survey (ph 4.1) has been performed in situ according to the principles of digital photogrammetry, using a digital camera (Canon EOS 100D). After the acquisition campaign, the frames have been processed within a Structure-For-Motion software (Agisoft Metashape©) for the elaboration of ortho-images for each building sub-components (masonry, roof, windows), finally scaled thanks to measurements acquired in situ (Figure 60 and Figure 61).

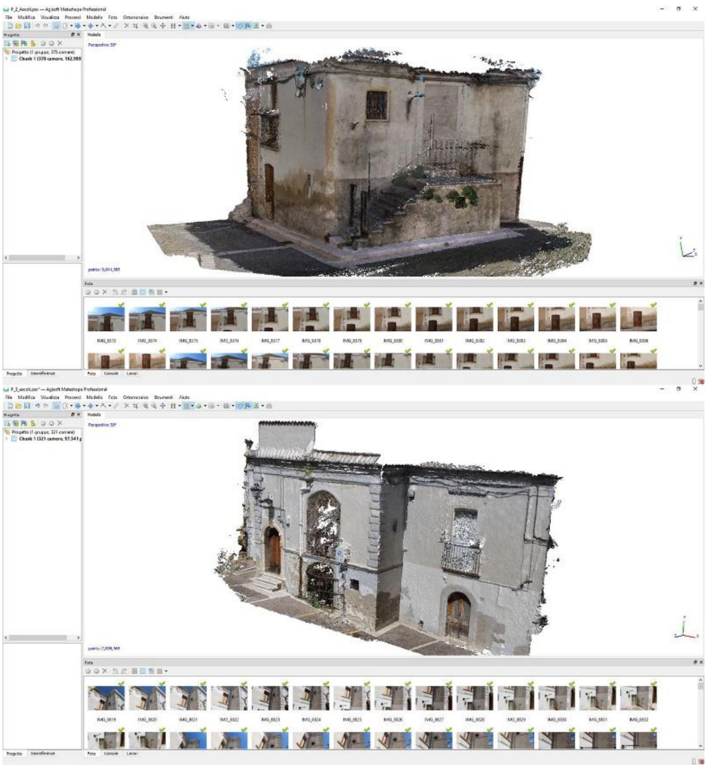

Figure 60 - Processing of point clouds of buildings using SFM software

Figure 61 - Orthophoto of a building in the Historic Centre of Ascoli Satriano

Thus, decays are identified in GIS environment (ph 4.2), using vector primitives, geolocated and associated to the related architectural entities in the shape file (Figure 62). Here, details on each decay (B_Td, B_S, B_In, B_Ex) and for each building sub-component are introduced in the associated attribute table in the r-DB, completing the implementation of data in the GIS environment. As recurrent results in the mapping process, five main classes of decays have been recognized for walls: washout in the higher part of walls due to the absence of well-design gutters; the presence of dampness in the lower part of walls caused by their direct contact with rain-flows along the impervious sidewalks; a consequent spread of detachment and degradation of surfaces, as well as local presence of vegetation. For roofs, the main decays identified are biological patina and degradation of the roof covering; while, for windows a low state of conservation of the shading elements has been identified, and the degradation of the wooden doors caused by the presence of dampness, and breakage/absence of glass for windows.

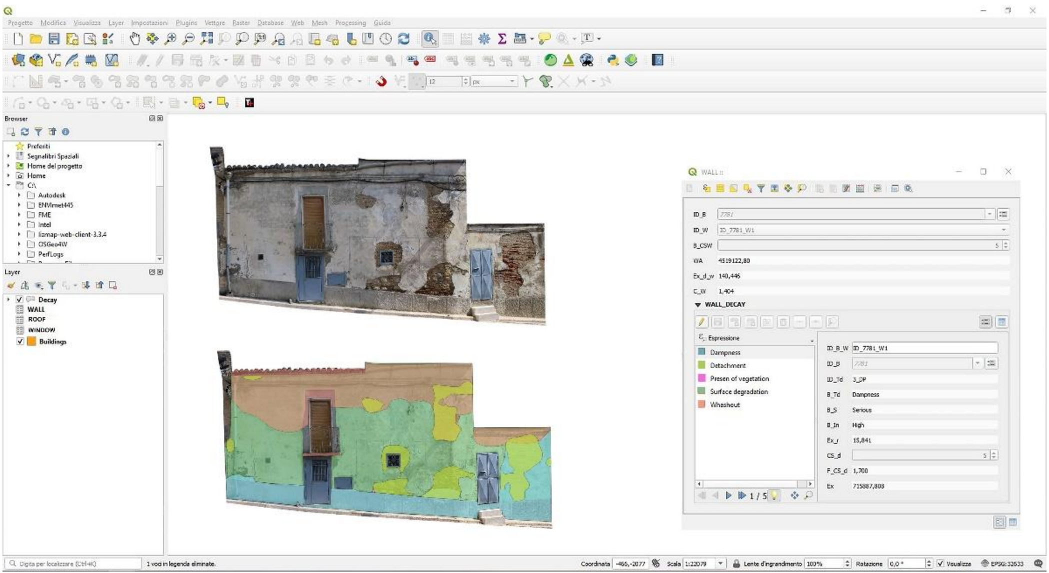

Figure 62 - Thematic map of the exposed wall of a building

Subsequently, for every single subcomponent, the graphic-vector restitution of the state of conservation has been performed, representing the areas of decay with vector polygons. Therefore, each vector polygon mapped on the ortho-image has been related to the "Conservation level" of the section r-DB. In this case, the logical relationships configured, and the calculator fields have been prepared to allow: i) the identification of the type of decay, from the defined choice set; ii) the definition of the severity and level of degradation; and iii) the calculation of the decay extension, codifying it in alphanumeric attributes. So, the calculating fields prepared in the specific tables, as well as according to the equations (§5.2.2); it has allowed the automatic compilation of the field relating to the primary factor of the state of conservation of each component of single architecture (Figure 62).

Consequently, the CityGML-based model has been created within the Safe FME visual programming platform (Figure 63). Here, according to creation of the parametric model (§ 5.2.3.5),the specific workbenches have been used for i) the creation of the geometric model in LOD1, extruding geolocated polygons using heights collected in the shape file, ii) translation of the semantic-thematic data according to the Building class, for the attributes that complied with the standard, and the GenericAttribute class, for the attributes external to the reference ontology, and iii) the implementation of the logical-relational structure of the T-DSS, for the automatic derivation of the class and priority of intervention.

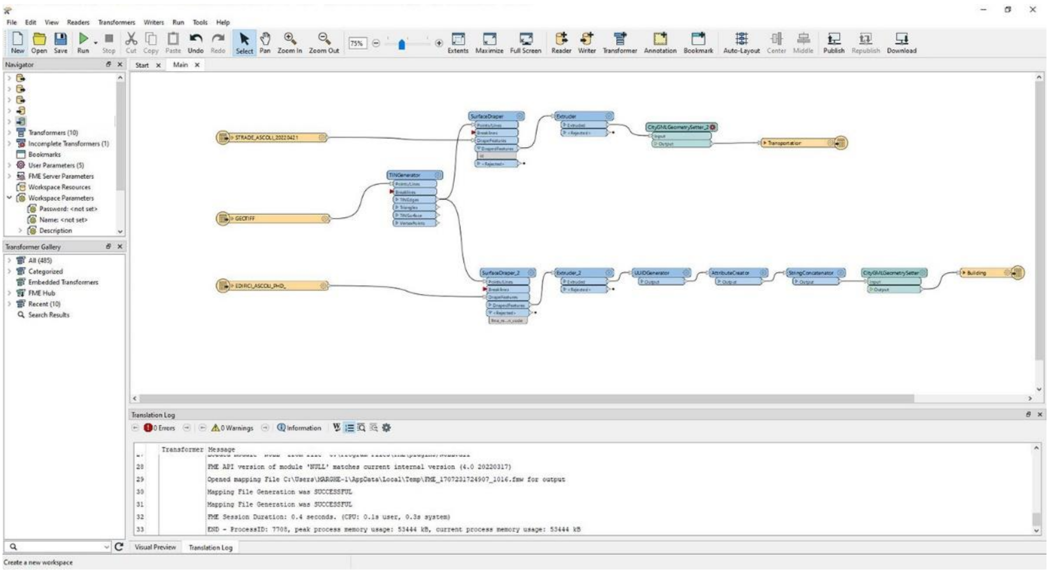

Figure 63 - FME screen with the specific workbenches used for creating the paratmetric model CityGML-based

The CityGML-based model created (ph 5.1) has been imported and archived within 3DCityDB, using PostgreSQL as a relational database with its PostGIS extension. The use of 3DCityDB (ph 5.2) has allowed the export of the geometric model (.json) and the semantic data (.csv) for subsequent visualisation and use in a web environment, as well as the management of archived data over time. In this way, the model is set up to be used in a web environment within the Cesium virtual globe. In the 3DCityDB-Web-Map-Client platform (ph 5.3), it is possible to query the individual architectural artefacts: at a semantic level, by creating a specific search against unique values; and at a geometric level, by selecting a single model. In both modes, the tool allows the display of semantic information relating to the queried object in a pop window. Additionally, a thematic three-dimensional map was created showing the intervention priorities of the buildings(Figure 64).

Figure 64 - Thematic map highlighting building intervention priorities. In detail, in grey the buildings that were not involved in the second level of analysis, in green the buildings with a low priority, in orange the buildings with a medium priority and in red the buildings with a high priority.

As far as the visualisation of information is concerned, at the right of Figure 65, the pop-windows shows all the catalogued and structured data for the selected building. Special attention is given to the “WebVrModel_link” attributes.

The database is structured using a link to the site (.http) which allows users to use the building in a virtual web-based mode.

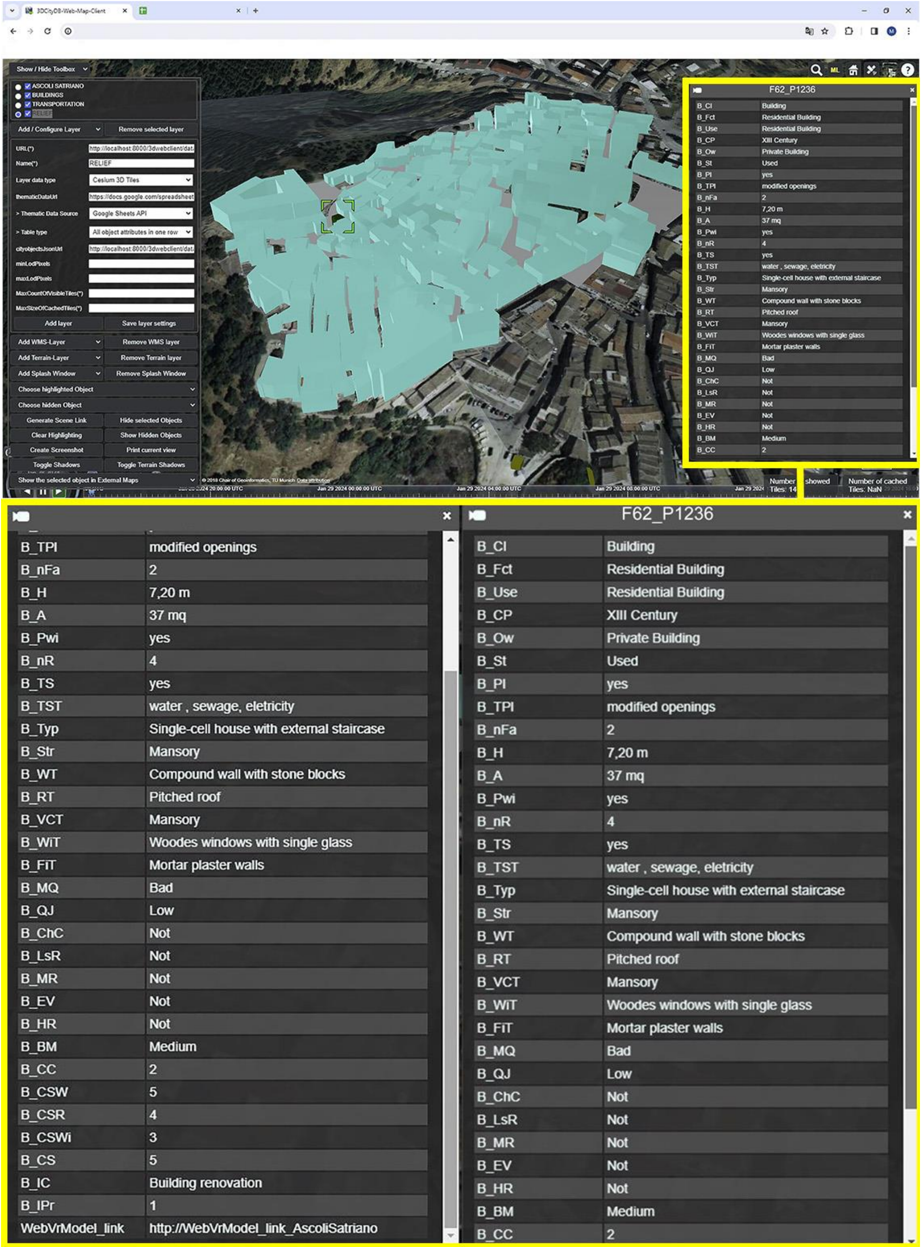

Figure 65 – Visualisation of the parametric model in the 3DCityDB Web Map Client and visible details of the selected building in the popup window on the right

7. STRENGTHS / WEAKNESSES AND GENERAL REMARKS

The challenges associated with understanding and managing the existing built heritage are inherently uncertain, complex, and multi-scalar. Therefore, effectively addressing these issues requires approaches that operate on different levels and involve several disciplines. These approaches should provide comprehensive support during the analysis, identification, and selection of possible intervention strategies.

In particular, uncertainty results from the variety of factors influencing the building stock, including structural conditions, regulations, environmental constraints and functional requirements. Complexity emerges from the interconnectedness of these factors and the need to consider the dynamic relationships between them.

The conservation process in the context of the existing architectural heritage has several strengths that contribute to the preservation and enhancement of existing structures, including:

- Cultural heritage preservation. The conservation process aims to preserve the Cultural Heritage of a community or society, ensuring that artefacts, buildings and sites of historical value are protected for future generations. This also contributes to preserving the identity value of places, enabling the community to connect with its past and understand the evolution of societies;
- Environmental sustainability. The conservation of existing buildings reduces the environmental impact associated with the construction of new buildings. In fact, the rehabilitation of existing buildings can lead to less consumption of resources and less waste production;
- Adaptability and flexibility. The existing architectural structures can often be adapted to meet new functional needs without compromising historical integrity. This flexibility translates into greater adaptability to the changing needs of society over time;
- Knowledge transmission. The preservation process enables the transmission of traditional building knowledge and skills, preserving ancient building techniques that might otherwise be lost over time.

Despite its many advantages, the conservation process in the context of the existing architectural heritage can present some criticalities and weaknesses, including:

- Complexity of technical knowledge. The conservation of historic buildings often requires specialised skills capable of analysing traditional building and historical-architectural techniques;
- The determination of intervention strategies. The decision-making process in conservation is unstructured with respect to the multiple parameters involved in choosing and prioritising an intervention strategy;
- Changing conditions. The conservation process faces challenges due to changing environmental conditions, natural disasters or human activities, which may affect the effectiveness of conservation strategies;
- Lack of standardised procedures. The traditional methodological approaches underlying the cognitive and conservation process are non-standardised with respect to objective conditions (period of construction, state of conservation, architectural type). This affects the practical-operational method of conservation activities, as well as the processing of results (recovery plans, urban regeneration programmes).

Therefore, overcoming these critical issues requires multi-level approaches that encompass in-depth analyses at different scales, ranging from the existing built environment to the individual architectural artifact. Furthermore, it is crucial to involve different disciplinary fields (historical, architectural, structural, conservation) to obtain a complete and integrated view of the problem. Multi-disciplinary and multi-scalar approaches can help identify innovative solutions, considering multiple perspectives and objectives.

In this scenario, the management of built heritage requires a holistic view that goes beyond simple maintenance, incorporating current and past cultural and social considerations. Indeed, the management and conservation planning of the existing architectural heritage delve into and correlate the concept of "maintenance" with that of "conservation".

The architectural artifact must be analyzed within a broader vision where the performance level of the technological components does not necessarily have to reach standard values, as required by regulations for new buildings and by the practice of planned maintenance, based on the systematic replacement of technological elements.

On the contrary, the level of permissible performance constitutes the parameter for defining the maintenance and conservation actions to be implemented. Additionally, the understanding and management of the existing built heritage require a synergy of skills and approaches so that sustainable, resilient, and adaptable intervention strategies can be developed. It is important to emphasise that the effectiveness of the conservation process is related to careful planning, community involvement, and the identification of adaptive strategies that consider both the cultural significance and the practical aspects of conservation. Therefore, in the specific case of the existing architectural heritage, it is necessary to identify and correlate all the main features that contribute to the fragile and deficient conditions of an architectural asset, but which at the same time may also constitute values to be preserved. This approach to analysis is part of the broader concept of assessing the state of conservation and risk.

7.1. Potential impacts

The most recent scientific studies have deepened and demonstrated the importance of standardised parametric models in architectural and building activities, emphasising their fundamental usefulness in the systematisation of technical knowledge for both simple and complex issues. Such models guarantee accurate representation at both geometric and semantic levels, thanks to the broad interoperability between survey and modelling tools and techniques, as well as the structuring of semantic and geometric models on widespread and thematic ontologies.

The effectiveness of these models is further enhanced when historical and cultural relevance contributes to the basic understanding of Cultural Heritage, regardless of its uniqueness or presence in the urban landscape.

The urban-architectural layout of historic districts represent an atypical category of Cultural Heritage, as their cultural significance is not associated with a single asset but with the complex of architectural elements. These elements are fundamental to the historical necessity of preserving such places, despite the limited interest on the part of major administrators in resolving the issue. The creation of recovery plans usually stemmed from the need to assess urban residential needs.

Moreover, the setting up of a recovery plan is often related to time-consuming and laborious activities on the part of the experts involved in the process, aimed at collecting, reorganising and understanding historical, archival and technological evidence for numerous urban areas. The objective is to identify levels of intervention and related priorities in a systematic set of rules and possible solutions in an integrated way. Within this complex framework, the state of conservation of a historic district plays a key role in the management and selection of conservation actions.

CONCLUSIONS

Historical urban areas represent complex components of our Cultural Heritage, requiring in-depth analysis, understanding and valorisation. Their complexity emerges from the multiple disciplines involved and the different temporal and spatial scales that characterise these contexts. In this scenario, the management of technical knowledge of data presents itself as a challenge, on the one hand among the actors involved in the process, and on the other hand also in the different phases of the conservation process. In the regulatory landscape, the lack of standardisation of preservation procedures is evident and can be attributed to several factors. Firstly, the criticality of the theoretical notions involved makes it difficult to establish universal guidelines. Secondly, the architectural complexity of the existing heritage contributes to the challenge, requiring flexible and adaptable approaches. Finally, the disciplinary disjointedness of technical information adds a further layer of complication, as it is often necessary to integrate approaches from different disciplines. The need for a reworking of the conservation process is clear, seeking solutions that can overcome the present challenges. This leads to the involvement of collaborative efforts between experts from different disciplines, the development of more flexible and adaptable methodologies, and the promotion of conceptual frameworks according to regulations that take into account the complexity and diversity of historic quarters. Furthermore, increased sharing and dissemination of technical knowledge ensures better management of Cultural Heritage, ensuring its preservation for future generations.

The overall aim of the research was methodologically carried out following the research questions.

RQ1. How can the existing architectural heritage be analysed using the CityGML standard?

The current scientific understanding underscores the importance of employing digital systems and models in the preservation of architectural heritage. Implementing these systems facilitates the organisation of technical knowledge and the structuring of conservation processes through seamless information flows. In this context, the CityGML standard plays a pivotal role, augmented by supplementary extensions, and enriched with ontologies and thematic details. This comprehensive approach ensures effective preservation strategies and promotes interoperability in handling diverse information related to architectural heritage conservation. Scientific research emphasizes the importance of a clear and open structural framework as a foundational element for conceptualizing, reading, and interpreting data. This framework is crucial for managing multidisciplinary information and intricate details across several levels. The extensibility of the standard, particularly its capacity to integrate generic attribute classes, facilitates the assimilation of data from historical, archival, and documentary analyses, especially when the existing structure is insufficient. This diminishes the necessity to create intricate application domain extensions (ADEs). The development of detailed ADEs has streamlined prior operational activities related to organizing technical knowledge data, thereby reducing computational demands in constructing the digital model. Additionally, this process fosters inclusive approaches, enabling domain experts to collaborate seamlessly on a unified platform, spanning from data collection to utilisation. Consequently, the parametric urban model can be extended in terms of both geometric-topological and semantic-thematic aspects, facilitating the application of the relevant databases to specific subject areas.

RQ2. Within the discipline of conservation, preservation, enhancement and management of the existing architectural heritage, for which types of assets is the CityGML ontological framework applied?

The conducted research has highlighted that within the specific field of conservation, the CityGML standard is applied in three primary categories of built heritage. In addition to architectural cases, which typically involve individual structures with distinctive features, historic districts have emerged as a more intricate application. Given their substantial cultural significance, CityGML-based models have been explored for both architectural and urban elements within these historic districts. However, the primary emphasis has been on the historical-architectural and material-constructive characteristics of assets situated in historic urban agglomerations.

This emphasis is driven by the need for a high level of detail in modelling architectural elements, both geometrically and semantically, essential for the conservation and restoration of Cultural Heritage. Apart from diffuse historical heritage, the CityGML standard is also applied in the thorough analysis of archaeological sites and industrial architecture.

Scientific studies in these areas share similarities with the modelling of individual architectural elements, as they require a highly detailed digital reconstruction (e.g. of archaeological areas, elements or their ruins) and the integration of extensive semantic information related to historical knowledge. Furthermore, the case of systemic buildings is still untried. The discussion in these cases focuses on geographical or site distribution, which in turn influences the semantic-geographical level of modelling in historical districts, archaeological sites and systemic architectures. Finally, in these subject areas, all classes of Cultural Heritage are analysed and evaluated, focusing on their constitutive characteristics (materials, construction techniques, uses) and their relationship to time and boundary conditions. Intrinsic characteristics such as physical and functional obsolescence play a significant role in the activities of maintenance and conservation engineers and policy makers. For this reason, the analysis and qualification of decay is the most proven mode in the literature when CityGML is combined with unstructured models such as point cloud models.

RQ3. In which phase of the conservation process (cognitive, diagnostic, intervention) is the CityGML ontology applied?

For the analysis of individual architectural artefacts, the main activities are related to the systematisation of technical knowledge through the integration of thematic ontologies. Similar levels of detail are achieved when conservation objectives exploit the extensibility of the CityGML standard to enrich the semantics of technical knowledge derived from other thematic ontologies and standard details (such as INSPIRE and IFC). Alternatively, the use of photogrammetric techniques is employed to study and evaluate the decay surface. On the other hand, the development of structured knowledge databases on Cultural Heritage has led to the creation of web-based systems for sharing data and results using CityGML models. This practice is particularly advantageous for disseminating technical knowledge between professionals with different subject expertise. In addition to meeting multidisciplinary needs in some thematic areas, the experience in developing web-based platforms for sharing digitised models and content promotes an inclusive approach to communicating activities related to historic buildings and places. In this context, collaborative promotion can potentially cover all phases involved in the analysed application fields.

RQ4. Can the steps of the conservation process be carried out holistically with the help of parametric models integrated with decision support systems?

The extensibility of semantics in the CityGML standard for the existing architectural heritage have showed several applications integrating Decision Support Systems (DSS), with wider experimentation in supporting experts in decision-making. In the context of the discussion on the use of CityGML for the conservation of Cultural Heritage and the resolution of complex issues for the automatic or semi-automatic improvement of semantics, a significant role of thematic standards (energy, statics, ISO standards), external tools and structured and unstructured decision-making methods such as AHP is highlighted. This is in alignment with traditional methods in which the choice of design strategies and solutions, both for individual architectural heritage and systemic buildings, involves the collaboration of specific technical skills, including architects, engineers and planners, together with the overarching regulations. The automatic or semi-automatic improvement of models, reflecting changes in internal conditions (such as physical obsolescence) or external conditions (such as change of use or climate change), depends on how the standards are implemented. However, most experiences associate dynamic properties with models, ensuring that details are visualised in viewers such as ArcGIS™ (ESRI) and 3D City Database (3DCityDB).

In general, the use of external rules and the implementation of DSS require a coherent and overlapping structure of semantics. However, while comparing these experiences, it emerges that most applications apply a generic extension of the standard, going beyond the ADE structure already experienced for the cataloguing of the same

Cultural Heritage classes. This does not represent a limitation, but rather confirms the inherent flexibility and adaptability of the standard for future and further applications.

This research work presents an overview of this complexity towards the development of a structured and integrated code for the digitisation of the conservation process using the CityGML standard. The research carried out for this thesis also addressed the issue of the standardisation of the conservation process, and in detail for the phases of acquisition and systematisation of technical knowledge aimed at the identification of intervention strategies on an urban district scale. The digital code of practice developed is based on the use of a CityGML-based three-dimensional model integrated with a technical decision support system. The conceptualisation of CityGML-based digital code of practice with T-DSS (3D Semantical Historic District Systematic Code) involves developing strategies for the restoration and conservation of urban areas. This approach leverages CityGML, a standard for representing 3D city and landscape models, and integrates it with the systematic code for historic districts.

In detail, the research work proposes an operational-methodological flow using innovative tools and approaches for the systematisation and management of complex knowledge layers. Accordingly, this treatment outlines the systematisation of data and information according to defined logical-relational schemes, enabling the definition of further attributes through automated analyses, considering all scales of analysis (element, component, building, urban element). This aims at the creation of a standardised and integrated digital model where data, in all scales and dimensions, are usable and accessible by sector users and public bodies. Therefore, the digital code of practice is designed to support local administrators in the strategic choices of interventions and priorities, as well as in subsequent transformations for enhancement. In particular, the elaborated code of practice is based on the CityGML model for the management of neighbourhood areas and is implemented with an articulated system of reports for the evaluation of the conservation status of buildings.

This makes use of the integrability of the CityGML structure with an external Information System based on logical-mathematical rules (T-DSS), defined according to the standards for the evaluation of the state of conservation (UNI EN 16096: 2012, UNI CEN TS 17385:2019) and the identification of intervention classes.

The digital code of practice elaborated according to a procedural flow of steps and sub-steps constitutes a solid support for setting up digital recovery plans. Furthermore, the operational-methodological process is designed to be open to innovative and traditional methods in the calculation of conservation status. Manual techniques and automatic methods supported by artificial intelligence applied to images or orthophotos (image processing, machine learning) for the assessment of decay extents can be easily included. Nevertheless, the introduction of the T-DSS rules within the FME transformation tool allows the realisation of a semantic model with a high updating potential over time. The continuous process of tissue enhancement determined by private owners can be easily included in the models, enhancing the prioritisation of district-scale interventions. Furthermore, this allows administrators to modify the models even if they do not have high IT skills or need external expertise for the purpose.

Added to this is the remote use of the historic district by means of digital models processed using Virtual Reality techniques. This follows from the non-existence of digitised parts of historic urban areas. In fact, historic urban areas precisely because of their morpho-typological component require specific operational protocols to be acquired and processed. Consequently, the use of Virtual Models based on spherical images certainly constitutes an intelligent tool for the rapid survey of the real environment, allowing in all phases, the continuous visualisation and complete fruition of the places, overcoming the need to repeat surveys by the same user or to physically involve several actors in the reading of the architecture. On the other hand, the integrated approach according to Virtual Reality techniques also offers the opportunity to share knowledge between different actors involved in the process. The sharing of virtualised knowledge on Cultural Heritage highlighted the potential in linking Virtual Models with external structured databases for coherent information management and semi-structured support to technicians in solving the diagnosis. Furthermore, the realised r-DB was tested for the objective, verifying its consistency with the traditional operational activities of the experts.

However, among the various ways of creating digital models, the use of structured ontologies allows the renewal of traditional procedures by guaranteeing the universality and independence of technical knowledge for the purpose, as well as the extension of analysis to thematic issues (energy, seismic and flood risks). Actually, the CityGML standard is an open data model developed to store and share parametric models of three-dimensional cities. This fusion allows for comprehensive digital recovery plans that incorporate detailed semantic information, fostering a holistic understanding of historical and architectural elements within urban environments.

The digital code of practice developed showed the potential in extending the structure of CityGML to cover all data classes of the existing architectural heritage as well as all stages of the conservation process.

The validation of the digital code of practice was assessed through the results obtained during its experimental application on the three pilot case studies. On the one hand, these pilot cases are comparable in terms of their historical-architectural and constructional characteristics, on the other hand, they present significant differences in relation to their particular conservation criticalities.

Future Developments

Future advances in the research objective aim to address both semantic and geometric aspects to support the standardisation and digitisation of cognitive and conservation processes in historic districts. Specifically, the focus will be on structuring a specific Application Domain Extension (ADE) for technical knowledge related to the built architectural heritage. This will enable a comprehensive understanding of the existing built heritage among experts from various disciplinary fields.

At the same time, efforts will be made to extend the urban parametric model to a higher level of geometric detail (LOD), improving the representation of architectural and urban elements within the CityGML standard. This advancement will contribute to a more accurate and sophisticated representation of historic neighbourhoods.

In addition, the integration of the CityGML-based model with BIM-based models will be pursued. This integration will merge geometric information with management data of historic buildings, enabling the creation of holistic models crucial for decision-making, preservation and maintenance strategies.

Finally, the research update aims to incorporate the latest version of the CityGML standard (version 3.0) to ensure its continued relevance and effectiveness.

In this way, the functionality and potential of digital systems and models can contribute more to the applicability of the research elaborated in this thesis, as well as solve the main critical issues related to the traditional conservation process.

NOTES

1. The President of the Italian Republic. Legislative Decree No. 42 of 22 January 2004, "Code of Cultural and Landscape Heritage", pursuant to Article 10 of Law No. 137 of 6 July 2002, (2004). Italy.

2. Getty Vocabularies, http://vocab.getty.edu/

3. The preventive maintenance supports a periodic assessment of risks and threats for evaluating the vulnerability of the architecture. In other words, it goes beyond analysing the building only when a clear problem emerges, instead of embracing a proactive approach that involves ongoing monitoring and the management of potential risks and threats..

4. "INSPIRE" stands for "Infrastructure for Spatial Information in the European Community." It's a European Union directive that aims to create a standardized framework for sharing and acces-sing environmental and geographic data across European countries. The INSPIRE Directive faci-litates better environmental policies and decision-making by making geographical information more accessible and interoperable.

5. IndoorGML stands for "Indoor Geography Markup Language". It is is an open standard develo-ped by the Open Geospatial Consortium (OGC) and is designed to ensure interoperability and da-ta exchange between different software and systems. It provides a common framework for re-presenting indoor spatial data and introducing the “cellular space” concept.

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Zoellner, M., Stricker, D., Bleser, G., & Pastarmov, Y. (2007). iTACITUS–novel interaction and tracking paradigms for mobile AR. *The European Research Network of Excellence in Open Cultural Heritage (EPOCH)*, 110–117.

Zonno, M., Capotorto, S., & Maiellaro, N. (2012). *Fotografia immersiva applicata ai beni culturali*.

CURRICULUM

INFORMAZIONI PERSONALI

Nome	**LASORELLA MARGHERITA**
Data di nascita	20/10/1993

ESPERIENZA LAVORATIVA

Date	31 Dicembre 2022 – in itinere
Nome e indirizzo del datore di lavoro	Comune di Brindisi, Piazza Matteotti, 1 – 72100 Brindisi (BR)
Tipo di azienda o settore	Ente Locale
Tipo di impiego	**Istruttore Direttivo Tecnico – Cat. D** **Posizione economica D1** Presso il Settore Pianificazione e Gestione del Territorio

Principali mansioni e responsabilità

Responsabile del servizio: Programmi di Rigenerazione Territoriale, Opere per reti tecnologiche e impianti FER, Piani di Settore e Servizio Cartografico.

Altre attività e funzioni svolte:

- RUP dell'intervento n. 4 "Realizzazione di piste pedonali e ciclabili verdi (green soft mobility) lungo il waterfront"
  Programma di Azione e Coesione complementare al PON, asse B "RECUPERO WATERFRONT DEL PAC "INFRASTRUTTURE E RETI" 2014-2020, Progetto "Brindisi Smart City Port".
  Dal 11/04/2023 – in itinere
- Supporto al RUP dell'intervento di "Recupero e Rifunzionalizzazione dell'Ex Consultorio e degli spazi di pertinenza antistanti per realizzare la casa della legalità e del benessere" al Quartiere Paradiso. Fondo di Sviluppo e Coesione 2014-2020 – Patto per la Puglia – Azione "Rigenerazione Urbana e Sostenibile"
  Dal 27/10/2023 – in itinere

	• RUP dell'intervento di "Recupero e Rifunzionalizzazione dell'Ex Consultorio e degli spazi di pertinenza antistanti per realizzare la casa della legalità e del benessere" al Quartiere Paradiso. Fondo di Sviluppo e Coesione 2014-2020 – Patto per la Puglia – Azione "Rigenerazione Urbana e Sostenibile" Dal 12/05/2023 al 26/10/2023 • Componente e Responsabile del Procedimento, del settore Pianificazione e Gestione del Territorio, dell'Ufficio FER
Date	12 Settembre 2022 – 30 Dicembre 2022
Nome e indirizzo del datore di lavoro	Comune di Mola di Bari, via De Gasperi – 70042 Mola di Bari (BA)
Tipo di azienda o settore	Ente Locale
Tipo di impiego	**Istruttore Tecnico – Cat. C (tempo indeterminato e parziale, 18 ore settimanali) - Posizione economica C1** Presso il Settore Urbanistica
Principali mansioni e responsabilità	Edilizia ed Urbanistica
Date	Marzo 2022 – Giugno 2022
Nome e indirizzo del datore di lavoro	Politecnico di Bari, via Giovanni Amendola 126/b.
Tipo di azienda o settore	DICATECh-Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e di Chimica
Tipo di impiego	**Conferimento di incarico relativo all'affidamento di attività integrativa alla didattica presso il DICATECh del Politecnico di Bari per l'A.A. 2021/2022**
Principali mansioni e responsabilità	L'attività integrativa alla didattica è stata svolta nell'ambito della materia di Architettura Tecnica.
Date	29 Dicembre 2021 – 6 Settembre 2022
Nome e indirizzo del datore di lavoro	Comune di Carovigno, via Giuseppe Verdi 1 – 72012 Carovigno (BR)
Tipo di azienda o settore	Ente Locale
Tipo di impiego	**Istruttore Tecnico – Cat. C (tempo indeterminato e parziale, 18 ore settimanali) - Posizione economica C1** Presso Servizio/Ufficio Area 3 Urbanistica/Lavori Pubblici
Principali mansioni e responsabilità	Istruttoria di Pratiche edilizie
Date	Aprile 2019 – Luglio 2020
Nome e indirizzo del datore di lavoro	Politecnico di Bari, via Giovanni Amendola 126/b.
Tipo di azienda o settore	DICATECh-Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e di Chimica

Tipo di impiego	**Assegno di ricerca nell'ambito del progetto "V.E.R.B.U.M.-Virtual Enhanced Reality for Building Modelling".** Bando della Regione Puglia INNONETWORK POR Puglia FESR-FSE 2014-2020 – Asse I - Azione 1.6 Partner: B.Re.D. srl (CAPOFILA), Boviar srl, Impresa Garibaldi Fragasso srl, Politecnico di Bari – DICATECh, Politecnico di Bari – DEI.
Principali mansioni e responsabilità	Titolo della ricerca: Elaborazione ed implementazione dei dati di conoscenza e diagnostica e progettazione per la fruizione in ambienti digitali di realtà aumentata.L'attività di ricerca ha riguardato l'analisi e la creazione di ambienti virtuali immersivi, attraverso l'utilizzo di specifici software (Tourweaver© e 3D Vista Virtual Tour©), per la fruizione di Beni Culturali.
Date	Ottobre 2018 – Gennaio 2019
Nome e indirizzo del datore di lavoro	Politecnico di Bari, via Giovanni Amendola 126/b.
Tipo di azienda o settore	SBA- Polo biblioteche.
Tipo di impiego	**Incarico di collaborazione a tempo parziale, in attività connesse a servizi universitari, di un totale ore pari a 120**
Principali mansioni e responsabilità	Assistenza, supporto e consulenza per la consultazione dei libri.
Date	Settembre 2018 – Novembre 2018
Nome e indirizzo del datore di lavoro	Museo Nazionale Archeologico di Egnazia, Fasano (BR)
Tipo di impiego	**Tirocinio formativo**
Principali mansioni e responsabilità	Nel periodo del tirocinio ho svolto la ricerca storica e il rilievo fotografico, metrico e fotogrammetrico, dell'antica città di Egnazia e in particolare del Criptoportico.
Date	Aprile 2016 – Settembre 2016
Nome e indirizzo del datore di lavoro	Politecnico di Bari, via Giovanni Amendola 126/b.
Tipo di azienda o settore	Biblioteca centrale M. B., aula multimediale.
Tipo di impiego	**Incarico di collaborazione a tempo parziale, in attività connesse a servizi universitari, di un totale ore pari a 120**
Principali mansioni e responsabilità	▪ Assistenza, supporto e consulenza nell'utilizzo delle tecnologie informatiche, ▪ Verifica dello stato di funzionalità ed operatività dei P.C., ▪ Installazione/disinstallazione di software.

Date	Gennaio 2016 – Marzo 2016
Nome e indirizzo del datore di lavoro	Studio tecnico Ing. Sciannameo Nicola, con sede in via Cianciaruso n. 42, Noicàttaro (BA)
Tipo di impiego	Tirocinio formativo
Principali mansioni e responsabilità	Nel periodo del tirocinio ho svolto il rilievo architettonico di un edificio storico ubicato in Noicàttaro (BA). Al termine del lavoro assegnato ho acquisito la padronanza dei metodi, degli strumenti e delle tecniche fondamentali del rilievo architettonico.

ISTRUZIONE E FORMAZIONE

Date	Gennaio 2023- Luglio 2023
Nome e tipo di istituto di istruzione o formazione	Università Politecnica di Valencia, Camí de Vera, s/n, Algirós, 46022 València, Valencia, Spagna **Attività all'estero svolta nel corso del terzo anno di dottorato** Co-tutor: Prof.ssa Yolanda Hernández Navarro
Date	Novembre 2020- in itinere
Nome e tipo di istituto di istruzione o formazione	Politecnico di Bari, via Giovanni Amendola 126/b. Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e di Chimica. Vincitrice con borsa, **Dottorato di Ricerca in "Rischio, Sviluppo Ambientale, Territoriale ed Edilizio", XXXVI Ciclo** Tutor: Prof. Fabio Fatiguso
Date	Giugno 2020
Nome e tipo di istituto di istruzione o formazione	Università telematica eCampus, Novredate (CO)
Qualifica conseguita	**Percorso formativo docenti (D.M. 616) – Corso singolo 24 CFU**
Date	Ottobre 2019
Nome e tipo di istituto di istruzione o formazione	Politecnico di Bari, via Giovanni Amendola 126/b.
Qualifica conseguita	**Abilitazione alla professione di Ingegnere civile e ambientale (SEZ.A)**

Date	Ottobre 2016 – Febbraio 2019
Nome e tipo di istituto di istruzione o formazione	Politecnico di Bari, via Giovanni Amendola 126/b.
Principali materie / abilità professionali oggetto dello studio	Competenze nella progettazione di sistemi edilizi complessi, con riguardo agli aspetti tecnologici, strutturali, di qualità ambientale, ovvero alle condizioni di benessere, alla vita di servizio e alle problematiche energetiche e di impatto ambientale; nel recupero, riqualificazione, manutenzione e gestione del patrimonio edilizio esistente; nella rigenerazione urbana; nello sviluppo del processo edilizio, per gli aspetti operativi, economici e gestionali; nella gestione dei processi tecnologici e produttivi relativi al comparto edile, con particolare attenzione ai problemi della sicurezza; nell'innovazione tecnologica e nella sperimentazione e nel controllo di qualità dei prodotti e delle opere.
Qualifica conseguita	**Laurea magistrale biennale in Ingegneria dei Sistemi Edilizi (LM-24)**
Livello nella classificazione nazionale	110/110 con LODE
Tesi di Laurea	TESI DI LAUREA IN RECUPERO DEGLI EDIFICI STORICI + MANUTENZIONE E CONSERVAZIONE DEL PATRIMONIO EDILIZIO ESISTENTE Relatore: Prof. Fabio Fatiguso Correlatori: Prof.ssa Mariella De Fino, Geom. Riccardo Tavolare Titolo della tesi: "Tecniche di realtà virtuale per il recupero e la fruizione di siti archeologici. Il caso di Egnazia." Il lavoro di tesi si inquadra all'interno del Programma INTERREG IPA-CBC (Italy -Albania - Montenegro), del Progetto di ricerca 3D IMPACT "Virtual reality and 3D experiences to IMProve territorial Attractiveness, Cultural heritage, smart management and Touristic development", avente come caso di studio il Criptoportico del Parco Archeologico di Egnazia.
Date	Ottobre 2012 – Aprile 2016
Nome e tipo di istituto di istruzione o formazione	Politecnico di Bari, via Giovanni Amendola 126/b.
Principali materie / abilità professionali oggetto dello studio	Conoscenza delle discipline fisico-matematiche (analisi I e II, geometria, fisica e chimica) e delle materie fondamentali proprie dell'ingegneria edile (storia dell'architettura, disegno dell'architettura, architettura tecnica, tecnologia dei materiali, ambiente e sistemi edilizi, estimo, topografia, progetto di servizi tecnologici, geotecnica, organizzazione del cantiere, scienza e tecnica delle costruzioni).

	Le competenze acquisite durante il corso di studi riguardano le attività di supporto della progettazione e di ingegnerizzazione del progetto, con le attività di rilevamento di aree e manufatti edilizi, l'organizzazione e la conduzione del cantiere edile, la gestione e valutazione economica dei processi edilizi, la direzione tecnico-amministrativa dei processi di produzione industriale di materiali e componenti per l'edilizia.
Qualifica conseguita	**Laurea triennale in Ingegneria Edile (L-23)**
Livello nella classificazione nazionale	109/110
Tesi di Laurea	TESI DI LAUREA IN DISEGNO DELL'ARCHITETTURA Relatore: Prof. Giovanni Mongiello Correlatore: Geom. Riccardo Tavolare Titolo della tesi: "Il rilievo e la rappresentazione per il progetto di ristrutturazione. Il caso dell'Ex Frantoio di Noicàttaro."
Date	Settembre 2007 – Luglio 2012
Nome e tipo di istituto di istruzione o formazione	Liceo Scientifico Statale "Ilaria Alpi", Rutigliano (Ba)
Principali materie / abilità professionali oggetto dello studio	Principali materie trattate: matematica, fisica, chimica, informatica, disegno e tecnologia, inglese e materie umanistiche.
Qualifica conseguita	**Diploma di maturità scientifico tecnologico**
Livello nella classificazione nazionale	100/100

CAPACITÀ E COMPETENZE PERSONALI

Acquisite nel corso della vita e della carriera ma non necessariamente riconosciute da certificati e diplomi ufficiali.

Madrelingua	Italiano

ALTRE LINGUA

	Inglese
Capacità di lettura	B2
Capacità di scrittura	B2
Capacità di espressione orale	B2

CAPACITÀ E COMPETENZE RELAZIONALI	Buone capacità comunicative e ottime capacità relazionali sviluppate sia in ambito universitario, durante il periodo dell'assegno di ricerca e il percorso di dottorato di ricerca presso il Politecnico di Bari, sia in ambito professionale. Attitudine a comunicare in modo chiaro e preciso, rispondendo a specifiche richieste della committenza e dell'utenza di riferimento. Capacità di lavorare in gruppo, maturata durante il percorso universitario e professionale, indispensabile per il raggiungimento di obiettivi.
CAPACITÀ E COMPETENZE ORGANIZZATIVE	L'istruzione tecnico-scientifica ricevuta durante gli anni di studio, unita all'esperienza lavorativa mi ha permesso di sviluppare ottime capacità organizzative verso i vari impegni sia di studio che di lavoro. Durante l'esperienza lavorativa ho maturato una buona capacità di problem solving nella gestione in autonomia di attività molteplici. Sono sempre riuscita durante il mio percorso universitario e professionale a rispettare le scadenze e i termini per le consegne dei risultati e lo svolgimento degli obiettivi nei tempi previsti.
CAPACITÀ E COMPETENZE TECNICHE	Competenze informatiche ▪ Sistemi operativi: Windows e Mac OS X; ▪ Pacchetto Office: Word, Excel, PowerPoint, OneNote, Outlook, Access, Publisher; ▪ Software CAD: Autocad (Autodesk); ▪ Software per la modellazione 3D: Cinema 4D (Maxon); ▪ Software render: Artlantis Studio; ▪ Software BIM: Revit (Autodesk), Archicad (Graphisoft); ▪ Software di elaborazione nuvole di punti: PhotoScan (Agisoft), Recap PRO (Autodesk); ▪ Software GIS: QGIS (open source) e ArcGIS (Esri); ▪ Software di foto editing: Adobe Photoshop (Adobe System); ▪ Software Virtual Tour: Tourweaver (Easypano), 3DVista Virtual Tour (3DVista Software); ▪ Browser: Google Chrome, Internet Explorer, Mozilla Firefox, Safari.
PATENTE	Patente di tipo B

ULTERIORI INFORMAZIONI

CERTIFICAZIONI

• Certificato BIM SPECIALIST for BUILDING con software Autodesk Revit
Rilasciato da: ICMQ S.P.A., Milano (Italia)
Data di emissione: 28/11/2018 Data di scadenza: 27/11/2021

• Certificato ECDL-European Computer Driving Licence
Rilasciato da: Liceo Scientifico Statale "Ilaria Alpi" Rutigliano, Bari
Data: 19/06/2009

CORSI

• Corso Aggiornamento Professionale BIM Specialist
Rilasciato da: Graitec, Autodesk Platinum Partener presso il Politecnico di Bari, Bari
Durata: 6 ore
Data: Settembre 2019

• Corso Preparazione certificazione Bim Specialist
Rilasciato da: Graitec, Autodesk Platinum Partener presso il Politecnico di Bari, Bari
Durata: 12 ore
Data: Ottobre 2018

• Corso Autodesk Revit
Rilasciato da: Graitec, Autodesk Platinum Partener presso il Politecnico di Bari, Bari
Durata: 40 ore
Data: Ottobre 2018

• Corso Autodesk REVIT Base
Rilasciato da: Politecnico di Bari, Bari
Data: Dicembre 2016

• Corso Portale Web-Grafica e template
Rilasciato da: Liceo Scientifico Statale "Ilaria Alpi" Rutigliano, Bari
Data: Maggio 2010
Competenze acquisite:
-gestione portale web;
-sviluppo portale e comunicazione;
-organizzazione dei contenuti

PUBBLICAZIONI

1. **Lasorella, M.,** de Dato, P., Cantatore, E., (2024). Web-based platform to collect, share and manage technical data of historical systemic architectures: the Telegraphic Towers along the Madrid-Valencia path. VIRTUAL ARCHAEOLOGY REVIEW, ISSN: 1989-9947, doi: 10.4995/var.2024.20341 (RIVISTA SCIENTIFICA)

2. De Fino, M., Fortunato, T., **Lasorella, M**., & Fatiguso, F. (2024). Moisture-Related Problems in Historical City Centres: A GIS-Based Workflow for Decay Assessment and Treatment. In Sustainability in Energy and Buildings 2023 (pp. 509-521). Singapore: Springer Nature Singapore. (**RIVISTA CLASSE A**)

3. **Lasorella, M**., Cantatore, E., (2023). 3D MODELS CITYGML-BASED COMBINED WITH TECHNICAL DECISION SUPPORT SYSTEM FOR THE SETTING UP OF DIGITAL CONSERVATION PLANS OF HISTORIC DISTRICTS. INTERNATIONAL ARCHIVES OF THE PHOTOGRAMMETRY, REMOTE SENSING AND SPATIAL INFORMATION SCIENCES, vol. XLVIII-M-2-2023, p. 911-918, ISSN: 2194-9034, doi: 10.5194/isprs-archives-XLVIII-M-2-2023-911-2023.(**RIVISTA CLASSE A**)

4. Galantucci, R. A., **Lasorella, M**., De Fino. M. (2023). A RAPID PIPELINE FOR PERIODIC INSPECTION AND MAINTENANCE OF ARCHITECTURAL SURFACES. INTERNATIONAL ARCHIVES OF THE PHOTOGRAMMETRY, REMOTE SENSING AND SPATIAL INFORMATION SCIENCES, vol. XLVIII-M-2-2023, p. 621-628, ISSN: 2194-9034, doi: 10.5194/isprs-archives-XLVIII-M-2-2023-621-2023 (**RIVISTA CLASSE A**)

5. **Lasorella, M.,** Cantatore, E., (2023). 3Dcitymodels to support technical knowledge and management of historic built environments. A semantic CityGML-based model for the ancient core of Carovigno (BR), Italy. SCIRES-IT, vol. 13, p. 101-116, ISSN: 2239-4303, doi: 10.2423/i22394303v13n1p10 (**RIVISTA CLASSE A**)

6. **Lasorella, M**., Cantatore, E., Fatiguso, F. (2023). MODELLI CITYGML-BASED SUPPORTATI DA SISTEMI DECISIONALI PER LA CONSERVAZIONE E LA GESTIONE DEL PATRIMONIO STORICO-CULTURALE. UNA REVISIONE SISTEMATICA. In: “In Transizione: sfide e opportunità per l’ambiente costruito”. p. 345-363, EdicomEdizioni, ISBN: 979-12-81229-02-0

7. **Lasorella, M.,** Cantatore, E., Fatiguso, F. CityGML-based models for the qualification of cultural built environment: the 3D Semantical City Model of the historic district of Carovigno (BR), Italy. In Xth ReUSO Conference- Documentation, Restoration and Reuse of Heritage, 2-4 November, 2022. Porto, Portugal (published abstract)

8. **Lasorella, M**., Cantatore, E., Fatiguso, F.. (2022). La conoscenza tecnica del patrimonio architettonico a bassa accessibilità mediante Modelli Virtuali. In: "Il patrimonio culturale pugliese. Ricerche, applicazioni e best practices.". vol. 2, p. 81-86, Edizioni Fondazione Pasquale Battista, ISBN: 9791221035810

9. De Fino, M., **Lasorella, M**., Fatiguso, F.. (2022). Managing diagnostic data for seismic vulnerability assessment of building stocks by an integrate GIS/VR approach. In: "REHABEND 2022 Construction Pathology, Rehabilitation Technology and Heritage Management". p. 881-891, ISBN: 978-84-09-42253-1, Granada (Spain), September 13th-16th, 2022

10. **Lasorella, M.**, Cantatore, E., de Dato, P., Fatiguso, F.. (2022). Ar.KnoWeb (Architectural Knowledge Web). Una piattaforma metodologica per la conoscenza tecnica di architetture sistemiche. In: "Memoria e Innovazione Memory and Innovation". p. 1439-1454, ISBN: 978-88-945937-4-7

11. Cantatore E., **Lasorella M..** (2022) Approfondimento A.4.1 La struttura del CityGML per la gestione della conoscenza tecnica del patrimonio diffuso e delle priorità d'intervento a scala di distretto - il tool tecnico informativo per il centro storico di Ascoli Satriano (FG). In: "Resilienza ai cambiamenti climatici dei distretti storici in area mediterranea. Teoria e metodi per l'analisi e la gestione", Roma, Gangemi Editore spa, pp 151 -166, ISBN 978-88-492-4513-4

12. Cantatore E., **Lasorella M..(**2022) Approfondimento A.4.2 L'uso dei Virtual Tour per la comunicazione del rischio – il modello pervasivo per il caso di Molfetta (BA). In: "Resilienza ai cambiamenti climatici dei distretti storici in area mediterranea. Teoria e metodi per l'analisi e la gestione", Roma, Gangemi Editore spa, pp 167 -175, ISBN 978-88-492-4513-4

13. **Lasorella, M.**, Cantatore, E., Fatiguso, F.. (2021). Smart approaches to enhance technical knowledge of in/low-accessible heritage. SCIRES-IT, vol. 11, p. 97-112, ISSN: 2239-4303, doi: 10.2423/i22394303v11n2p97(**RIVISTA CLASSE A**)

14. Cantatore, E., **Lasorella, M.**, Fatiguso, F.. (2021). Resilient Improvement of Historic Districts via Digital Tools. The Virtualization of Energy Retrofit Actions Using Simplified CityGML-Based Plans. In: Computational Science and Its Applications, ICCSA 2021 : 21st International Conference, Cagliari, Italy, September 13-16, 2021. LECTURE NOTES IN COMPUTER SCIENCE, vol. 12956, p. 155-172, Cham:Springer, ISBN: 978-3-030-87009-6, ISSN: 0302-9743, doi: 10.1007/978-3-030-87010-2_11

15. Cantatore E., **Lasorella M.**, Fatiguso F. (2021). La gestione della resilienza dei centri storici con modelli digitali. Virtualizzazione di azioni energetico-resilienti in piani CityGML-based. In: "Design and construction: tradition and innovation in the practice of architecture = Progetto e costruzione : tradizione e innovazione nella pratica dell'architettura". p. 1627-1645, MONFALCONE (GORIZIA):EdicomEdizioni, ISBN: 978-88-96386-62-0

16. Fatiguso F., De Fino M., Ceppi. C., Martino A., **Lasorella M.**, Galantucci M. L., Documentazione digitale di beni architettonici mediante integrazione di sistemi informativi e modelli fotorealistici in realta' virtuale. In: "Dialoghi multidisciplinari per la ricerca, la tutela e la valorizzazione: atti Primo convegno Beni culturali in Puglia". p. 195-202, Bari: Edizioni Fondazione Pasquale Battista, ISBN: 979-12-200-9282-1

17. Cantatore, E., **Lasorella, M.**, and Fatiguso, F (2020). Virtual reality to support technical knowledge in cultural heritage. The case study of cryptoporticus in the archaeological site of Egnatia (Italy). INTERNATIONAL ARCHIVES OF THE PHOTOGRAMMETRY, REMOTE SENSING AND SPATIAL INFORMATION SCIENCES, vol. XLIV-M-1-2020, p. 465-472, ISSN: 1682-1750, doi: 10.5194/isprs-archives-XLIV-M-1-2020-465-2020 (**RIVISTA CLASSE A**)

PARTECIPAZIONE A CONFERENZE COME MEMBRO

1. Convegno Colloqui.AT.e 2023
14-17 Giugno 2023 - Bari
In qualità di membro della Segreteria Scientifica e Organizzativa

2. International Conference on Advanced Research in Technologies, Information, Innovation and Sustainability – ARTIIS 2023
18-20 Ottobre 2023 - Madrid, Spagna
In qualità di membro del comitato di programma e con ruolo di revisore.

PARTECIPAZIONE A CONFERENZE COME RELATORE

1. International Conference on Sustainability in Energy and Buildings – SEB-2023
18-20 Settembre 2023
Bari, Italia
Titolo della Presentazione: Moisture-related problems in historical city centers: a GIS-based workflow for decay assessment and treatment

2. The 29th International CIPA Symposium " Documenting, Understanding, Preserving Cultural Heritage: Humanities and Digital Technologies for Shaping the Future"
25-30 Giugno 2023
Firenze, Italia
Titolo della Presentazione: 3D MODELS CITYGML-BASED COMBINED WITH TECHNICAL DECISION SUPPORT SYSTEM FOR THE SETTING UP OF DIGITAL CONSERVATION PLANS OF HISTORIC DISTRICTS

3. Conferenza ReUSO - Documentation, Restoration and Reuse of Heritage
2-4 Novembre 2022
Porto, Portogallo
Titolo della Presentazione: CityGML-based models for the qualification of cultural built environment: the 3D Semantical City Model of the historic district of Carovigno (BR), Italy

PARTECIPAZIONE A PROGETTI DI RICERCA

Progetto di ricerca scientifica afferente al fondo di ricerca di ateneo "Valutazione e gestione del patrimonio storico-architettonico mediante modelli 3D e ambienti digitali immersivi" (2021). Responsabile scientifico: Prof.ssa Mariella De Fino

Progetto "V.E.R.B.U.M.-Virtual Enhanced Reality for Building Modelling". (2018-2020)

Abstract
La conservazione del patrimonio architettonico esistente richiede un processo multi-livello e multi-tematico in grado di collazionare e relazionare entità architettoniche (edifici, chiese…) e urbane (strade, spazi aperti…), nonché proprietà dei componenti (murature, coperture…) e servizi (reti idriche, elettriche…), in maniera strutturata e sistemica. Nel corso del tempo, i tradizionali strumenti e protocolli procedurali tradizionali per la creazione e la restituzione di piani di recupero hanno evidenziato criticità in termini di organicità e interpretazione dei dati raccolti, nonché un'eccessiva richiesta di tempi per la loro elaborazione. Parallelamente, le recenti attività di ricerca e applicazione nell'ambito dei sistemi IoT hanno evidenziato come i modelli digitali parametrici, basati su ontologie strutturate (CityGML, BIM) e i sistemi informativi (Geo-Database e database relazionali), consentono la sistematizzazione dei dati di conoscenza tecnica e la determinazione di relazioni univoche nel rispetto delle esistenti normative del settore. In questo scenario, il lavoro di ricerca mira alla sistematizzazione delle informazioni di conoscenza tecnica già disponibili, e al contempo ad individuare flussi operativi-metodologici finalizzati a colmare le esistenti procedure lacunose e farraginose mediante l'utilizzo di modelli digitali. Nello specifico, l'obiettivo dell'attività di ricerca del dottorato propone un codice di pratica digitale per la conservazione e la gestione del patrimonio architettonico esistente attraverso l'ausilio di modelli parametrici, nonché mediante approcci speditivi VR-based. Conseguentemente, il codice di pratica digitale è stato applicato e validato su tre casi pilota emblematici rispetto alle criticità intrinseche legate all'obsolescenza fisica e normativa delle aree storiche individuate.

Cover image: Il modello CityGML-Based del Centro Storico di Ascoli Satriano (FG)

Abstract

The conservation of existing architectural heritage requires a multi-level and multi-thematic process for their analysis and diagnosis, capable of collecting and correlating architectural entities (buildings, churches...) and urban entities (roads, open spaces...), as well as properties of the components (walls, roofs...) and services (water, electricity networks...), in a structured and systemic way. Over time, traditional procedural tools and protocols for crafting and presenting recovery plans have highlighted critical issues in terms of organicity and interpretation of the data collected, as well as an excessive request time for their processing. In parallel, recent research and application activities in the field of IoT systems have showed how digital models based on structured ontologies (CityGML, BIM) and information systems (Geo-Database and relational databases) allow the systematization of technical knowledge and the determination of unique relationships in compliance with existing sector regulations. In this scenario, the research work aims to systematise the technical knowledge information already available and, at the same time, to identify operational-methodological flows aimed at filling the existing incomplete and jumbled procedures through the use of parametric and virtual digital models. Specifically, the objective of the present research proposes a code of digital practice for the conservation and management of existing architectural heritage through the aid of parametric digital models, as well as through expeditious VR-based approaches. The digital code of practice has applied and validated on three emblematic pilot cases with respect to the intrinsic criticalities linked to the physical and regulatory obsolescence of the identified historical area.

Cover image:The 3D Model CityGML-Based
of the Historic Centre of Ascoli Satriano (FG)