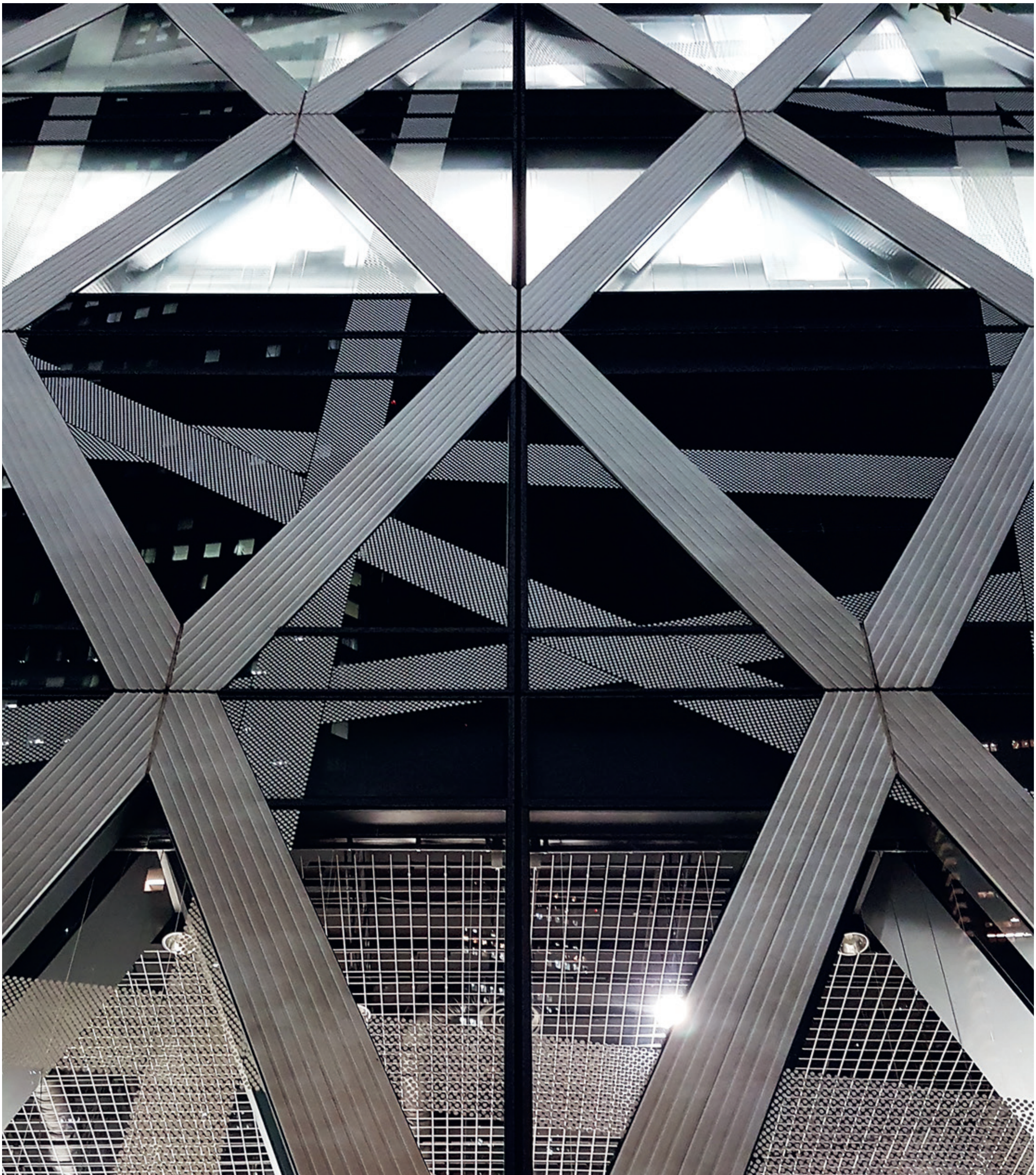

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Cover illustration: Mode Gakuen Cocoon Tower in the Nishi-Shinjuku district (Tokyo, Japan) by Kenzō Tange, external view. © Riccardo Gulli, 2018

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INTEGRATING DECISION SUPPORT SYSTEMS INTO CITYGML-BASED TECHNICAL MODELS FOR THE MANAGEMENT OF TECHNICAL INTERVENTIONS IN HISTORIC DISTRICTS

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Abstract

The digitalisation of architectural heritage represents a valuable opportunity to improve the management and transfer of technical knowledge related to refurbishment and conservation practices in historic districts. Within this context, the CityGML standard has emerged as a robust framework for organising and sharing structured, multiscale, and multidisciplinary information. However, to fully meet the requirements of heritage rehabilitation planning, CityGML-based models must evolve from static data containers into dynamic decision-support tools.

This paper presents a methodology for developing a Technical Digital Model enhanced with a Decision Support System (T-DM DSS), designed to support the refurbishment and conservation process of historic buildings through the integration of technical, regulatory, and semantic knowledge. The method converts traditional refurbishment practices (such as manuals, codes of practice, and administrative constraints) into a coherent CityGML-based structure, enriched with logical rules that guide intervention choices and ensure regulatory compliance. The approach is supported by a modular workflow composed of a structured technical database, a CityGML-based model, and a web-based sharing platform with differentiated user access.

The application to the historic district of Corleto Perticara (PZ) demonstrates the system's ability to unify fragmented data sources and provide a scalable tool for both practitioners and policymakers. Through the use of the FME visual programming environment, conditional rules were embedded to automate the classification of intervention strategies based on physical and regulatory parameters. Moreover, the use of a platform to share database contents not only ensures consistent data interpretation but also enhances transparency, interoperability, and accessibility of recovery-related information.

Keywords

Historic district, Refurbishment and conservation, Intervention types, Informative system, Digital modelling.

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1. INTRODUCTION

The refurbishment and conservation of architectural heritage in historic districts are inherently multidisciplinary processes, encompassing technical, historical, cultural, and administrative layers of knowledge. These layers are relevant to buildings characterised by diverse uses and morphological typologies [1–3]. Alongside special-purpose structures such as churches and convents, serial civil buildings – primarily residential – are widely distributed throughout historic urban cores. These structures form systems of similar typologies that reflect the historical and cultural evolution experienced over time.

Due to their historical and landscape significance, interventions for the refurbishment and conservation of such buildings demand the management of multi-layered information. This information must align coherently with the associated value system, involving:

- the broader system of buildings, considered as the landscape dimension of these urban areas;
- their sub-components, detailing building techniques and materials;
- distinctive elements that contribute to the uniqueness of the local built environment.

These layers of information constitute the basis of the technical knowledge typically employed during the preliminary stages of refurbishment processes, serving as a cornerstone for the assessment of architectural heritage. The identification of suitable interventions must also be integrated with administrative requirements (e.g., structural and sanitary regulations) and statutory heritage protection constraints. Although these aspects are traditionally embedded in the knowledge and management practices for architecture in historic districts, their inherent complexity – stemming from the multidimensional and multi-thematic nature of the data – has underscored the need for a coherent structure capable of systematically gathering and organising such information. Beyond preliminary phases, this structured knowledge system must be shared with practitioners, who are the end users of technical information in the refurbishment process. It also acts as a mediator between administrative interpretation and the design of appropriate interventions for conservation of architectural qualities [4–6].

Despite variations in administrative frameworks, rehabilitation and conservation plans for historic districts play a central role in directing data collection, organisation, and analysis. However, due to the complexities involved, such plans are often unavailable or fragmented, and their content is instead dispersed across thematic reports. This lack of coherence in information structures compromises the overall quality of knowledge and management processes for architectural heritage, leading to fragmented data, inconsistencies, and diminished technical rigour in practitioners' work.

Recent advances in the digitalisation of the built environment offer promising solutions, transforming physical buildings into digital models enriched with thematic data. Initial experiments using GIS tools for the documentation of historic districts and data management [7–9] have since evolved into more robust applications involving Industry Foundation Classes (IFC) and CityGML standards, each operating at different spatial and semantic scales [10]. The key distinction between GIS-based and IFC/CityGML-based systems lies in data structuring, with the latter offering more rigid yet expandable frameworks. Among these, the CityGML standard is particularly well-suited for managing spatial details in 3D modelling. It combines the strengths of traditional geographic information systems with standardised data structures [11, 12]. Its granular structure enables consistent representation across scales – from individual building components to entire urban areas – and supports the integration of external ontologies through a modular and logically governed framework. This enhances the technical robustness of modelling and facilitates comprehensive knowledge management.

In this context, CityGML emerges as a valuable tool for addressing the multidimensional and multi-thematic challenges involved in the refurbishment and conservation of architectural heritage within historic districts. Furthermore, the formulation of coherent logical rules within structured datasets enables the alignment of administrative processes through Decision Support Systems (DSS), offering structured guidelines for practitioners and actionable datasets for policymakers.

Accordingly, interactive platforms serve an essential function, working as graphical interfaces through which geometric and thematic data can be shared among stakeholders involved in data collection, organisation, and revision, as well as practitioners responsible for technical employment.

Building on these premises, the paper presents and discusses a CityGML-based modelling approach applied to a real case study. The study outlines the creation and enhancement of a Thematic Digital Model (T-DM) for managing technical knowledge and refurbishment strategies for traditional architecture in historic districts. This model is further extended through the integration of a DSS. Specifically, the paper builds on a methodology previously proposed for structuring a CityGML-based T-DM for rehabilitation planning [13], detailing its enhancement through the integration of logical rules derived from complex and fragmented local administrative and documentary sources. These rules govern the classification and typology of interventions. Simultaneously, the method is proposed as a set of digital guidelines to support local policymakers across all phases of technical development, advocating the setup of multidisciplinary teams with both practical/IT and technical/administrative expertise. The subsequent paper's sections are organised as follows:

- section 2 presents an overview of existing CityGML-based applications integrated with DSS tools, identifying current opportunities, addressed challenges, and the innovative aspects of this research;
- section 3 details the methodology and tools used to enhance the T-DM CityGML-based model with a DSS to evaluate interventions at both building and component scales;
- section 4 applies the methodology to the Corleto Perticara case study, illustrating the specific structure and logic of the associated DSS;
- section 5 concludes with a comprehensive discussion of the findings.

2. BACKGROUND AND WORK AIM

As introduced in the previous section, the CityGML standard and its modelling capabilities represent a powerful tool for addressing multidisciplinary and multidimensional challenges related to the preservation of historic buildings. Its modular structure and parametric configuration enable the systematisation of technical knowledge in alignment with thematic details and the appropriate scale of information. Furthermore, when enhanced with external ontologies, the same content structure can be unambiguously interpreted by all technical experts involved in the processes of data collection, analysis, and management.

While such thematic dimensions have already been explored in prior scientific studies applying or examining CityGML standards for individual cases of historic and cultural built heritage [14, 15], an additional area of interest concerns the enhancement of the CityGML structure through the integration of logical rules. These aim to embed technical requirements or thematic application knowledge in the form of Decision Support Systems (DSS) to facilitate activities of refurbishment, maintenance, and management.

Enhancements of CityGML standards through DSS integration in the context of architectural heritage have been addressed in the literature across three principal thematic domains.

The first domain is the risk assessment, with particular focus on hydrogeological hazards. In studies by Büyüksalıh et al. and Gandini et al. [16, 17], external DSS tools – resulting from Analytic Hierarchy Process (AHP) methodologies – are embedded within CityGML-based models to organise data and compute risk levels for each building in historic districts. Here, geomorphological terrain data, supported by the spatial dimension of the standard, are combined with expert-based evaluations of physical vulnerability at both building and component levels. These data are integrated semantically and geometrically to generate risk maps. Furthermore, the correlation between physical vulnerabilities and risk classes is used to determine appropriate intervention priorities.

The second domain concerns energy resilience. Applications in this field are more widespread and largely stem from the EFFESUS project [18–20]. As in the previous case, intervention priorities are derived from an external system of vulnerability indices and relationships, which are then structured within hierarchically organised CityGML-based models. Building typologies, uses, and sub-component configurations are analysed to determine energy consumption classes and prioritise intervention types, followed by assessment of potential thermal performance improvements at the sub-component level.

The third domain involves the prioritisation of interventions based on the state of decay of opaque building elements, as demonstrated in the work of Lasorella and Cantatore [21]. In this study, rules integrated into the

CityGML content structure are derived from national technical standards (UNI 11182:2006 and UNI/CEN TS 17385:2019). These rules associate types, extents, and severity of decay in walls and roofs with a normalised index, which then informs the priority level of interventions.

A common feature across these three thematic applications is the management and analysis of data focused on individual buildings to establish intervention priorities using simplified values or indicators. However, the subsequent identification of required interventions is often overlooked, particularly in relation to the need for compliance with local regulations. Conversely, all the referenced applications employ CityGML-based modelling in combination with web-based services or platforms designed to collect and/or disseminate data and results among researchers and policymakers, aligned with the objectives of each study. These platforms can support the structured management and dissemination of technical knowledge among professionals operating under shared guidelines (e.g., policymakers, technical officers), as well as among experts engaged in subsequent phases of complex processes (e.g., public authorities, practitioners). Ultimately, they provide a set of information and attributes that can accommodate different levels of detail and interest, in line with specific project objectives. Translating these functionalities to the broader aims of traditional rehabilitation plans for historic districts – particularly regarding the technical dimension of architectural conservation – data collection and organisation primarily support professionals in identifying appropriate intervention strategies. In this process, policymakers define possible categories of intervention, which are then integrated with overarching constraints intended to preserve architectural, aesthetic, and cultural values as core principles of rehabilitation plans.

By combining these operative insights from prior scientific applications with the established practices of traditional rehabilitation processes in historic districts, CityGML-based modelling can substantially reinforce the preliminary phases of knowledge systematisation. Specifically, it enables the integration of policymaker-defined rules into a structured DSS framework, thereby generating a Technical CityGML-based Digital Model enhanced with a DSS (T-DM DSS).

As the main work aims, the methodology outlined in the next section involves the systematisation of knowledge as a preparatory step for checking, collecting, and analysing technical data related to historic buildings. It also facilitates the organisation of such data into a structured dataset, enabling decisions regarding levels of intervention. Within this framework, the T-DM DSS model is set up to achieve the following objectives:

- a digital information structure for technical data collection, as defined by traditional sources such as Rehabilitation Manuals and Codes of Practice;
- a technical CityGML-based model augmented with structured guidelines for practitioners, aligned with principles that ensure the preservation of architectural heritage;
- a multi-access platform for content management and dissemination, regulating the level of detail and user access according to the dual nature of the dataset's use.

In particular, the methodology builds upon the CityGML-based database structure presented in previous work by the authors, which serves as the core for systematising technical information relevant to Rehabilitation plans and coherent with the concept of "building types". However, the approach follows a building-centric perspective to offer a practical tool for professionals, with a specific focus on intervention requirements. Furthermore, the planning dimension traditionally embedded in the plans – and their various administrative interpretations – is also incorporated, through the development of thematic content maps for the district (e.g., historical evolution, spatial distribution of building types). However, the analysis of intervention priorities is not addressed at this stage.

3. METHOD AND TOOLS

In line with the objectives described above, this section outlines the method and tools adopted for setting up the T-DM DSS, designed to systematise and manage technical knowledge while supporting refurbishment and conservation activities for architectural assets in historic districts. Figure 1 provides a general overview of the

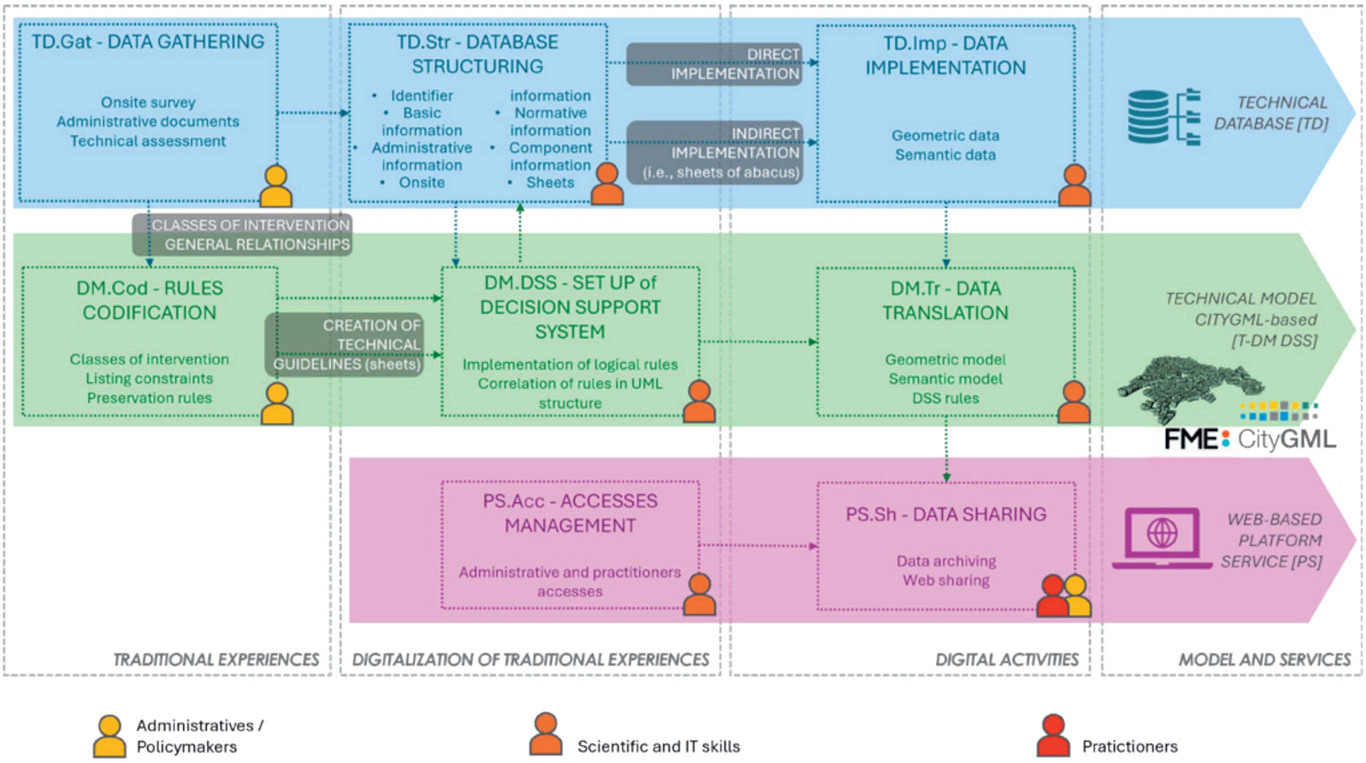

Fig. 1. *Phases, activities, and expertise involved in the method for the setting up of a T-DM DSS for buildings in historic districts.*

methodological phases. As previously stated, the method builds upon earlier work that systematised technical information through CityGML-based models, the outcome of a structured and coherent digitalisation of traditional practices embedded in rehabilitation plans for historic districts. This basis enhances the potential of such models in supporting decision-making processes for local policymakers.

The method translates traditional refurbishment and conservation practices (e.g., manuals, codes of practice) into digital procedures by leveraging structured knowledge and adapting it to function as a new set of digital tools for the end-users involved in the processes. The method also defines three progressive goals, each corresponding to a step forward in the digital maturity of the models: from a Technical Database – in which data and information are gathered and systematised – to a CityGML-based technical model where structured technical knowledge is integrated with predefined intervention types, in alignment with overarching regulatory constraints designed to safeguard architectural heritage. Finally, this CityGML-based technical model is transformed into a service for practitioners, facilitating the selection of appropriate strategies and enabling effective oversight by local administrative bodies. Within this process, the involvement of IT-skilled researchers is crucial to ensure the smart integration of digital technologies and process innovation.

Focusing on the individual models and services, the first product is the Technical Database (TD), which originates from an initial data gathering phase (TD.Gat). This phase draws upon both possible existing administrative documentation (archival, documentary, normative, etc.) and technical assessments (i.e., previous analyses or preliminary studies), as well as on-site surveys, to populate the database with the necessary information. The TD includes both geometric and semantic data, organised according to the classes and data types (TD.Str) outlined in [13] for rehabilitation plans, spanning from buildings to their sub-components and finer elements. The collected data may be either direct (e.g., cadastral records, administrative details, geometric measurements) or indirect (e.g., codification of sub-components, preservation values, associated catalogues). Table 1 provides a detailed overview of the data required for the TD and relates them to the associated informative dimensions that involved

CLASS OF DATA	CONTENTS	INFORMATIVE DIMENSION
Identifier	Cadastral data	S
Basic information	Building footprint	S
	Height	S
	Number of floors	S
Administrative information	Toponymic data	RF
	Class of building	S
	Construction period	RF
	Property	RF
	Use of building	S
On-site information	Function	S
	State of conservation	PE
	Altitude	S
	Utilities	PE
	Building Typology	PE
	Recurring Type	PE

CLASS OF DATA	CONTENTS	INFORMATIVE DIMENSION
Normative information	Restrictions	RF
Component information	Building technique of wall, inner floor, pitched roof, horizontal base floor, window, ...	PE
	Material of architectural element, ...	PE
	Types of wall, inner floor, pitched roof, horizontal base floor, window, architectural element, ...	PE
Sheets	Sheets of wall, inner floor, pitched roof, horizontal base floor, window, ...	RF

Tab. 1. *Details of semantic data required for the TD setup organised in classes, contents, and informative dimensions (Regulation Framework [RF], Past Experiences [PE], Standard [S]), in accordance with [13]).*

the process: previous experiences [PE] in refurbishment activities, the regulation framework [RF] of normative usually involved in the conservation process, and standard [S] mainly declined in solving the digitalisation of contents and process.

All database content classes are structured to accommodate additional, derived information.

Intervention activities are managed in parallel with the technical data, contributing to the evolution of the database into the CityGML-based technical model.

Classes of intervention and overarching preservation rules are encoded (DM.Cod) and logically structured as part of the core Decision Support System (DM.DSS). When such intervention categories are not predefined in the existing documentation, they are inferred through the evaluation of local specificities and administrative constraints. These sub-phases of classification and assessment also facilitate the development of practical guidelines for implementing interventions on site. Within the technical model (T-DM DSS), logical rules, as well as geometric and semantic data, are converted into CityGML format using the FME (Feature Manipulation Engine) visual programming environment. This ensures a multidimensional representation of data and associated properties. Specifically, the implementation of the logical-relational structure in the T-DM for the automatic derivation of intervention classes was achieved through a conditional, action-based approach within the FME Workspace environment. This enabled the configuration of the "Intervention" attribute based on defined relationships between the values of attributes' "Building technique of wall" and "Wall type", as a rule-driven automated classification process aligned with the intended decision logic.

Subsequently, the structured data are stored in a 3DCityDB spatial database to support advanced operations such as spatial management, querying, and processing. These tasks are carried out by expert IT users through a dedicated graphical interface, enabling efficient interaction with the CityGML-based technical model. Once the relational schema is implemented in 3DCityDB, the model can be exported for its use, making it available for 3D visualisation and further thematic analysis.

As the final output of the third methodological phase, the web-based platform service (PS) is designed to publish and share the T-DM DSS via a web browser. A key requirement in platform selection is the capability to host, manage, and query CityGML-based models (PS.Sh), such as the 3DCityDB Web-Map Client. In addition, the platform supports a structured user management system, differentiating access rights between read-only visualisation and full data management for practitioners and administrators, respectively (PS.Acc). Specifically, end users can: i) query the model and access information associated with each building without needing to use programming languages such as SQL, thanks to a user-friendly graphical interface designed for practitioners; ii) modify and enhance the semantic data of the CityGML-based technical model, thereby streamlining the updating and management of information by administrative and policymakers.

4. APPLICATION TO A CASE STUDY. THE HISTORIC DISTRICT OF CORLETO PERTICARA

The methodological phases described in the previous section have been applied to the ancient core of Corleto Perticara, a small Lucanian village. Corleto Perticara is an Italian town of 2,287 inhabitants (as of 31 December 2023, ISTAT), located in the province of Potenza in the Basilicata region, in the upper Sauro Valley at an altitude of 757 metres above sea level. The selection of this case study is grounded in its fragmented system of historical and technical documentation, the absence of a thematic plan for the historic district, and the accumulated stratification of knowledge and practices resulting from the seismic events in 1857 and 1980 and the US air bombardments in September 1943.

4.1. THE BUILT ENVIRONMENT IN THE HISTORIC DISTRICT OF CORLETO PERTICARA

The settlement's morphological evolution followed patterns typical of medieval tradition, linked to defensive needs, management of land and water resources, and adaptation to the orographic, climatic, and socio-economic conditions. Overall, the built-up area is characterised by a high degree of spatial saturation.

The historical core developed from the original settlement, now disappeared, located below the feudal Castle, and expanded southward during the 14th-15th centuries. This agglomeration followed a radial layout centred around the Mother Church. During the 17th-18th centuries, the expansion continued to the south-west according to a cluster layout, marked by compact blocks with complex morphologies set on gently sloping terrain. Between the 18th and 19th centuries, development shifted westward, adopting a linear row layout, with elongated, iso-oriented, and shallow blocks. These evo-

CLASS OF DATA	CONTENTS	TYPE OF ANALYSED DETAIL	TYPE OF DOCUMENT
Identifier	Cadastral data	Documentary	Cadastral map
Basic information	Building footprint	Documentary	CTR
	Height	Documentary	DTM, DSM
	Number of floors	On-site	
Administrative information	Toponymic data	On-site	
	Class of building	On-site	
	Construction period	Normative	RU: Drawing 8
	Property	On-site	
	Use of building	On-site	
On-site information	Function	On-site	
	State of conservation	Normative On-site	RU: Drawing 9
	Altitude	Documentary	DTM
	Utilities	Normative On-site	RU: Drawing 7B
	Building Typology	Normative On-site	PR: Bill of Quantities
	Recurring Type	On-site	
Normative information	Restrictions	Normative	RU: Technical Implementation Norms, Refurbishment Guidelines, Building Regulation
Component information	Building technique of wall, inner floor, pitched roof, horizontal base floor, window, ...	Normative On-site	PR: Special Contract Specifications, Bill of Quantities VPdR: Technical Implementation Norms
	Material of architectural element, ...	On-site	
	Types of wall, inner floor, pitched roof, horizontal base floor, window, architectural element, ...	Normative On-site	PR: Special Contract Specifications, Bill of Quantities VPdR: Technical Implementation Norms
Sheets	Sheets of wall, inner floor, pitched roof, horizontal base floor, window, ...	Normative	PR: Special Contract Specifications, Bill of Quantities VPdR: Technical Implementation Norms RU: Technical Implementation Norms, Refurbishment Guidelines, Building Regulation

Tab. 2. *Summary of building typologies, techniques, and materials used in the historic district of Corleto Perticara.*

Fig. 2. *(A) Distribution plan of buildings and orthophoto of the municipality of Corleto Perticara. (B) Courtyard house-type building (above, horizontally): schema of façade, plan, and section; photos of an example building, a detail of its hewn stone wall, and its portal. Palatial house-type building (below, horizontally): schema of façade, plan, and section; an example of a real building, detail of its stone mixed with brick wall, and its door.*

lutionary stages collectively define the structure of the historic core. Due to the continuous elevation difference, buildings generally consist of at least two levels: a lower semi-basement used as storage, and an upper residential floor, with approximately square floor plans of about 6 m x 6 m. Regarding building typologies, materials, and structure techniques recognised for recurrent sub-components and architectural elements, Table 2 (on the previous page) summarises the identified details, highlighting the traditional practices and the use of low-cost materials sourced from local resources (Fig. 2).

What is observed in the historic district clearly indicates a built environment extensively modified over time, employing solutions and materials often inconsistent with the original fabric. This is a consequence of suffered external stressors (seismic and air bombings), as well as policies that encouraged building elevations or interventions on existing structures starting from the 1970s. As a result, the built environment is now extremely fragmented and complex, both architecturally and in terms of regulation, which complicates the development of potential refurbishment and conservation strategies.

4.2. THE SETUP OF THE T-DM DSS FOR CORLETO PERTICARA AND THE WEB SERVICE

All these data and details briefly described for the architectural heritage of Corleto are derived from a complex set of archival and administrative documents that characterise the fragmented technical knowledge for practitioners. Among the most relevant reference documents for the analysis of the built heritage are:

- the 1948 Post-War Reconstruction Plan (PR), preserved in the State Archive of Potenza, composed

of graphic drawings, Special Contract Specifications, and a bill of quantities for the repair of buildings damaged by war. The analysis of this material provided insight into the typologies and building techniques characterising the fabrics. In particular, it reports the techniques and materials used in the repair work, while floor plans accompany some bills of quantities;
- the 1988 Variant of the Rehabilitation Plan (VPdR), preserved in the Municipal Archive, includes graphic documents and Technical Implementation Norms (NTA) that helped identify materials and techniques used in refurbishment interventions under Law no. 219/81;
- the 2008 Urban Planning Regulation (RU), currently in force and required by Regional Law 23/99, is composed of graphic documents, the NTA, and Refurbishment Guidelines, and, together with the Building Regulation, provides administrative and prescriptive guidelines for planning interventions.

These geometric, quantitative, qualitative, and documentary details were preliminary codified and collected into a GIS database, linking buildings, sub-components, and element characteristics to each architecture, coherently with the building-centred structure, and maintaining the spatial-distributive details of the district. These data were thus used to populate the queryable database coherently with the method for the technical database (TD). Table 3 summarises content sources and their level of implementation in compliance with the database structuring presented in [13]. Specifically, among the documentary sources are the Regional Technical Map (CTR), the Digital Terrain Model (DTM), and the Digital Surface Model (DSM) stored in the GeoPortal - RSDI Basilica-

BUILDING TYPOLOGIES	
TYPE NAME	*DESCRIPTION*
Palatial House	Single-family, one or more floors, one or two rooms per floor, with street-facing façades on all free sides
Single House	Multi-family, two or more floors, with one independent dwelling unit per floor accessed via internal or external stairs, featuring one or more rooms per floor, with façades on all free fronts
Multi-family House	Two or more floors, with multiple and independent dwelling units per floor, all with street-facing façades
Courtyard House	Multi-family, one or more floors, with independent housing units located at the back of the plot and facing a shared or private open space (courtyard)
Palace	Single-family, two or more floors, a single dwelling with multiple rooms, facing the street or a private/common space on all open fronts
SUB-SYSTEM DETAILS	
SUB-SYSTEM	*DESCRIPTION*
Wall	Almost exclusively made of load-bearing masonry with significant thickness (though not cavity-filled) built using different masonry techniques: rough stone, hewn stone, squared stone, mixed with bricks, exclusively solid bricks, or cement blocks
Intermediate floor	Made of wooden structures, mixed iron and brick systems, or reinforced concrete slabs (latero-cement)
Roof	Generally pichted with one or more slopes, made out of wood or in reinforced concrete and covered with clay roof tiles
Ground-floor	Generally lacks of an insulated layer and consists of stone slabs or brick paving placed directly on the ground
Windows and doors	Highly varied, as many have been replaced over time
ARCHITECTURAL ELEMENTS	
ELEMENT TYPE	*DESCRIPTION*
Portals and doors	Embellishing the wall openings with decorated arches or stone/brick frames
Window openings	Differentiated according to their type, size, or adopted decorative features
Doorsteps	Made from locally cut stone with exposed finishes and sharp edges, often supported by iron or stone brackets, or mixed systems with iron and bricks
Fixed protection systems	Balaustrades and grilles, in either simple or decorative wrought iron
External stairs	Various types and configurations to access upper levels following vertical extensions when internal space was insufficient
Bathrooms on balconies	Created within small rooms placed in loggias, introduced after the installation of the sewerage network
Gates	Various types, often replaced over time with elements alien to local tradition

Tab. 3. *Data sources and contents structured in accordance with the database architecture defined in [13]: CTR – Regional Technical Map, DTM – Digital Terrain Model, DSM – Digital Surface Model, PR – Reconstruction Plan, VPdR – Rehabilitation Plan Variant, RU – Urban Planning Regulation.*

ta, as well as the cadastral map. All these sources enrich the geometric and semantic basic informative structure of the DM. Administrative documents include the previously mentioned technical/regulatory documents. In this activity, a check of available data has been done, highlighting some gaps. It is the case of abaci for all the sub-components and elements to preserve that were properly designed (Fig. 3). Each abacus reports all the

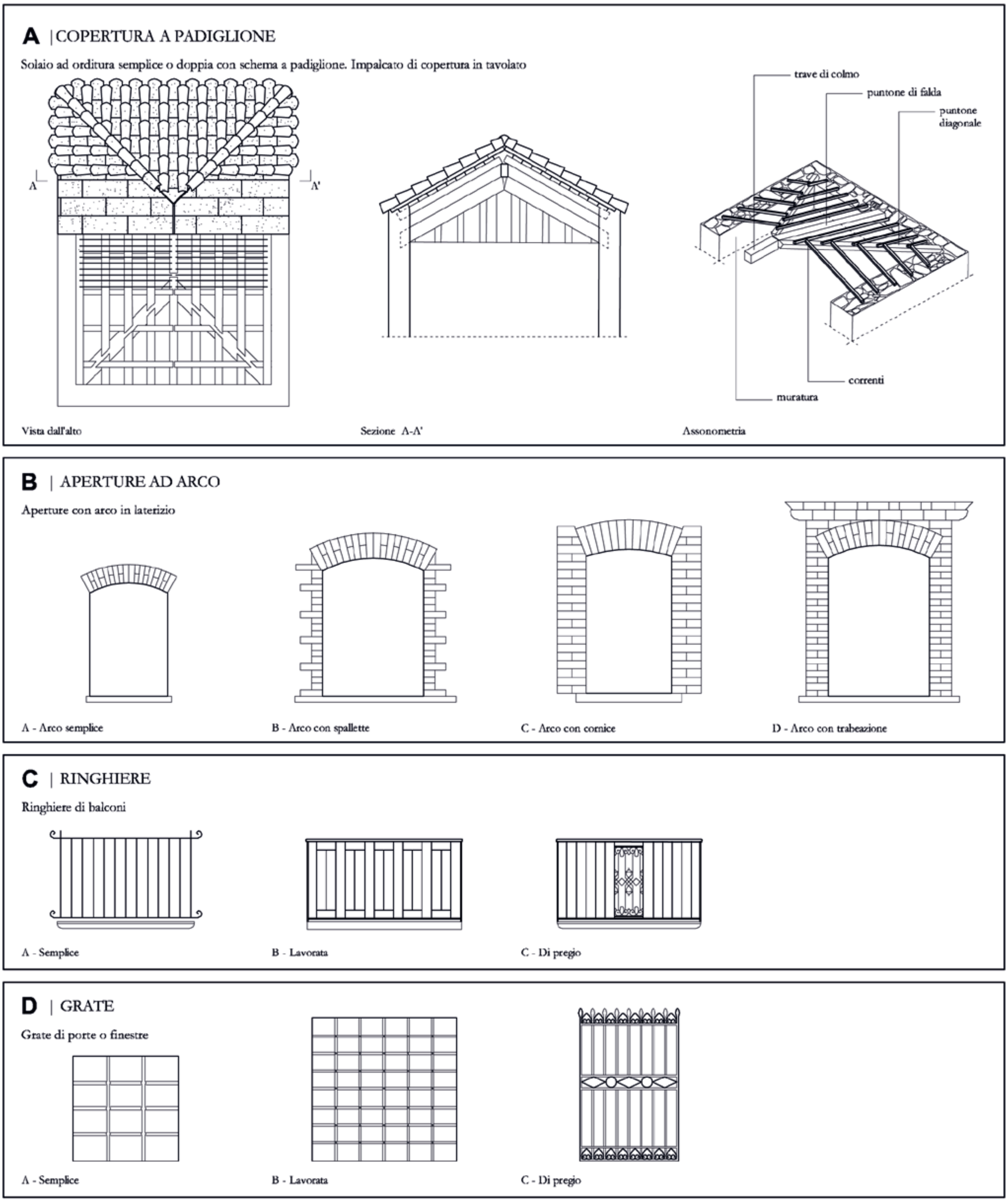

Fig. 3. *Examples of abacus sheets for: (A) multiple pitched roofs, (B) arched openings, (C) metallic railings, and (D) metallic gates.*

variations of the identified components, derived through the correlation between component type, building technique, and materials used.

As far as the interventions on existing buildings are concerned, the main classes are described in the NTA of the current Urban Planning Regulation (RU), which presents them descriptively and classifies them according to the type of intervention: ordinary maintenance, extraordinary maintenance, restoration, conservative rehabilitation, and building renovation. In addition, the document entitled Refurbishment Guidelines, also part of the RU, outlines general criteria in a descriptive manner, focusing on the rehabilitation of the external surfaces of buildings. Lastly, the Building Regulations also set out provisions governing the external appearance of buildings, as well as the procedures for carrying out such interventions.

Similarly, for the abaci, specific infographic sheets of operative details of interventions were prepared to be related to the associated field in the database. Following that, types of interventions are codified and analysed in order to structure the related relationships in the DSS (Fig. 4). In detail, the intervention types are linked to the possible classes of intervention derived from the Urban Planning Regulation, Refurbishment Guidelines, and Building Regulation. A set of 29 possible intervention types for walls, roof, intermediate and ground floor, and windows is identified, imposing the identification of intervention types through filters based on sub-component "Types" and "Techniques". A similar process has been pursued to determine intervention for architectural elements. As a peculiar example, Figure 5 shows the specific conditional logic underlying the DSS for the wall sub-component, in which the identification of the most appropriate intervention stems from the combination of attributes such as the type and building technique. In fact, the two types of walls are associated with 14 different techniques. The resulting combinations serve as a starting point for associating the 15 possible interventions derived from the three distinct regulatory documents.

Data is systematised, and the setup of the DSS is then combined into the final CityGML data model, which enables the 3D and georeferenced modelling of the historic district. The translation of attributes and their integration into the 3D model was carried out

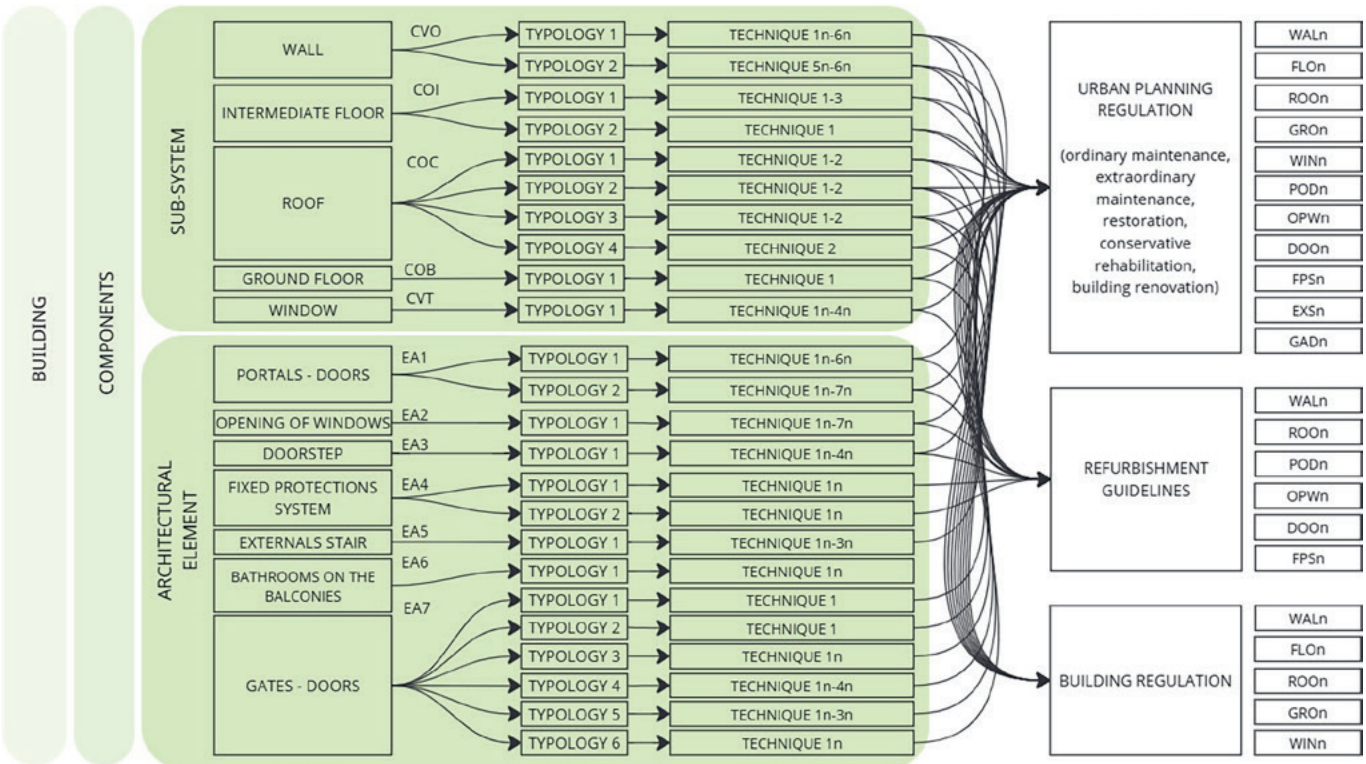

Fig. 4. *Structure of the DSS imposed for Corleto Perticara, detailing the types of sub-systems and architectural elements codified, their potential combination, and the codified intervention derived from the local documentary sources.*

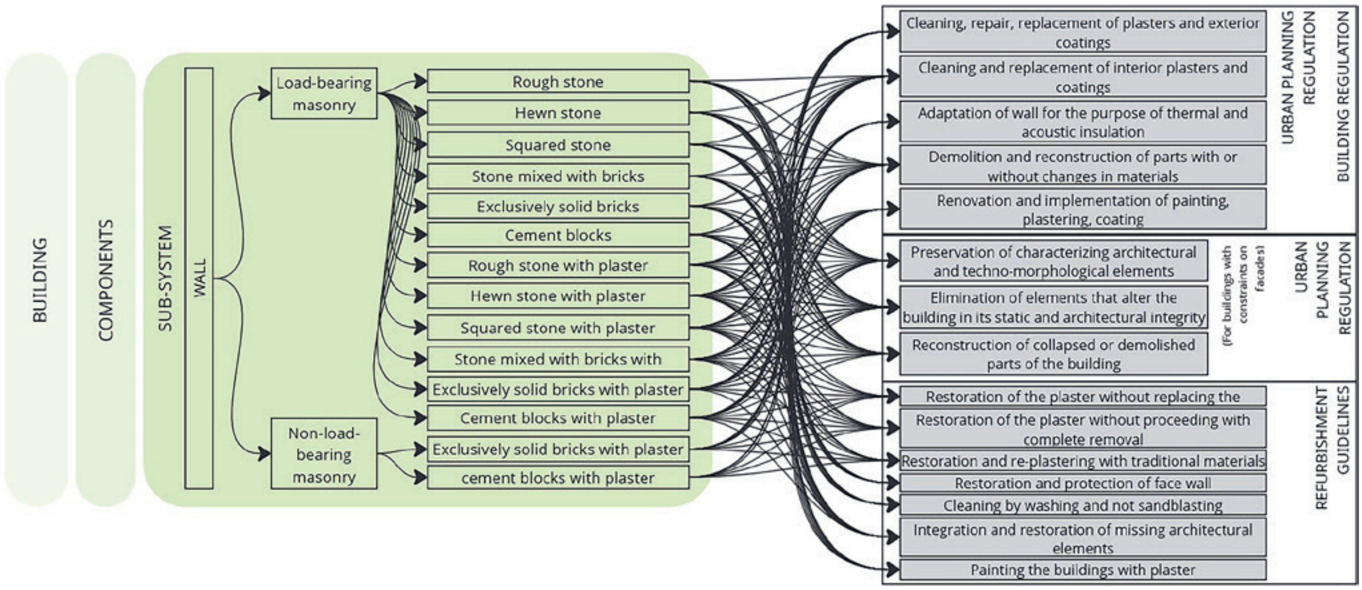

Fig. 5. *Detail of data relationships between types and techniques for the wall, and possible interventions derived from Urban Planning Regulation, Refurbishment Guidelines, and Building Regulations.*

through a workflow developed in FME, which enabled the extrusion of building volumes, the correlation with thematic attributes, and the automated assignment of potential interventions to CityGML objects. In particular, the use of the AttributeManager transformer allowed the implementation of a set of conditional logical rules based on "if" expressions; these make possible the association of each building with a set of intervention types consistent with its building technique and historical characteristics.

As for the web-based service developed to share the T-DM DSS of Corleto Perticara, the CityGML-based model was made accessible through export for visualisation using 3DCityDB (based on PostgreSQL/PostGIS) and integrated into the 3DCityDB Web-Map Client. This client is structured on Apache and operates as an extension of the CesiumJS WebGL Virtual Globe, fully compatible with KML/gITF files exported via the 3DCityDB Importer/Exporter tool. To support both practitioners and administrators, multiple levels of access were tested using a simple Google Sheets API on the Google Cloud Platform. The lower level of access was configured to simulate practitioner use, allowing users to search for building-specific information within the model. As illustrated in Figure 6, the practitioner can search for a building using its cadastral ID and view all associated systematised data after receiving temporary authorised access. Administrators and policymakers can have direct access to the database managed via Google Sheets, enabling them to modify existing records, add any missing technical data, and update properties. This supports the dynamic and continuous management of semantic data, ensuring that information remains accurate, complete, and updated in real time.

Alongside general technical information, the pop-up windows offer a quick overview of possible interventions for walls and roofs, displaying the corresponding guideline sheets. Specifically, suppose the pop-up window shows all the codified details of structured knowledge. In that case, sheets of intervention are introduced as an external data source, properly linked into the sub-component/element of the building, and updatable with other access controls.

Conversely, the administrative access level, intended for policymakers, allows the use and updating of database content in response to changing requirements or new information.

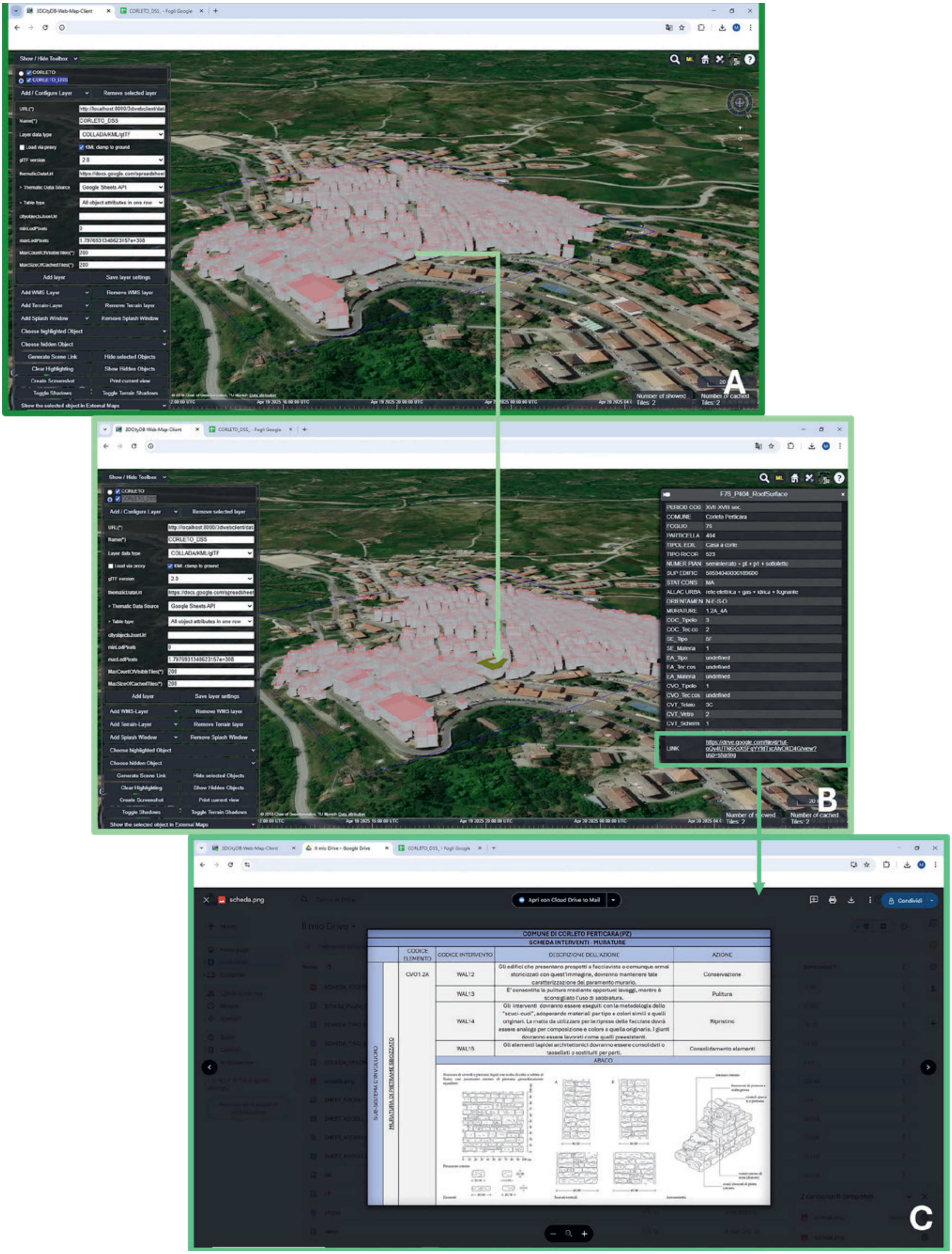

Fig. 6. *Overview of platform visualisation details. (A) Preliminary page where the entire model is uploaded. (B) Details of a selected building are shown in the pop-up window (on the right). (C) Details of contents in the interventions sheet for the wall, including its abacus.*

5. CONCLUSIONS

The integration of Decision Support Systems (DSS) into CityGML-based models for the refurbishment and conservation of historic districts represents a significant advancement in the digital management of architectural heritage. The transition from traditional planning tools to structured digital models is not merely a technological upgrade, but a methodological shift that enhances the quality, coherence, and thereby improves practical implementation of technical knowledge in conservation practices. This can be ensured by merging traditional and digital knowledge into a controlled yet informed process that transcends mere content systematisation, providing coherent details that are useful in addressing the motivations behind digital modelling.

In this framework, the proposed Technical Digital Model enhanced with a Decision Support System (T-DM DSS) demonstrates how standardised, scalable, and semantically rich modelling environments can be effectively used to bridge the gap between an organised and regulated knowledge and practitioners involved in the refurbishment activities for single buildings in historic districts. In the widespread scenario of digital modelling typologies, the T-DM DSS uses the CityGML standard as a comprehensive alternative to BIM for managing the spatial dimension of the historic district, while ensuring a coherent and granular semantic description for buildings, sub-components, and elements characterisation.

This work builds upon previous systematisation efforts and expands them by incorporating conditional logic, regulatory constraints, and expert-derived intervention strategies into a unified model structure. The T-DM DSS not only facilitates the organisation and dissemination of multiscale and multidisciplinary data, but also introduces a logic of decision-making by design, where the structure itself guides and restricts interventions according to shared rules and encoded priorities.

The application to the historic centre of Corleto Perticara highlights the capability of the model to manage fragmented and heterogeneous data sources, transforming them into a cohesive and accessible digital knowledge base. Here, the complex and varied architectural systems resulting from historical evolution and external stressors in Corleto Perticara have led to fragmented knowledge, which is challenging to manage and control by policymakers, and difficult to organise by practitioners when selecting appropriate intervention categories.

However, the preliminary structuring of knowledge also allows the systematisation of concepts and lexicons, improving the overall quality of technical details while preserving local specificities [22–24].

At the same time, the systematisation of knowledge for experimentation has revealed some gaps in the technical content of available documents, revealing the opportunity to study the case of Corleto Perticara as representative of several other cases in Italy, as well as to improve the quality of technical knowledge available for suitable intervention.

The web-based sharing platform developed for the case study further proves how digital modelling can support different users – from practitioners to policymakers – by providing differentiated access levels and customised guidance tools. However, building on the advantages already demonstrated in the literature for policymakers and final users involved in the specific application of CityGML-based modelling and the subsequent sharing of data content, the comprehensive activities aimed at reorganising architectural knowledge in the historic district of Corleto, along with the service setup, should be tested and shared with local practitioners and administrators to assess their effectiveness and appeal in addressing the systematisation and management of intervention selection in a digital format [25].

Crucially, this approach recognises that the complexity of buildings in historic districts – shaped by time, cultural specificity, and local constraints – cannot be reduced to mere geometric representations. The model thus becomes a knowledge-based infrastructure, where semantics, regulations, and technical prescriptions converge to enable not only documentation and analysis, but informed action.

Beyond its methodological value, the smartness of the digitalisation process, as presented for the case study, can also be described in terms of time and effort. Preliminary data indicate that the activities involved may require approximately 2 to 4 person-months per hectare of building commercial area. This time effort varies according to the architectural peculiarities of the buildings, the complexity of the DSS structure, and the availability and organisation of existing documentation. Additionally, the digital skills of the technicians involved in modelling and process management play a critical role in optimising the duration and effectiveness of implementation. On the other hand, a higher digital quality of the final service ensures timely and continuous updating of data and models, thereby enhancing the overall quality of the process.

Looking forward, the T-DM DSS structure offers a versatile foundation for further extensions, including performance-based assessments (e.g., energy efficiency, structural vulnerability), longitudinal monitoring of interventions, and integration with additional urban datasets. As such, the proposed method contributes to the evolving discourse on digital heritage by offering a practical, adaptable, and standards-based strategy to embed conservation intelligence within spatial planning and technical workflows.

Authors contribution

Conceptualisation, E.C.; Methodology, E.C.; Software, V.A. and M.L.; Validation, E.C., V.A. and M.L.; Formal Analysis, V.A.; Investigation, V.A.; Data Curation, M.L.; Writing – Original Draft Preparation, E.C.; Writing – Review & Editing, F.F.; Visualisation, M.L.; Supervision, F.F.

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