# Spatio-Temporal Data Integration for Knowledge-Driven Analysis of Historic Built Heritage Conservation State

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**Abstract**

The conservation process of a historic architectural building has the objective of a continuum of knowledge that originates in the past and must persist into the future (ISPC CNR, 2021), in the logic by which the components of architecture are internal to evolutionary processes that leave a tangible trace (Moioli and Baldioli, 2018). Thus, the digitisation of an architectural asset is a progression of knowledge capture and management. Its flow of information moves from observation to processing of data up to their contextualized digital representation. The next step is the ability to produce predictive content. This article explores the in-progress experimentation of a doctoral thesis. It is proposing a methodological contribution for the optimization of the information flow continuity within a digitisation process functional to a conservation strategy for the Historical Built Heritage. The instrumental result of the experiment is a query, visualization and inference environment optimized for the analysis of building transformation over time, to support diagnostic activities through multidimensional representation and access to a structured knowledge base. The integration between virtualization and descriptive information improves the understanding of the asset framed in a space-time system. The methodology was applied to the ecosystem of data on the conservation state of the church of San Giovannello di Gerace (RC) and considering the main transformations that have affected it over time.

## 1. Introduction

The process aimed at the conservation of a historical architectural building, is confronted with relevant issues: knowledge of the asset and resulting operational choices. The objective is to guarantee a continuum of knowledge that originates in the past and must persist into the future (ISPC CNR, 2021). This process, iterative and interactive, is enriched with periodic updates, forming the basis for planning interventions and defining coherent management models. The evaluation of the conservation state of an asset is a management tool (Moioli and Baldioli, 2018). In view of the foregoing requirements, the digitisation of an architectural asset is a process of knowledge capture, distribution and use. Its information flow moves from observation to data processing to their contextualised digital representation, in which knowledge is encoded and can be shared, as shown in Figure 1.

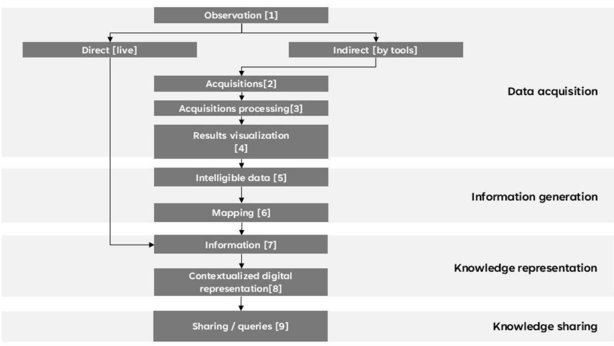


Figure 1. Information flow scheme elaborated by the authors

In the operational reality, breaking points in the information flow are due to both procedural factors, related to the interpretation and understanding of the data, and instrumental limitations (Lauria et al., 2024). These compromise the full satisfaction of the processing and transmission needs of the information content. The most delicate transition is that from raw data to structured information. A key objective is to increase the degree of automation and control.

Rapid technological development has made it possible to collect raw data in reduced time and with optimised resources (Vozzola, 2022). Despite this, the existence of a semantic gap is evident (De Luca, 2020). Alongside the vast but uneven production of digital resources related to cultural heritage, there is a proportional increase in uninterpreted data. This underlines the urgency of developing innovative methods for the production of semantically enriched digital resources.

To achieve this, the intelligibility of the data is a crucial issue. The phase of mapping is understood as the orientation of information content to the satisfaction of specific needs. Information are contained in the answers to questions (Bernstein, 2009). A possible perspective is to use formal models capable of capturing the implicit semantics of the data. This clearly defines the boundaries within which the information are interpreted, reducing the effort for moving from raw to intelligible material. Mapping becomes faster and more effective, guided by methodological lines derived from prior knowledge. The last is, in turn, enriched through the continuous cycle of information and coding.

The entire process is geared towards producing content that not only answers specific questions, but anticipates future scenarios. Inputs are combined with already acquired knowledge, thus enabling more complex inferences to be generated. The accumulated experience becomes the foundation for ‘the transformation of information into instructions’ (Ackoff, 1989). The next step is the ability to produce predictive content, generating a circular, continuous and implementable flow. The


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reinterpretation of its diagram, according to these premises, is illustrated in Figure 2.

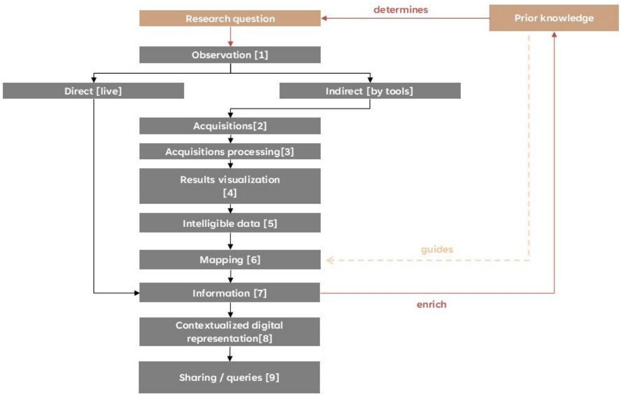


Figure 2. Circular information flow scheme elaborated by the authors

This article explores the in-progress experimentation of a doctoral thesis. It is proposing a methodological contribution for the optimization of the information flow continuity within a digitisation process functional to a conservation strategy for the Historical Built Heritage.

The present experimentation reinterprets the static nature of the synchronic analysis of the artefact, in a multidimensional logic in which individual temporal frames reconstruct its evolution diachronically. This is possible considering the components of architecture are internal to evolutionary processes that leave a tangible trace, located within an oriented and irreversible time (Moioli and Baldioli, 2018). The knowledge of the building is represented in its spatial and temporal dimension, investigating the correlation of the data through the morphological and semantic attributes of the multilayer analysis.

The main objective is the limitation of flow breakpoints. Through the provision of an implementable knowledge base, the mapping phase is simplified, resulting in the semi-automatic processing of information from the data. The basic conceptual structure also favours the reduction of effort in the production of intelligible data with a view to greater process economy. The innovation lies in ensuring the circularity of the flow by adopting a predictive logic.

For demonstration purposes, the methodology was applied to the ecosystem of data on the state of conservation of the church of San Giovannello di Gerace (RC) and considering the main transformations that have affected it over time.

The application case does not delineate the boundaries of the applicability of the proposal. It extends to broader contexts requiring an integrated and multidimensional analysis. The proposed approach is aimed to the observation of recurring elements among similar buildings (e.g. in homogeneous urban areas) and to allow for the formulation of complex inferences through the interaction of different typologies of variables.

## 2. Operational state of art

In the conservation process, knowledge is characterized by the stratification of data horizontally (multidisciplinary) and vertically (temporally). This is resulting in a heterogeneity of information and communicative complexity that undermine understanding and transmission between the subjects involved. Documentation standards and thesauri are necessary tools for simplification and consistency of the data coding process. The normalization of terminology reduces the risk of creating lexical confusion and conceptual ambiguities. The choice of recording standards represents a guarantee for the future use of the data (D'Andrea, 2006). These tools are necessary conditions, as they ensure the formal correctness of what has been detected. At the same time they are not sufficient in order to establish a real connection and interoperability between the various records. This is even more true considering that data resulting from specialized analyses reflect cataloguing standards that differ in structure, not always automatically alignable.

As regards the integration of the qualitative and quantitative dimensions, annotation platforms (e.g. Aïoli) and parametric models (e.g. BIM) allow to collect geometric and semantic data in a single environment. However, there are still weak points in the field of parametric modelling such as the complexity and length of the geometric reconstruction and the imposition of rigid semantic standards. This leads to the possibility of only partial data input, resulting in limited information granularity. Finally, there is also a recognized immaturity of the exchange formats.

In summary, due to the heterogeneity of values, the information modeling tools are not able to return a single model capable of correctly receiving, describing, synthesizing and transmitting the large amount of information. There is an integration at the level of formats and languages, but what is urgent is the implementation of methods capable of ensuring semantic interoperability through mapping and knowledge harmonization operations. Knowledge engineering techniques and the use of conceptual models make it possible to explore pathways for integrating digital resources.

## 3. Materials and Methods

### 3.1 Workflow

In line with the preservation requirements, the operational objectives were:

1. Recording the evolutionary trend and changes in the state of conservation of technological components through a multidimensional representation;
2. Assisting smart survey and continuous monitoring practices for a semi-automated database updating;
3. Providing inference and visualization tools for knowledge based multidimensional qualitative analysis.

The experimentation made use of the potential offered by existing enabling technologies and is structured as follows:

a. formalization of knowledge through a conceptual model;
b. contextualization of data emerging from the observation of reality distributed in space;
c. development of multidimensional inference skills.

The experimentation is based on a methodological workflow, illustrated in Figure 3, whose chronological sequence of the phases are described in Figure 4.

The use of conceptual modeling was essential to make explicit the semantic and technical relationships and the logical structure of domain concepts. As well as to organize and link data in a graph database, making it effectively queryable. In addition, the conceptual model guides the reading and analysis of the acquired and acquirable data, allowing to validate and/or update the degradation models.

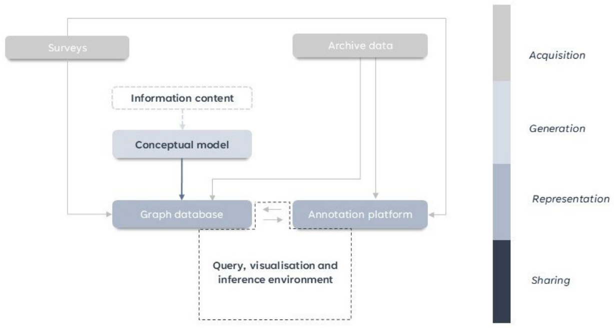


Figure 3. Methodological workflow developed by the authors

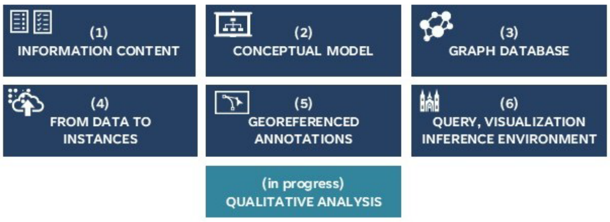


Figure 4. Chronological sequence of the methodological workflow phases developed by the authors

### 3.2 Case study

The church of San Giovanni Crisostomo, known as San Giovannello, is a Romanesque-Byzantine building located in the historic center of Gerace (RC). Built between the 11th and 12th centuries, it recalls a specific scheme of Eastern origin and is considered an epigone of the more advanced Basilian buildings (Paolini, 1969). The single hall, with a gabled roof, wooden ceiling and trusses, is equipped with a high extradosed apse oriented to the east and the prothesis and diaconikon of the Orthodox liturgy. Natural lighting comes from a system of single-lancet windows and a west oculus, enclosed, together with one of the two portals, between a pair of protruding masonry pillars.

Despite the simplicity of its forms, the building was chosen as a case study for its prototypical and easily recognizable morphological, typological and technological characteristics, whose alterations over time have left visible and documented traces. Added to this is the availability of the data contained in the various documentary sources, making it possible to outline the stages and characteristics of the evolutionary process in the last century.

In 1961, the church of San Giovannello in Gerace underwent restoration works, funded by the Cassa per il Mezzogiorno. They concerned structural consolidation, rebuilding of the roof, recovery of the original entrances and protection from humidity. A further intervention was carried out in 1997 by the Orthodox Archdiocese of Italy, involving the reopening of a walled-up passage and the consolidation of a stone arch. In 2011, the Superintendence started new works to counteract the degradation caused by humidity, creating a ventilated crawl space and installing an electrical system and environmental monitoring systems. Prior to these works, a territorial level seismic risk assessment (LV1) was carried out.

### 3.3 Data collection and pre-processing

The data available for this research included the laser scanner (2023) and photogrammetric (2024) surveys of San Giovannello, carried out as part of the project GEstioNE del rischio SISmico per la valorizzazione turistica dei centri storici del Mezzogiorno (GENESIS) and in the documentary apparatus relating to the project interventions described in the previous paragraph. Documentary sources have been obtained from the Archive of the Superintendence of Archaeology, Fine Arts and Landscape for the metropolitan city of Reggio Calabria and the province of Vibo Valentia and the Central State Archive of Rome - Fondo Cassa per il Mezzogiorno.

The available files contained technical descriptive reports, site and floor plans, sections, elevations, details drawings both before and after the works. For the 1960s project and the one carried out between 2011 and 2013, it was also possible to analyse cost estimates and other financial, administrative documents. The documentation was further enriched by historical photographs.

### 3.4 Information content

The information structure of the model was defined from existing standards for the characterization of descriptors and the assessment of the state of conservation.

The first reference was the Manuale Tecnico of the Piano di Conservazione. The latter was introduced in the Lombardy Region's guidelines as a compliant alternative to the Piano di Manutenzione under public procurement regulations, specifically tailored for historical assets. It is part of a medium-long term strategy, the Conservazione Preventiva e Programmata, which has paid particular attention to information management aimed at prevention and constant care of cultural heritage. The Manuale Tecnico defines the object of the Piano di Conservazione, providing the framework of preliminary knowledge (Moioli and Baldioli, 2018). The Piano di Conservazione aims to ensure continuity in the process, through the structuring of documents with standardized and consequential coding. The tools acquire and feed on the information of the previous phases, so that they can be interpreted in an analytical and predictive sense.

A specific operational approach for contexts with environmental, morphological, constructive and material values, such as small historic centers, was formalized in the Piano Programma di Conoscenza (Azzalin, 2007). Although the research objective was the evaluation of Service Life, by applying the Factor G, the plan aimed at construction systems efficiency, by means of the information forecasting, planning and management strategies. In this regard, the Anagrafica phase, preparatory to the diagnostic stage, was decisive. The collection of detailed data on the behaviour of building systems, were based on survey sheets. It ultimately contributed to the creation of a comprehensive database. The experience has given rise to a reading of the state of conservation of the possible causes of degradation referred to the technical elements of the external envelope of the buildings in relation to the context. The strength of this approach lay in its ability to consider the variability introduced by the relationships between building elements and their surrounding environment, despite the relative homogeneity of the construction types.

By virtue of the guidelines, the information content of the model has been structured according to a tripartite organization articulated on three distinct yet interconnected levels: Urban, Building, Technical element. This multilayered approach allows for a progressive refinement of information as one moves from broader contextual aspects to increasingly detailed components.

**3.4.1 Urban level**: Within it, there are thematic sections that include the registry and location of the urban centre, its climatic characterization and exposure, as well as the definition of seismic risk. The urban level also extends to the closer scale of the neighbourhood and the street or square where the building is located, providing each geographic unit registry and location data, along with a detailed geomorphological description.

**3.4.2 Building Level**: The building unit is described through registry and localization data, accompanied by administrative information, and includes the identification of any existing protection constraints. Also, it provides a summary of general historical information, a typological-functional characterization, the number of floors, and the building's technological composition.

**3.4.3 Technical Element Level**: The greatest information granularity is contained here. The technological breakdown by technical elements enables a controlled and incremental representation of the structure evolution and the state of conservation of the building's components. For each technological element, the cognitive framework includes a registry data sheet, a material-construction description, and detailed historical information, including previous treatments. Particularly important are the records of the state of conservation, current anomalies, related causes and risk areas. In addition, the identification of problems and the verification of the performance level of the element are carried out. It also includes the system of spatial, structural and interaction relationships with other components, with special attention to the modes of propagation of degradation.

### 3.5 Conceptual model

The interpretative process is based on the observation and measurement of data, which constitutes its elementary component. As explained by (Kuhn, 1969), it is always possible to superimpose more than one theoretical construction on a set of data. When referring to the knowledge of the architectural asset, this implies the creation of an interpretative model of reality that allows the analyzed work to be read and transmitted (Cardaci et al., 2012). The search for a language capable of describing any phenomenon in an exhaustive and objective form is an academic and illusory exercise (D'Andrea, 2006). The reality is intrinsically n-dimensional and poly perspectival: concepts, relationships and meanings vary depending on context, analytical goal and perspective. Hence the need to consider the other interpretation of the model provided by the literature. As it is abstraction, interpretation of the object through shared and potentially multiple lenses (Peroni et al., 2014). This perspective finds full application in the domain of historic built heritage conservation. Alignment to a predefined formal system may limit interpretative flexibility and adaptability to emerging or multidisciplinary perspectives.

It is in this scenario that the adoption of a native graph database is a strategic choice. Graph databases allow coexistence and semantic interoperability between competing or complementary ontologies within the same infrastructure. Each ontology can be seen as a conceptual projection onto an underlying graph, richer and more flexible (Guillem et al., in press), capable of simultaneously representing explicit relationships and latent inferences. A graph allows relationships between entities and properties to be modelled directly, letting the structure gradually emerge. Information can be added, restructured, or reinterpreted without compromising the overall integrity of the system. This make it possible not only to maintain the disciplinary specificity of each interpretative approach, but also to harmonize its logical and semantic structures in a common framework.

This does not imply the absence of a preliminary design. On the contrary, it proved to be fundamental for defining key entities, relevant semantic relationships and significant properties with respect to analytical objectives. The model played the role of a heuristic map for the consistent representation of the domain. A conceptual scaffolding that also allowed for subsequent extensions, adaptations and refinements emerging during the interpretative process and data analysis. Moreover, the initial conceptual definition is also necessary to facilitate interoperability, semantic traceability and integration with any existing ontologies or thesauri.

The graph database supports the conceptualization, processing and representation of information, including those that are tacit or not easily formalizable, thereby enabling truly dynamic management. Characterisation actions, pattern detection, similarity measurements between entities, also according to multidimensional criteria, are possible. The graph becomes an active investigation context, in which knowledge can be explored, enriched and constantly reinterpreted on the basis of the questions asked and the relationships observed.

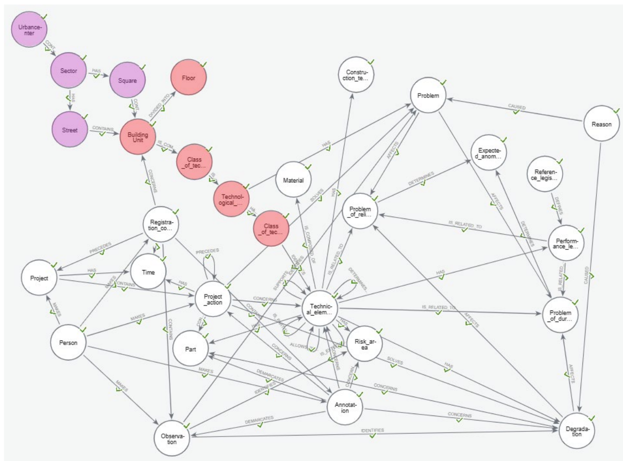


Figure 5. Structure of the conceptual model developed by the authors. The purple parts correspond to the urban information level, those in red to the building level and the white ones refer to the technical element.

Given the high level of detail required for conservation purposes, each element in the information structure was evaluated in terms of whether it should be modelled as a node, relationship, or property. For instance, the description of the urban centre was represented through the set of properties associated with the node of the same name. Conversely, urban subcomponents (sector, square, and street) were standalone nodes in order to gradually detail the framing of the building. These considerations help to illustrate the aforementioned characteristics of modularity and dynamism of graphs.

In line with the information levels described previously, the core elements in the graph are the Building Unit and the Technical element. The first is linked to nodes and their respective properties, of the urban-environmental characterization domain. From there, a taxonomic decomposition leads down to the technological element. This is described through a network of semantic relationships that explain its composition, different types of interactions with other elements, state of conservation and interventions associated with it. The above is illustrated in Figure 6 and 7.

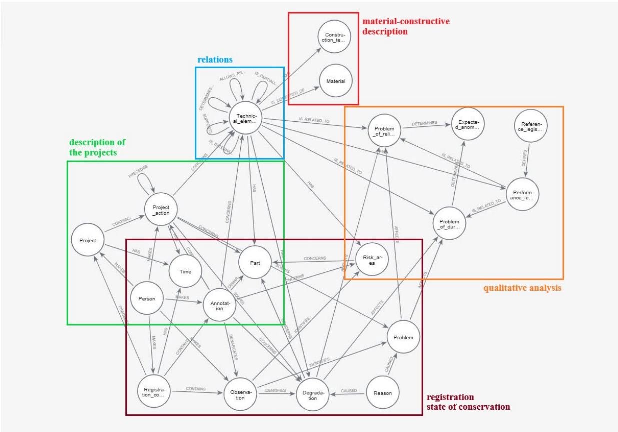


Figure 6. The diagram illustrates the conceptual organization of the technical element information model: the material-constructive description is highlighted in red, interactions between technical elements in blue, the registration of the state of conservation in brown, the description of project actions in green, and the qualitative analysis in orange.

```
Technical_element
├── Material                                    (IS_COMPOSED_OF)
├── Construction_technique                      (HAS)
├── Part                                        (HAS)
├── Interaction relationships
│   ├── Technical_element                       (DETERMINES_ENVIRONMENTAL_CONDITIONS_TO)
│   ├── Technical_element                       (ALLOWS_PROPAGATION_OF_DEGRADATION)
│   ├── Technical_element                       (IS_PARTIALLY_OVERLAPPED)
│   ├── Technical_element                       (IS_EXTERNALLY_CONNECTED_TO)
│   └── Technical_element                       (SUPPORTS)
├── Registration state of conservation
│   ├── Degradation                             (HAS)
│   │   ├── Reason                              (← CAUSES)
│   │   ├── Observation                         (← IDENTIFIES)
│   │   │   ├── Person                          (← MAKES)
│   │   │   └── Time                            (HAS)
│   │   └── Part                                (CONCERNS)
│   └── Risk_area                               (HAS)
├── Projects description
│   └── Project_action                          (IS_CONCERNED_BY)
│       ├── Person                              (← MAKES)
│       ├── Time                                (HAS)
│       ├── Degradation                         (SOLVES)
│       └── Problem                             (SOLVES)
├── Qualitative analysis
│   ├── Problem_of_reliability                  (IS_RELATED_TO)
│   │   └── Expected_anomaly                    (DETERMINES)
│   └── Problem_of_durability                   (IS_RELATED_TO)
│       └── Expected_anomaly                    (DETERMINES)
│   ├── Performance_level                       (HAS)
│       ├── Problem_of_durability               (IS_RELATED_TO)
│       └── Problem_of_reliability              (IS_RELATED_TO)
```

Figure 7. Relational structure of the information entities connected to a technical element. Semantic relationships between nodes are expressed in parentheses, with direct or reverse orientation.

### 3.6 Implementation of graph database

A graph database is any storage system that uses graph composed of nodes and edges, to represent and store data (Pokorný, 2015). In particular a (labelled) property graph model (Robinson et al., 2013) defines nodes and relationships as entities that can both carry an arbitrary number of key-value properties. Relations are directed but can be navigated in either direction, and multiple relationships can exist between the same pair of nodes. A key feature of a native graph database is the ability to quickly navigate connections in the data because it uses adjacency without an index. Each node acts as an index for neighbouring items. Native technologies tend to execute queries faster, maintaining their speed as the size of the dataset increases, and to work more efficiently, requiring much lower hardware requirements. For the purposes of this experimentation, Neo4j was used, a graph database management system (GDBMS), capable of storing a very large number of nodes and relations, as well as having high query performance thanks to a native language called Cypher.

### 3.7 From data to instances

The graph database has been fed by instances, the result of a work of harmonization of documentary sources, whose heterogeneity has posed numerous critical issues:

- Terminological misalignments, due to the use of non-normalized and diachronic specialized lexicons, with semantic variants also for the same phenomena (e.g. lesion and fracture);
- Differences in interpretation, found in the diagnosis of the causes of degradation, with conflicting attributions between contemporary or subsequent sources (e.g. presence of rising moisture);
- Inconsistencies within the documents, especially between textual content and metric computations, revealing misalignments in the quantitative transposition of observations;
- Inhomogeneous levels of information granularity, with significant differences in the degree of technical detail and in the localization of the phenomena;
- Problems of traceability and provenance of data, not explicitly attributed to a single source, date or methodology.

A significant contribution was made by the graphic drawings, on which precise indications were given relating to the presence of forms of degradation or the location of the interventions. These were used as a reference for the definition of the annotated areas within the Aïoli platform. The harmonization was an operation of conceptual disambiguation and semantic alignment, based on cross-comparisons between sources, mapping of recurring terms and construction of categorical equivalences. It is important to underline that, although the highest degree of consistency, reliability and traceability has been pursued, the resulting reconstruction remains hypothetical. Once the population of the graph with the instances was completed, the interrogability check was carried out in order to test the system’s ability to return the complexity of the knowledge system useful for the purposes of monitoring and preserving the asset. For this step Neo4j Bloom was used. It enables dynamic graph visualization and semantic query execution through assisted natural language and Cypher. The semantic graph enables searches oriented to any node of the information domain, not limiting the interrogability to specific configurations. Some queries used to validate the database structure are described in Figure 8, 9 and 10.

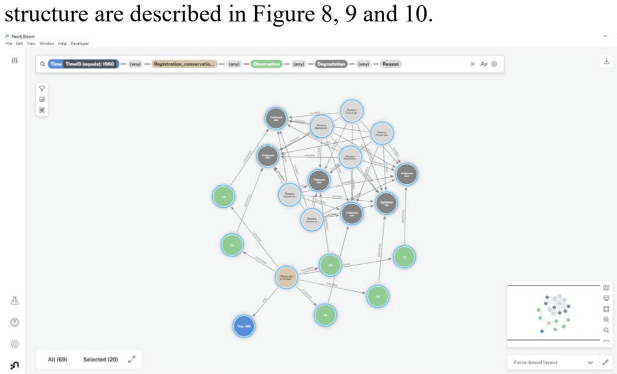

Figure 8. Display, in Neo4j Bloom, of the answer to the following query: What forms of degradation have occurred in time T1, and what are the stated causes?

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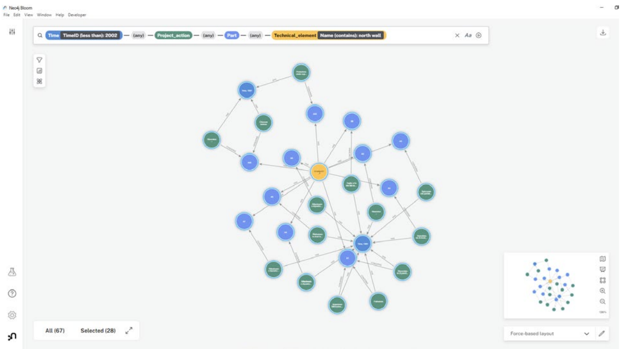

Figure 9. Display, in Neo4j Bloom, of the answer to the following query: What project interventions were carried out on an element (e.g. north wall) before time T1?

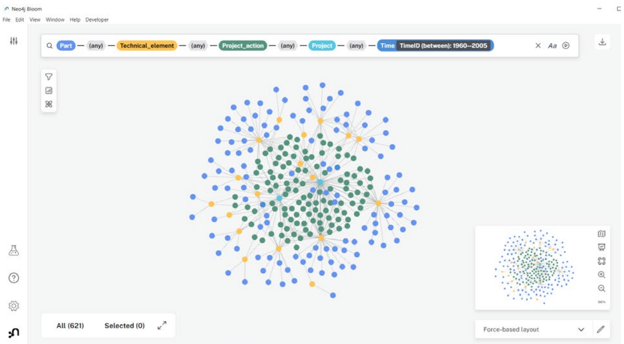

Figure 10. Display, in Neo4j Bloom, of the answer to the following query: What are the portions of the building that have undergone interventions in the period of time between T1 and T2?

The verification of interrogability was not purely operational, but constituted a key phase to demonstrate the diagnostic capacity of the system. The possibility of crossing the graph according to multiple trajectories and differentiated purposes returns a dynamic representation of the conservation history of the asset, opening up scenarios of advanced use also in the decision-making and programmatic fields.

### 3.8 Georeferencing of data

The observation of the state of conservation of the building was completed by georeferencing the data on the CNRS (MAP) Aïoli platform, dedicated to the semantic annotation of cultural heritage objects, from small to large scale. The platform interface is shown in Figure 11.

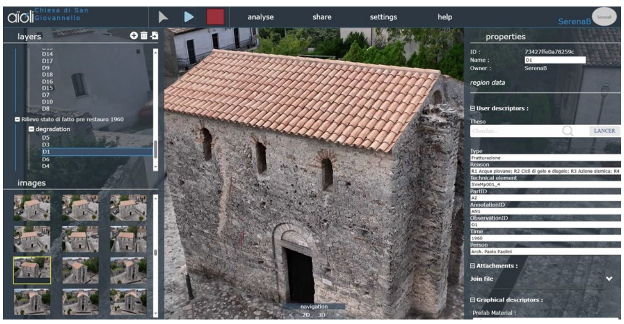

Figure 11. Example of annotation in CNRS (MAP) Aïoli platform. On the left is the structure of the project and uploaded photos, while on the right are the fields for entering annotation parameters.

It is accessible online by the user, who has the possibility of uploading photographs of the asset in order to generate a dense point cloud, around which the original images are spaced. The internal drawing tools allow users to select an image and delimit regions, uniquely identified by a code, property of the Annotation node in the graph. The annotation can be associated with descriptors of various types and is propagated on the 3D model and all images where the same area is visible. Each annotation is enriched with semantic, temporal and relational metadata.

To understand how the geometric content relates to the qualitative one, it is necessary to make a brief specification on the conceptual model. Within it, a node called Part has been defined, representing a crucial entity for the spatial and conceptual formalization of conservation and design evidence. It constitutes the minimum measurable localization unit, aimed at supporting the georeferencing of phenomena. Its physical boundaries are defined by the Annotation node. The adoption of the Part as an autonomous and relatable entity responds to the need to model phenomena not as abstract events, but as localized movements of matter, endowed with an explicit geometric component and an implicit relational one. These are physical parts of the technical elements. Each of them is a trace of a transformative action, connected to an observing or planning subject, and to a defined time. During the pre-annotation phase, the parts were identified through a critical process of overlapping between historical graphic drawings and updated digital surveys. From a semantic point of view, this node can be linked to one or more degradation phenomena, each of them related to one or more causes, to potential predictive hypotheses, risk areas, or project actions. Mediation through the Part node make it possible to track transformations over time and the exchange of matter between functionally and geometrically contiguous elements.

The model allows each action to be linked to a specific geometry and to be related to the entire surface of the element. In terms of describing interventions, an emblematic example is represented by the case of single-lancet windows previously filled in and subsequently reopened and equipped with a frame. In this context, the architectural transformation consists of two distinct but logically related actions, each associated with its own Part. The first describes the removal of the infill, formalized as the subtraction of material related to the wall, the second represents the addition of the frame, a material insertion intervention concerning the window. Although coincident in physical space, the two regions are semantically distinct and temporally successive, and their co-presence in the graph enables the representation of the sequence of operations.

In other cases, different actions involved the same portions of the technical element, as in the case of the partial replacement of the roof tiles. The Part refers to a region where distinct operations of removal and restoration have taken place. The same logic lies in the description of the removal and integration of the glass of the window. In this way, the Part node is configured not only as a spatial container, but as a logical device of mediation between material states, technical elements and interventions, capable of returning the building’s transformative depth in a computable, queryable and historically traceable form. The three-dimensional geolocation of the data allows the identification of recurring geometric patterns and the evolutionary reconstruction of portions of the building through the semantic and graphic accumulation of annotations.

The implementation presented some critical issues. Firstly, the annotation phase was not automated. Furthermore, as mentioned, the process of identifying parts is based on interpretations of preliminary data subject to geometric deficiencies or inconsistencies between sources. As a result, each annotation retains a hypothetical component. Despite this, the approach adopted paves the way for a system in which annotations become interrogable, relatable, and analytically active.

### 3.9 Query, visualization and inference environment

During the final phase of the experimentation, an integrated system was developed that connects an interactive web interface, built in HTML and JavaScript, to the Neo4j graph database, using the Neo4j JavaScript driver for API communication, in direct dialogue with the CNRS (MAP) Aïoli platform. The result is represented in Figure 12. The resulting environment consists of two sections for the execution of parameterized queries. This allows specific analytical objectives to be achieved.

The first one involves assessing the state of conservation of a technical element over a defined time interval. This type of query isolates and correlates degenerative phenomena observed across time. The variables that define the perimeter of the query are: Name of the technical element; Type of degradation, as an optional filter to restrict the analysis to a specific phenomenon; Reason (e.g. environmental, structural, anthropogenic); Time interval.

The second objective concerns the succession of conservation interventions on a technical element in a specific time range. A tool for reading the evolutionary process of the component that passes through the changes that have characterized it. The variables that can be queried include the Name of the technical element, the reference time interval for the dating of the interventions; the Degradation Identifier, to relate the intervention to a specific pathological phenomenon and the Project identification data, enabling more precise filtering.

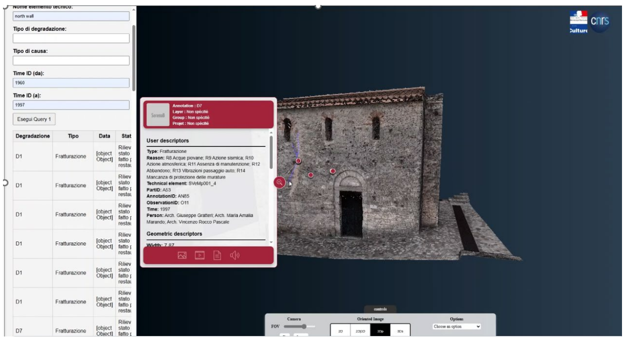

Figure 12. Interface of the query, visualization and inference environment

Through these combinations of inputs, users can activate circumstantial, comparative or transversal interrogations, defining customizable logical trajectories. This process yields a dual output: a detailed table of results and dynamic visualization of the corresponding geolocated annotations within both the 3D model and associated images, enriched by semantic inheritance. The system ensures selective loading of annotated areas for smooth navigation. These queries, though formally explicit, maintain logical flexibility and not only retrieve data but activate an inferential system capable of identifying correlations, recurring patterns, and interconnected assessments across space, time, and matter. The environment thus functions as a computational laboratory. It enables, for instance, the joint evaluation of intrinsic and extrinsic factors affecting conservation, the identification of areas at risk, the analysis of pathological propagation within a single component or between contiguous elements over time and space, the overlay of predicted and observed anomalies, and the comparison of pathological trajectories with other parameter categories.

## 4. Results

The experimentation achieved the objectives of continuity and circularity of the information flow, the reduction of critical points in the transition from raw data to structured information and the development of an inferential environment capable of producing analytical content. Thanks to this, it is possible to correlate historical data, geometric surveys, observations and events, reconstructing the evolutionary path of the technical elements according to an explicit spatio-temporal logic. The representation of the artifact is no longer limited to a synchronic photograph, but is articulated in a diachronic story that can be computable, queryable and updatable over time.

Semantic modelling and graph population produced an implementable backbone. In future, manual instances entry will no longer be required. Each Aïoli annotation, geolocated and semantically structured through predefined classes, will directly populate the knowledge base.

The transition from raw to intelligible data will be fluid and rapid, leveraging indexed mapping to enhance semantic and temporal traceability. Information generation will occur through multi-layered content analysis.

On the representation point of view, the system demonstrated a strong capacity to integrate quantitative and qualitative data, producing semantically enriched and accessible models. In terms of data sharing, the environment supports coherent synchronization between heterogeneous information systems, organizing knowledge according to a chronological and centralized logic. Interoperable technologies were used in the workflow in order to reduce instrumental blocks between software.

The possible multidimensional inferences concern the correlation between heterogeneous entities, such as technical elements, degradation phenomena, interventions and causes, along spatial, temporal and semantic axes. One illustrative example of inference might involve evaluating the recurrence of pathologies on sections of a masonry façade exposed to a persistent triggering factor and linked to previous, ultimately ineffective, interventions.

As demonstrated, the system enables the identification of evolutionary patterns, causal relationships, and complex conservation trajectories, thereby supporting analytical assessments and forecasting scenarios.

## 5. Conclusions

Future developments aim to enhance automation through machine learning and natural language processing tools. These could enable automatic recognition of relevant entities, relationships, and spatial parameters, speeding up the semantic alignment process and expanding inference capabilities.

Another objective is ensuring documental continuity with BIM, achieved through chronological interaction and centralized synchronization. The underlying principle is that annotations,

regardless of where they are made, can automatically propagate updates to the graph database.
Although the experimentation focused on a single building, it succeeded in systematizing a replicable approach that yields a representation of the historical artifact that is not only documentary but also computational, relational, and proactive. The extension of the experimentation to a larger scale is envisaged. As the volume of available data and the density of semantic, environmental, and spatial interconnections increase, the system’s predictive capabilities will grow more robust. The proposed methodology therefore represents a first step towards the construction of a broad information ecosystem in which the amplification of the knowledge base and inferential logic constitute the operational core for sustainable and intelligent asset management policies.

The experimentation highlighted some critical issues, such as the manual component for the semantic coding of sources, with a high investment of time and resources, especially on a large scale. The adoption of artificial intelligence will be a game-changer, but it will require datasets for training. The reconstruction process remains partly hypothetical, especially when based on fragmentary sources, introducing a research perspective on the alignment of multidisciplinary vocabularies belonging to different historical phases.

Although preliminary, these results provide a solution for optimizing the flow of information and increasing the shareability, interrogability and management. Benefits include simplified access to technical data for professionals and researchers, spatial-temporal contextualization of pathologies and interventions, and the use of multidimensional inference to support more informed maintenance planning by professionals and administrations.

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