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Edited by Koraljka Kuzman Šlogar
and Anamarija Žugić Borić

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DIGITAL PROCESSES FOR THE CONSERVATION AND VALORISATION OF BUILT HERITAGE

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The impact of digital technologies on heritage sciences has increased the speed and automation of processes and practices aimed at the survey, representation, modelling, and information management of the built, architectural, and archaeological heritage. These digital resources are progressively increasing, but only some of them are stored and disseminated, resulting in data loss, which means loss of connection between past, present and future and dispersion of memory and knowledge of the crafts, cultural traditions and *genius loci* related to the design and construction of historic buildings. This paper intends to illustrate, based on experiences in the field of built heritage modelling, the potential that a model-based approach can offer in order to build a main point of contact for architects, expert conservators, and researchers interested in implementing digital-based methodologies and strategies in the search for information models that can represent the uniqueness of the architectural heritage, and thus provide the ideal space in which data can take on a richer meaning and value, becoming an integral part of an information network that allows its correlation with different disciplines and fully reveals its value.

Keywords: built heritage, digital process, knowledge modelling, HBIM

INTRODUCTION

The built heritage is an expression of techniques and knowledge to be considered as a unique and irreplaceable source of aesthetic, historical, and cultural values, and therefore must be studied and documented in order to prevent any loss or damage, also ensuring that any restoration, maintenance, and reuse activities are undertaken consciously. Loss of data means loss of the link between past, present and future; loss of memory and loss of knowledge.

It should be noted that, in this field, we are dealing with a body of knowledge held together by experts who go on to investigate both the individual object and the artefact as an individual object, as well as its relationship with its context. Those activities are characterised by complex, multidisciplinary processes aimed at research, conservation and management of the architectural asset; during which every choice and action made by specialists is based on "what is known" about the asset and how that knowledge is represented and shared (Cursi, Simeone, and Toldo 2015).

Today, digital models play a key role in making historical buildings an integral part of contemporary urban life, fostering the convergence of past and present knowledge to facilitate their interpretation and preservation and supporting the prefiguration of their possible future use.

Digital transformation is having a significant impact on the information and communication technologies (ICT)-based methods and tools for the collection, analysis, production, interpretation, and dissemination of research and practices related to built heritage. This digital transformation has paved the way for important methodological changes, advancing documentation and conservation processes, favouring participative activities that bring together different experts with various technical or cultural backgrounds, and enhancing maintenance activities. Furthermore, the increasing ease of use of digital tools and the decreasing costs of instruments and software have favoured their diffusion to transdisciplinary communities of practice, increasing their application and experimentation in multiple fields and contexts.

A recent phase of this ancient journey intends to exploit digital technologies to create information systems capable of integrating the 3D representation of a historic building with evolving data produced during its life in a centralised, robust, coherent, and nonredundant repository, offering fundamental support for decision-making. These information systems can optimise and integrate conservation, restoration and enhancement processes, applied at different scales of intervention and for different purposes. However, despite the potential benefits, there is still much to be done in terms of methodological development, interoperability between software environments, open processes and tools, sharing of guidelines and best practices, and training and dissemination to the community of researchers and practitioners.

Based on the above, this paper aims, in the first instance, to offer a critical contribution to the cross-fertilising relationship between traditional approaches and the most advanced digitally-enabled research for the study, conservation, and valorisation of built heritage, as well as define an outline of the problems encountered in current approaches of digital information modelling for the built heritage, with particular attention to aspects concerning data exchange among different disciplines. Furthermore, it aims to illustrate the results of work completed and strategies pursued by work still in progress, conducted by the Built Heritage innovation Lab (BHiLab) at the Institute of Heritage Science (ISPC) of the National Research Council BHiLab research group, aimed at improving the semantic enrichment of digital models for the preservation and transmission of historical knowledge.

STATE OF THE ART

With the advent of digital transformation, survey activities have undergone a profound transformation, becoming a virtually unlimited container of information from which to extract different forms of representation (Herman et al. 2020).

Among the first experiences, we find the methodologies of 3D surveying and modelling and integration with 2D images aimed at creating a realistic digital model, called reality-based models (Cipriani, Bertacchi, and Bertacchi 2019; Jiménez Fernández-Palacios, Morabito, and Remondino 2017; Remondino (ed.) et al. 2018).

The main techniques to see considerable technological development are digital photogrammetry (Apollonio et al. 2021; Ulvi 2021) and 3D laser scanner acquisition (Buscemi et al. 2020; Hamal, Sari, and Ulvi 2020).

More recently, Historic Building Information Modeling (HBIM) (Murphy, McGovern, and Pavia 2009) has been recognised as a possible solution that can improve the representation of the built heritage and related knowledge (Logothetis, Delinasiou, and Stylianidis 2015; Pocobelli et al. 2018), mainly due to its ability to create a database containing a digital building description including geometry and other semantic information, such as components' classification and properties (Volk, Stengel, and Schultmann 2014).

At the architectural scale, it is possible to distinguish several strands of research on the use of HBIM for conservation and restoration. A pivotal theme is the stratigraphic analysis; a form of investigation done to reconstruct the history of a building, trying to understand what modifications were made and in what epochs. This, together with documents and written testimonies, allows us to reconstruct the will of the workers, the history of the building and the different phases of its life. To this end, Beltramo et al. (2019), building on the previous work conducted by Chiabrando et al. (2017) for mapping masonry decay in a BIM environment and by Diara et al. (2018) for the extraction and management of Industry Foundation Classes (IFC) data using Database Management System (DBMS), experimented, on the Abbey of S. Maria di Staffarda, an operational workflow for the integration of stratigraphic analysis in the HBIM environment.

For the representation of the Harris matrix, which is a methodology that uses diagrams to represent in an abstract way the temporal succession of soil layer formation, surface use, masonry construction, and their destruction, Mammoli et al. (2021) proposed a system for its semi-automatic construction and the mapping of stratigraphic units directly on the point cloud. More recently, Banfi et al. (2022) conducted work that aims to identify, in the BIM environment, stratigraphic surfaces and volumes capable of being mapped with descriptions and materials, allowing a bidirectional relationship between objects and information.

A second theme concerns the identification and semantic enrichment of architectural components. We can place within this strand the work conducted by Dore et al. (2015), which integrated building modelling created from historical data with procedural modelling developed from the laser scanner survey. Many researchers defined libraries of HBIM components using the resources made available by commercial software to create dedicated libraries of parametric objects (Garagnani, Gaucci, and Gruska 2016; Lopez et al. 2017; Oreni et al. 2014).

The new generation of tools that support the integration of data from laser scanners into BIM environments has led to the development of reality-based methodologies to overcome the representation's limitations of HBIM (Bolognesi and Garagnani 2018); although, to date, no algorithm has been developed to automatically convert point clouds into BIM components.

Other works focused on the creation and management of masonry abacuses in the HBIM environment. Specifically, Adami et al. (2020) proposed a new classification method, attempting to overcome the limitations of the traditional 2D system and exploiting the full potential of the solutions offered by BIM authoring tools.

Parallel to, but distinct from, the previous ones are the researches concerning abacuses of structural unrest. In this area, Zuccaro et al. (2010) proposed a multimedia self-training tool for the assessment of the damage caused by seismic events. We can also include the previously mentioned work of Dore et al. (2015) and that of Valero et al. (2018), who proposed a system for monitoring ashlar masonry walls of historic buildings by integrating reality capture tools, data processing (including machine learning) and HBIM models. The work of Bernardello et al. (2020), on the other hand, proposed two alternatives for creating three-dimensional semantic objects in a BIM environment in which to integrate information usually embedded in two-dimensional drawings.

Furthermore, in the literature, there is a large body of research in the field of semantic data enrichment through the use of Semantic Web-related technologies (Pauwels, Zhang, and Lee 2017). Among these works, only a few have focused on the representation of architectural heritage. On the architectural scale, De Luca et al. (2011) have proposed the development of an information system that takes into account the relationships that can be defined between the representation of the building (shape, size, state of preservation, reconstructive hypothesis) and information, of a heterogeneous nature, from different fields (such as technical, documentary, or even historical), while a domain-specific ontology deals with the analysis of degradation, its diagnosis, and possible restoration interventions (Cacciotti, Blaško, and Valach 2015).

In addition, some research has focused on the integration of knowledge bases regarding architectural heritage, created through information ontologies, with a BIM environment (Acierno et al. 2017; Beetz et al. 2016; Maietti et al. 2018; Pauwels et al. 2013; Quattrini, Pierdicca, and Morbidoni 2017; Simeone, Cursi, and Acierno 2019). Recently, Yang et al. (2019) proposed a semi-automated mesh-to-BIM conversion through Dynamo and model translation to IFC owl, while Bonduel et al. (2020) investigated the applicability of Resource Description Framework (RDF) literals in a heritage context built to include a wide variety of existing geometric patterns. In addition, Borin et al. (2020) develop a model for visualising the Harris matrix (a methodology used for dating wall layers) through the use of a BIM-based ontology.

A further theme in the development of HBIM methodology deals with the representation and management of knowledge not directly traceable to building components. Several works demonstrate how these limitations can be overcome by integrating the HBIM environment with external resources and databases (Cursi et al. 2022).

Among the strategies for semantic enrichment of HBIM models, to extend model representation capabilities with dynamic data, we find experiences related to the Internet of Things (IoT) (La Russa and Santagati 2021; Masciotta et al. 2021; Shahinmoghadam and Motamedi 2019; Tang et al. 2019).

The architecture envisioned for this line of research involves a physical deployment of sensors in the field, managed at the logical level by a layering of software capable of storing and making queryable the data produced by the sensors. This data will then be integrated into a database within which the HBIM model manages the positioning in space of the sensors and enables visualisation and querying.

DIGITAL STRATEGIES FOR UNDERSTANDING, PRESERVING, AND SHARING CONSTRUCTIVE KNOWLEDGE

COLLABORATION AND KNOWLEDGE EXCHANGE IN BUILT HERITAGE PROCESSES

Based on the above, today, digital models play a very important role within the complex historical-archaeological framing of an artefact, because they foster convergence between knowledge of the past and the present and facilitate its interpretation.

From the experiences mentioned in the previous paragraph, it is evident how the past decade has witnessed a sharp increase in the use of digital models in the field of cultural heritage, fostered mainly by the technological evolution of digital surveying tools and the growing awareness of the potential of digital techniques in a field in which the public visibility and importance of cultural content determines its ideal testing ground.

There are currently many digital resources available on the market that are designed to improve design capabilities in specific areas and solve even very complex problems in well-defined subject areas (as in analysis, conservation and restoration projects, modelling, and simulation).

It is also true that the introduction of new technologies while helping to improve the processes of a field in a broad sense, brings with it a whole range of minor issues that contribute to increasing the complexity of the process. Although these software programs work well within the specific domain for which they were built, they do not help at all in making design collaborative, making it, on the contrary, more complex by increasing the distance between the communication and understanding of actors having different skills, while referring to the same objects on which they are working.

As already mentioned, however, the architectural heritage sector suffers from the scattering of this wide variety of digital data distributed in numerous independent archives, especially regarding unstructured artistic and cultural heritage. A further element of suffering is given by the great heterogeneity relating to the type of media and formats used for publication at accessibility levels and logical representation of models.

The greater number of disciplines involved and their intricate linkages lack coordination: the interdependence of activities, divergent design goals, and the difficulty of making known the reasons for one's design choices are just some of the problems that make life difficult for the designer (Borkowski et al. 2001; Garner and Mann 2003).

These causes are largely due to difficulties in communication and understanding of different models of reality that are used by actors to highlight aspects of their interests (Woo, Lee, and Sasada 2001). It is clear, however, that it is not only a problem of the quantity and correctness of the information exchanged but, more importantly, of its interpretation and the meanings associated with it (Gabriel and Maher 2002; Kalay 2001).

The exchange of reliable and consistent information among the actors in the process is always a necessary prerequisite for the successful outcome of the process (Carrara et al. 2015).

The lack of mutual understanding between such specialised tools is mainly due to issues related to the interoperability and semantic level of the ICT tools used, and the synchronisation methods they are forced to use to exchange information at a high level.

In fact, the proper formalisation of exchanged information and technical knowledge in general still remains an open problem: the excess of low-level information exchange, cause and effect of the potential of the new ICT, implies the simplification of the exchanged information, thus leading to misunderstanding among the actors and a step backwards in their effective communication.

It is therefore evident how much the methodologies used to digitise and share the knowledge of an architectural asset turn out to be key nodes for it to be preserved and passed on.

As mentioned before, in recent times, the emergence of Building Information Modeling in the field of new construction has been matched by the interest of the scientific community in the search for new avenues to follow in defining a similar methodology applicable in the field of built heritage, now known by the acronym HBIM. The interest in this methodology is mainly due to its ability to create a repository of information, containing a digital description of the building that includes both 3D geometry and other semantic information, such as classification and properties of components (Volk, Stengel, and Schultmann 2014). This approach is based on the use of conceptual models typical of databases, with particular reference to the Entity-Relationship model. These models consist of first identifying some basic entities (such as the technological components of the building) and then identifying the relationships between these entities. The main computer applications are based, in this context, on relational databases that collect information according to well-defined standard schemas. A process, the latter, that allows the creation of a coherent conceptual model in which the central role is assumed by the represented object.

It is precisely this object-centred view, which is concerned only with describing its characteristics through a set of properties, that does not allow for the representation of semantically more complex associations and thus for the provision of a high enough level of formalisation to enable machines to perform tasks of understanding and inferring new information or linking different resources. In addition, complex metadata declarations related to provenance, context, reliability, and uncertainty of data are difficult or impossible to include in the model, despite being ubiquitous in heritage processes (De Luca et al. 2011; Gómez-Romero et al. 2015). Because BIM applications were originally developed for the design of new buildings, they often lack effective modelling tools to create geometries adherent to the needs of specialists involved in a process regarding the historic built environment. Moreover, in the case of new design, the need for accurate and complete knowledge of what we are going to model is crucial. This requirement aligns with the information consistency imposed by BIM environments, which provide valuable support for the construction and management of a building. In contrast, considering the processes that characterise the activities of investigation and restitution of an existing asset, our knowledge on the asset often comes from extremely heterogenous sources. It is subject to continuous changes, interpretations, uncertanties, and gaps that must persist throughout the process and beyond. This limitation also extends to the relationships that are established between the components used, which, to simplify the work done by users, tend to impose constraints that reflect design principles and construction rules that are generally always valid for new construction but are also severe limitations in the documentation of historic buildings.

Therefore, works that led to the definition of innovative digital methodologies and technologies for the knowledge and documentation of historic buildings are illustrated, with the strategic objective of experimenting with a path that rediscovers, highlights, and traces the set of design and construction criteria of those artefacts, analysing the building techniques of the period and their specific application on the construction site, toward an approach projected into the entire building process.

In light of this, it then becomes essential to prefigure a modelling methodology in which both geometric and nongeometric aspects characterising a historic building can converge. As a consequence of the limitations imposed by the above systems, one possible solution is to integrate specific architectural heritage Knowledge Bases with the BIM environments.

Below, new modelling approaches and prototypes are illustrated that are the result of completed and ongoing research projects involving the authors of this paper being part of the BHiLab, together with other research institutions, universities, and industrial partners.

DIGITAL APPROACHES FOR BUILT HERITAGE MODELLING

Those illustrated below are some recent projects that tackle the abovementioned issues from different perspectives: the information system for the management and preservation of built heritage and cultural sites; the study of built heritage from an energy and environmental point of view; the integration of static and dynamic diagnostic and monitoring data within a 3D model; the structural analysis of unreinforced masonry structures; and experiments on the integration of ontological structures with HBIM models.

It is important to emphasise that knowledge of the building is a fundamental step and prerequisite in all the projects illustrated; an aspect that strongly influences both the way models are constructed and the results obtained depending on use.

The research conducted on the National Archaeological Museum of Naples (*Museo Archeologico Nazionale di Napoli* – MANN) (Martinelli, Calcerano, and Gigliarelli 2022; Calcerano et al. 2023), aims to support the planning and implementation of building documentation, maintenance, and conservation activities. To ensure that an HBIM model can effectively support this range of tasks, it should incorporate the results of analysis and expert knowledge that enable critical understanding of the building's construction system, its methods, materials, integration, and assembly of technological elements, and the different periods of construction of each part of the structure, to be represented within the HBIM model. In this way, the model assumes a central role in the building management and maintenance processes as a digital environment shared among specialists and specifically the managing authorities.

In this case, as mentioned earlier, data collection assumes a fundamental role in a solid understanding of a historic building, especially for an HBIM-based process aimed at representing the building's construction systems.

The analyses of the historical cities of Frigento (Italy) and Chuandixia (China), or Palazzo Maffei-Borghese (Rome, Italy) are instead characterised by the integration of the discipline of environmental design, through a simulation-based approach. The use of these tools as a non-destructive analysis technique, coupled with environmental monitoring and field surveys, allows deepening the comprehension of the environmental behaviour of built heritage, shedding new light on the understanding of ancient settlement principles, construction techniques, and design solutions (Gigliarelli et al. 2022; Gigliarelli, Calcerano, and Cessari 2016), a wealth of knowledge of the past to be preserved and shared.

The research conducted as part of the project IDEHA – "Innovation for Data Elaboration in Heritage Areas", with the case of the Royal Site of Carditello, an 18th-century Bourbon palace near the city of Capua, presents a workflow solution to integrate environmental sensors and HBIM into an online platform, with the aim of developing a real-time data collection and monitoring services.

The results obtained, both from the visual analysis and from specific tests to investigate aspects of construction and studies of similar and/or coeval buildings, useful for identifying masonry stratigraphy or characterising deteriorated portions of the masonry, have been compiled within the model, which therefore assumes the role of common data environment (CDE).

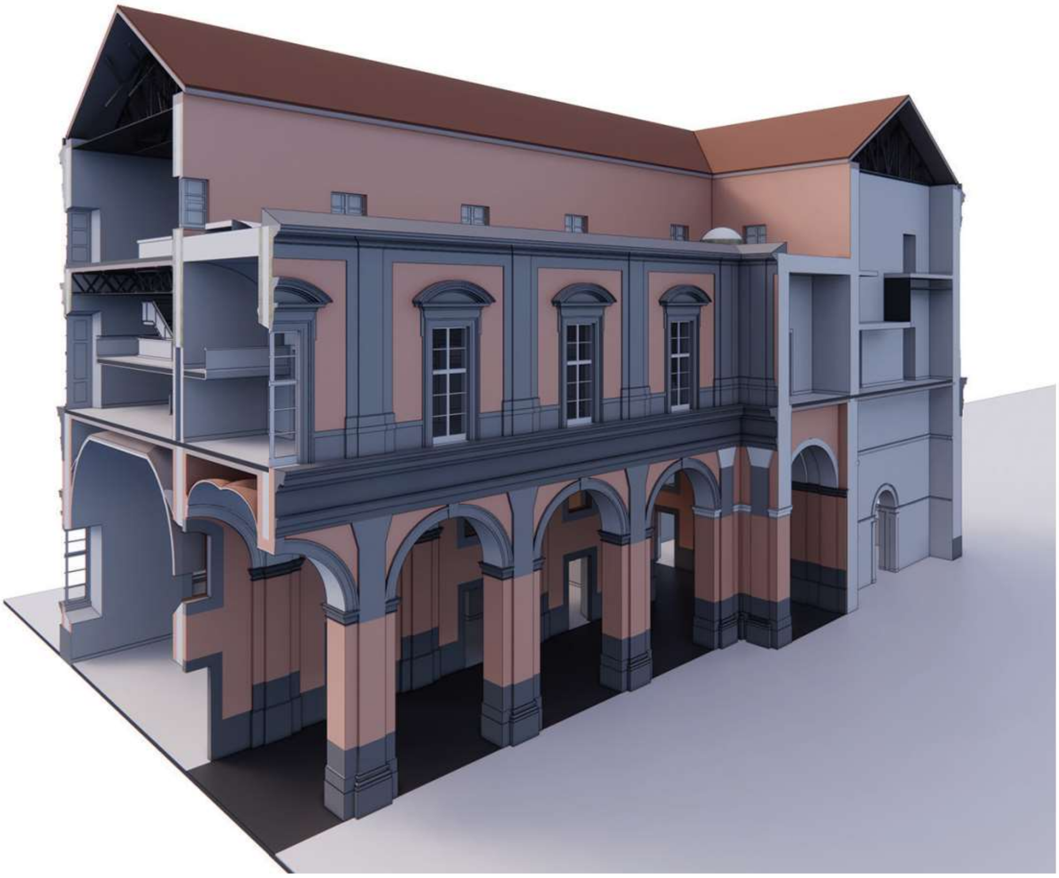

Figure 1: Perspective section view from the inner courtyard of the HBIM model of the southwest wing of the National Archaeological Museum of Naples (project: HBIM4MANN, author: BHiLab-ISPC).

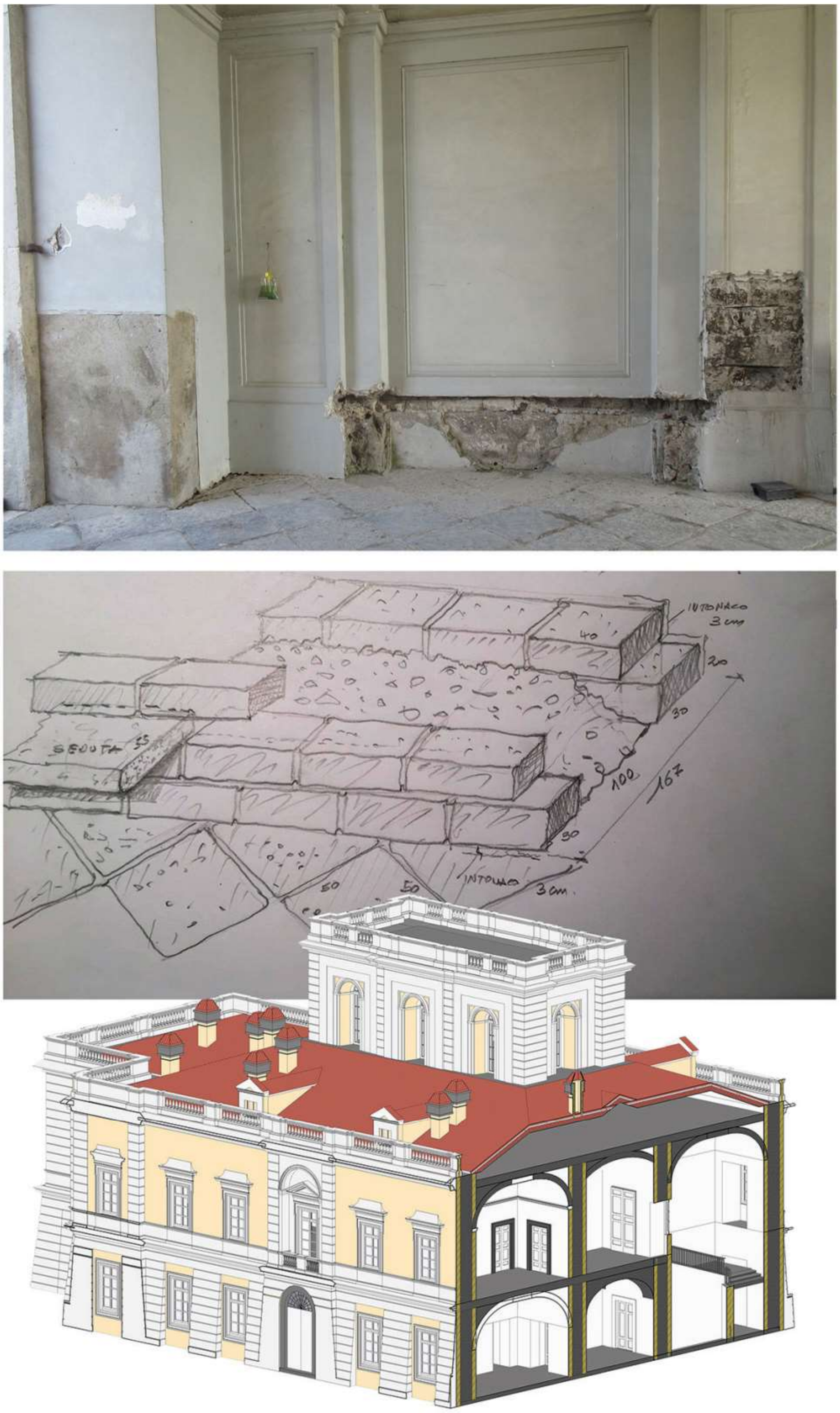

Figure 2: Royal Site of Carditello (IT). Methodology of modelling families through a first phase of visible analysis of the wall face and consultation of literature on coeval construction techniques in the Neapolitan area and a second phase of realisation of system families with the definition of the wall stratigraphy from a metric and textural point of view (project: IDEHA, author: BHiLab-ISPC).

An ad-hoc developed web interface will allow users who are not experts in BIM modelling to both view the model as well as access, query and manage the information collected and linked to it; both static information present in the model, and dynamic information coming from the sensors installed in the case study and traced back to the virtual counterparts. The solution is being tested in the case study with the monitoring of room temperature and humidity, in support of preventive conservation of the artworks exhibited there. This system will promote the sustainable enhancement of the built heritage through the use of innovative technological tools that will enable both the provision of integrated ICT systems to make heritage management, protection, restoration, and conservation activities sustainable, and the integration of cultural offerings with multi-channel front-end applications and services, including through mobile devices, that can generate added value for tourism, enhancement, and development of cultural sites.

With the HBIM4lazioHERITAGE project, BHiLAB is exploring the possibilities of integration between HBIM environments and IoT systems. The aim is to develop a prototype of a platform capable of integrating into real-time the data stream produced by sensors for user monitoring with the information model of the building housing the museum facility. The experimentation is taking place at the Bramante Cloister of the Church of Santa Maria della Pace, a building currently hosting the DART Museum in Rome, where exhibitions, temporary displays, and cultural events of contemporary art are organised.

In addition to the analysis of museum, visitor flows, again, the model will allow the storage, consultation and sharing of data resulting from the historical-architectural analysis that involved on-site study and in-desk research of bibliographic and archival records, historical maps and cartographies, and studies of similar and/or coeval buildings, providing a historical-critical guideline for other analyses.

Send-and-return data flow between the HBIM and IoT model is being tested in both of the above projects.

As part of the SISMI project – "Technologies for Safety Improvement and Reconstruction of Historic Centers in Seismic Areas", the work of Calvano et al. (2022) tests on a building in the historic centre of Cornillo Nuovo (Italy), a digital workflow aimed at connecting an HBIM modelling environment with the Quality Index of Masonry (IQM) method; developed in 2000 by the University of Perugia and updated by the Network of University Laboratories of Earthquake Engineering (ReLUIS). The proposed process involves overcoming the limitations of some rigidities due to BIM tools by using visual programming (VPL) for the analysis of the IQM.

Also in this experience, the construction of the system presupposed both direct and indirect surveys conducted on the building; information that was collected within the model. Specifically, particular attention is paid to the retrieval and organisation of data aimed at understanding the building's construction systems, such as the shape and dimensions of technical elements (especially when not visible from a geometric survey, e.g., the beam system of a wooden floor slab), construction nodes, etc.

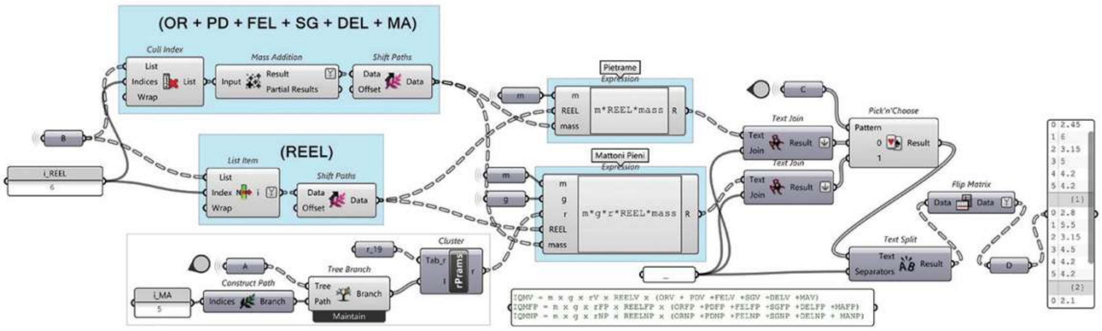

Figure 3: Part of the code (Calvano et al. 2022) used to calculate the IQM expressed for the three stresses for the selected walls (project: SISMI. author: BHiLab-ISPC).

The work conducted on the monastery of St. Mary in Goranxi (Gigliarelli, Cangi, and Cessari 2022) focuses on the integration of a BIM environment with an artefact-specific knowledge base that aims to provide a solution that can fully cover the knowledge processed in a heritage process and necessary for its documentation and informed decisions regarding its preservation. At this stage, the proposed integration has been applied to the representation of some key heritage knowledge domains, namely typological components, structural components, temporal discontinuity components, masonry abacus, and structural failure abacus. The formalisation of knowledge related to these disciplines was integrated with a component-based representation provided by the BIM environment and necessary to control the geometric and technological characteristics of the architectural heritage artefact. In this process of integrating a BIM model with an ontological structure, a delicate aspect to be carefully considered is related to defining the right location in which to formalise information, as well as what information can be used to link the BIM area with the knowledge base to ensure interoperability between the two systems and to limit data duplication. As shown in Figure 4, the dialogue between these two environments is ensured by the transposition, in the ontology-based model, of the set of instances that make up the building model, guaranteed by a unique identifier that ensures one-to-one correspondence and that can be used as a reference for the development of ad-hoc solutions to transfer data from one environment to the other.

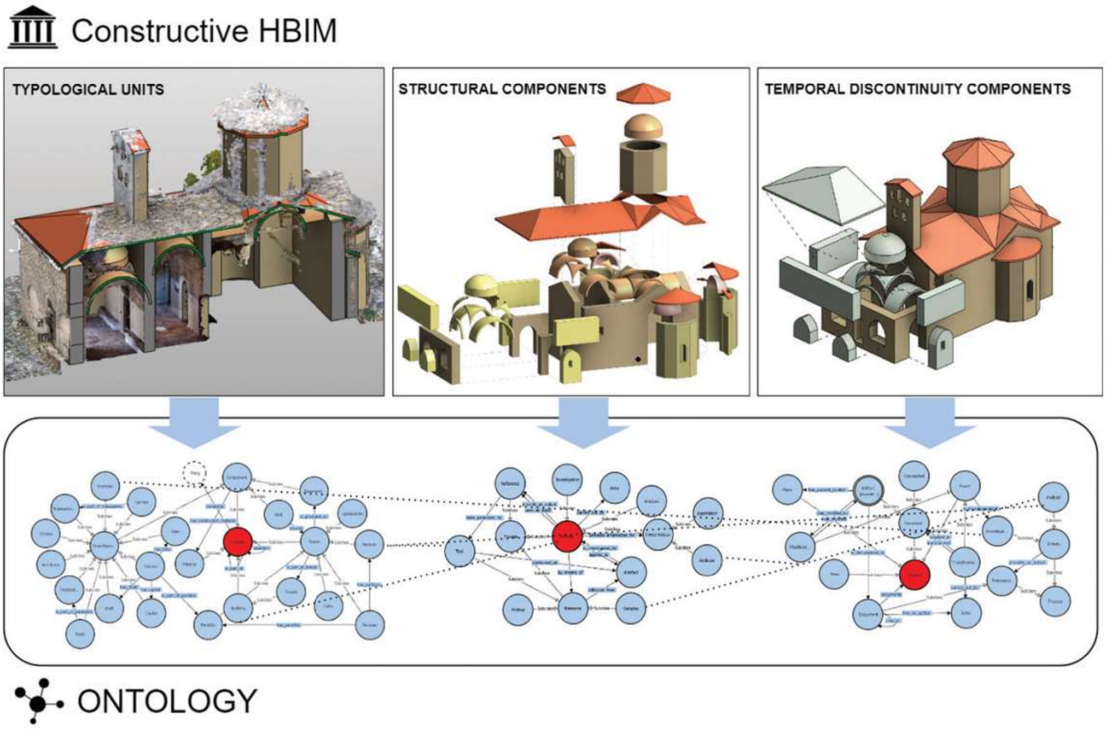

Figure 4: The adoption of ontologies enables the enrichment of BIM semantics through a consistent, flexible, homogeneous and computable formalisation of both direct and indirect knowledge (project: "Multidisciplinary Technologies for the Study and Conservation of Post-Byzantine Monasteries in Southern Albania" (*Tecnologie multidisciplinari per lo studio e la conservazione dei Monasteri Post Bizantini in Albania meridionale*), author: BHiLab-ISPC).

The first advantage of this approach is related to the possibility of assigning different labels to a node representing a building component, ensuring its proper definition without being limited by the families defined in the BIM environment, usually constrained by the authoring software representation hierarchy. At the same time, technologies related to the Semantic Web allow multiple labels to be assigned to a node/object, and this is particularly useful in processes concerning the built heritage where building elements often take on different roles, and, consequently, refer to different classes, in the evolution of the building over time. All the data collected and interpreted by the experts were compiled into the ontological framework that allows the development of the building over time to be traced and interpreted from different points of view.

These works testify to the shift from a document-based information system, in which information about an artefact is stored in unstructured incremental repositories, to a model-based system, where each piece of information is part of a coherent and integrated, up-to-date representation. This faces several issues of current information systems, such as inconsistency or data duplication.

CONCLUSIONS

The results and experiences of the projects described above have solidified the conviction that it is necessary to systematically survey and systematise a specific body of knowledge in the field of historic building techniques, the loss of which can be traced back to the waning of "crafts", of traditional "making". The unavoidable purpose appears to be to record the various expressions of local history, tradition and technical culture that people have been able to express over centuries of building activity.

Conveying traditional knowledge into a computable digital environment allows for completely new pipelines to be followed for obtaining, preserving, sharing, and passing on constructive knowledge.

The experiences illustrated show how a model-based approach can offer clear advantages in the field of built heritage modelling. These solutions can facilitate the search, dissemination and sharing of content and help the understanding of cultural assets and the logical connections between works and places.

A further step forward is to build a point of contact for architects, expert preservationists and researchers interested in implementing digital-based methodologies and strategies in the search for information models that can represent and witness the multifaceted richness of the uniqueness of built heritage, and promote discussion on how these digital approaches can be employed to improve knowledge, conservation, and sustainable management of architectural and archaeological heritage in the arts and humanities.

In this perspective, a research infrastructure such as DARIAH would provide fertile ground for building a working group that can become a Pan-European Virtual Hub, aimed at offering services, resources, guidelines and practices for the representation and management of knowledge collected and produced by research groups and specialists working in the field of historical, architectural, and archaeological built heritage.

The adoption of a Pan-European Virtual Hub will make it possible to reconstruct a new picture of the construction techniques spread around the world, the permanences and mutations of common typologies with the contribution of skilled workers who moved through Europe over the centuries. This will enable interdisciplinary exchange and interoperability, as well as help promote a culture of data sharing related to the permanence and mutations of common architectural types built over the centuries in Europe and a deeper engagement of heritage in modern society.

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