UNIVERSITY OF TRENTO

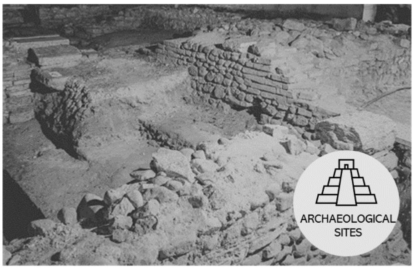
Doctoral School in Civil, Environmental and Mechanical Engineering

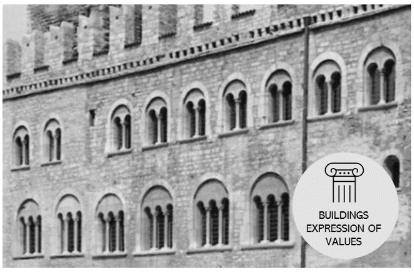
Curriculum 4. Architecture and Planning, Landscape

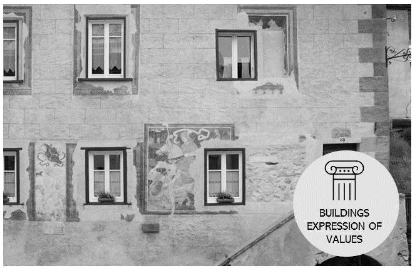
Ambra Barbini

Built Heritage Interface Models

Multipurpose information access and data exchange







2024 - Doctoral thesis

Abstract
The research investigates models as interfaces to the built heritage, intended as representation forms and strategies for multipurpose information access and data exchange to enhance collaboration among practitioners and promote communication with stakeholders and generic audiences. After analyzing the research keywords through a theoretical framework, the study focuses on different methods and techniques for digital model development from data acquisition and processing, according to specific purposes and priorities. This focus relies on both literature review and real case studies, including integrated survey campaigns and paying particular attention to accessible and interoperable workflows also through the exploration of open solutions. Follows a section oriented to the potential uses of the developed models, offering some fruition options to allow specialized and generic users to access technical and cultural data. The point of view of different professional categories of the construction supply chain is further investigated through a questionnaire disseminated in the Province of Trento on data exchange and collaboration forms, digital tools adoption, and built heritage data collection and processing. Some of the solutions tested within the research are made available in tools such as self-orientation surveys and a check-list as user-friendly and easily accessible alternatives to traditional guidelines to promote knowledge transfer and benefit from further contamination between the academic state of art and professional praxis.

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Ambra Barbini

Built Heritage Interface Models

Multipurpose information access and data exchange

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CONTENTS

ABSTRACT

The research investigates models as interfaces with the built heritage, intended as representation forms for multipurpose information access and data exchange to enhance collaboration among AECO (Architecture, Engineering, Construction and Operation) practitioners and promote communication with stakeholders and the general public. Through a theoretical framework on the research keywords, built heritage emerges not only as the expression of outstanding values but also as the entire built asset inherited from the past and available for current and future generations. The term interface is understood as a connection enabling knowledge transfer or joint operations, supporting content communication and empowering professional collaborations. Model is intended as a discretization and simplification of the complexity of reality and as the result of an interpretation-oriented process of imitation. After this framework clarifies the research objects, purposes and tools, the study focuses on different methods and techniques for digital model development from data acquisition and processing. This focus relies on literature review and case studies developed within the Laboratory of Architectural Modelling and Analysis Representation and Communication (LAMARC) as part of master's theses, teaching or research activities. These case studies include integrated survey campaigns oriented to the acquisition of accurate data or the evaluation of expeditious and low-cost procedures. For the processing, modelling and fruition phase, particular attention is paid to accessible and interoperable workflows exploring free and open solutions. Various model types, from numerical to informative, are considered a possible interface with the built heritage and are associated with different priorities, such as geometric accuracy, parametric flexibility, information or detail richness.

Moreover, different strategies for Heritage Building Information Models (HBIM) development are studied according to the object peculiarities, testing and comparing different solutions to represent the irregular and complex geometries typical of historic buildings despite the constraints of the BIM environment. The potential uses of the developed models are also explored through case studies, testing some options to allow specialized and generic users to access technical and cultural data. Some

tests are performed assuming that users are technicians already employing advanced digital technologies, and others consider practitioners mainly relying on traditional procedures and tools. The point of view of different professional categories of the construction supply chain is further investigated through a questionnaire disseminated in the Province of Trento on data exchange and collaboration forms, digital tools adoption, and built heritage data collection and processing. To conclude, three tools have been developed to make the research outputs more accessible for AECO operators and other stakeholders of the built heritage:

- an orientation tool that supports defining which kind of model is the most appropriate interface according to the project's purposes and priorities;
- a dynamic guide tool aimed at helping select the most suitable modelling strategy according to the object peculiarities, including site accessibility and the management of irregular shapes;
- a checklist that recalls the multiple interoperability layers to facilitate collaboration and communication among AECO professionals.

1. INTRODUCTION

Following the European Directive (CE 24/2014) promoting innovation, sustainability and digital implementation within the construction sector, the latest updates of the Italian Public Procurement Code (D. Lgs. 50/2016 and D. Lgs. 36/2023) have introduced the requirement of specific methods and tools for the digital informative management of the design and realization of new construction and for the interventions on existing buildings in public procurements. These methods and tools refer to Building Information Modelling (BIM), intended as a set of processes, tools and policies, including interoperable platforms for data sharing based on open formats, such as the Industry Foundation Classes (IFC), developed by buildingSMART to promote easy access and exchange of contents developed within BIM environment.

The output of a Building Information Modeling process is a Building Information Model. We can consider a Building Information Model as a combination of geometric and thematic data, manageable and adjustable through parameters, that can dynamically follow the user purposes and therefore suitable to support several AECO (Architecture, Engineering, Construction and Operations) activities during the life cycle of a construction, from design to building, to facility management and conservation or to recycle, transformation and demolition processes.

BIM follows a multidimensional logic and beyond 2D and 3D geometry, time is an essential dimension and variable of the process: this means having tools to plan and trace the multiple stages of the life cycle of constructions, facilitating the evaluation of economic and environmental impacts during decision processes, according to circular and sustainable development principles, strongly promoted at the global level.

During the life cycle of a construction, a Building Information Model can progressively include a wide amount of data, systematically collected and logically organized, that can be exchanged and further developed involving different AECO operators (i.e. designers, suppliers, manufacturers, clients, building companies, facility managers) and supporting flexible, integrated and multi-/inter-/transdisciplinary processes, especially using open formats. IFC format allows access to geometric and alphanumeric data, regardless of the BIM software that generated them and even without any BIM software license, by using IFC viewers.

Including data connected to many different aspects of a building or an infrastructure life cycle, a Building Information Model can easily evolve into a wide and complex system. The collaborative use of BIM data is often connected with the risk of working with a model overloaded with unnecessary or redundant data or with a model missing the essential data for the planned applications, especially in the case of the built heritage.

Because of their heterogeneous nature and the singularity of their shapes, the built heritage is often more challenging to fit into parametric modelling schemes. At the same time operating on built heritage will be increasingly required, to avoid soil consumption, to adapt buildings to current standards and to maintain elements of historical interest, which require protection and conservation measurements. In a country with a vast and stratified built heritage, like Italy, the interest to adopt the BIM methodology for heritage building is progressively spreading, also because it is expected that most of the future construction works will involve the preservation and transformation of the built heritage. Currently, some of the main challenges related to the built heritage modelling are determined by the huge amount of data available thanks to digital survey techniques and the fragmentation of the AECO sector, with many experts on the same project.

Experts collaborating on the same project need specific representation and often storage of information in heterogeneous data formats, this brings interoperability issues. It is then necessary to understand all the aspects connected with interoperability to improve the collaborative use of built heritage data. Indeed, AECO operators could benefit from clear strategies and workflows to access heritage building data effectively and efficiently.

Interface models are proposed in this research as a key tool to enhance the accessibility of new technologies for many potential users beyond operators involved in the AECO sector. This could facilitate not only maintenance, conservation and promotion of the built heritage but also data access for decision-makers, and daily and occasional users interested in the history of the building or other available information.

After analysing the research keywords through a theoretical framework, the study focuses on different methods and techniques for digital model development, starting from data acquisition and processing, according to specific purposes and priorities. This focus relies on both literature review and case studies development, including integrated survey campaigns and paying particular attention to accessible and interoperable workflows exploring solutions based on free and open so. Follows a section oriented to the potential uses of the developed models, offering some fruition options to allow specialized and generic users to access technical and cultural data.

The point of view of different professional categories of the construction supply chain is further investigated through a questionnaire disseminated in the Province of Trento on data exchange and collaboration forms, digital tools adoption, and built heritage data collection and processing. Some solutions studied and tested within the research are made available in tools such as self-orientation surveys and a checklist as user-friendly and easily accessible alternatives to traditional guidelines to promote knowledge transfer and benefit from further contamination between the academic state of art and professional praxis.

The work is broken down in 5 chapters and it is closed by a 6th one containing the conclusions. As the research question appears in the 3rd chapter, the first two are intended to present and discuss the background of the work, namely the introduction in the 1st and the keywords in the 2nd chapter. The 4th chapter illustrates[1] built heritage data acquisition, processing and modelling strategies, and the 5th focuses on the possible exploitation of the developed models as interface, on the questionnaire disseminated among AECO professionals and on the developed tools.

This study started after a master thesis on an interoperable BIM object library aimed at supporting public works and two research experiences

[1] All figures presented in this work without reference have been newly developed by the author.

in collaboration with the Department of Civil Environmental and Mechanical Engineering at the University of Trento (September 2019 -July 2020) and within the Process Engineering and Construction team at the Fraunhofer Italia Research Institute in Bolzano (January-October 2020). The first research project focused on retrofitting processes designed through BIM methodologies based on precast wooden frame panels and the second on life cycle impacts of building components visualization.

Both these experiences had an impact on this research, as well as the effects of the pandemic, rapidly transforming communication needs and accelerating the digitisation process in professional and private routines, but also limiting direct access to objects of investigation and contacts with stakeholders. Moreover, this research took great advantages of the involvement in local and international projects, as well as educational activities with younger and senior students of the Master courses of Building Engineering and Architecture, Civil Engineering and Energetic Engineering at the University of Trento, including various opportunities to investigate and explore the peculiarity of various case studies.

2. THE RESEARCH KEYWORDS

The stratification of meanings that words can acquire over time and within different scenarios witnesses the complexity and, simultaneously, the power of languages as communication tools. Words can encompass diverse connotations and nuances, offering the opportunity to connect concepts and build bridges between fields of knowledge that may be far apart. The inherent richness of language supports the exploration of the different settings where words emerge, evolve, and reshape with varied shades of meaning depending on their application and temporal context.

With the awareness that each term carries multiple levels of interpretation beyond dictionary definitions, this keywords investigation aims to define a research framework. The following pages serve as a guide to the foundational words shaping this study and its title, namely "built heritage", "interface", and "models".

This chapter systematically explores these pivotal terms, unravelling their layers of connotations and highlighting their significance for the research. The analysis of each term, acknowledging the dynamic and complex nature of language, explicitly outlines the intended meanings of each keyword within the study. Starting from meaningful definitions and etymologies, the exploration of each term supports defining the research objects, purposes and tools.

Different possible built heritage categories, their peculiarities and possible intervention forms emerged from the exploration of the concept of heritage. This analysis shows that, despite each nation having different forms of recognition, management strategies and regulatory evolutions, built heritage acts globally as a magnet for humanity.

Among the multiple stakeholders interacting with the built heritage, we can count generic users, experts and specialists, including several networks of organisations committed to the management and protection of heritage at the local, national, or international level. Each stakeholder interfaces differently with the built heritage, depending on their point of view and purpose. Some may only need to access specific information, while others need to exchange data for further elaborations.

With the analysis of the term *interface*, the attention shifts to the difference between simple information access and the use and transformation of data received from others, distinguishing the ability to interface (interface-ability) with the ability to operate with others (interoperability). The features of a good interface are retrieved, considering the evolution of human-object interaction and the technologies available today. Interoperability dimensions are also studied, analysing and comparing academic and regulatory frameworks.

Last but not least, the term *model*, intended both as a representation and imitation device, offers the opportunity to highlight the role of theoretical models in the various scientific fields and recall the multiple uses and applications of tangible models in design processes. Most of its functions are today accomplished with the development of digital models in virtual environments, working as intermediate structures between the imagined design and its realisation or the realised object and its analysis.

This first chapter mainly reflects the first investigations and the intent to develop a glossary to support further research activities. Still, it is also the result of a progressive awareness of the research topic.

2.1 Built Heritage

The term *heritage* is employed to denote that which has been or could be inherited ("Heritage N.", 2023). Historically, concerning private individuals, it typically refers to property, such as building assets or lands[2], passed down through the right of succession, or received from ancestors by right of birth thanks to a condition or status[3]. Over time, the term evolved, indicating anything handed down from one generation to another and encompassing not only tangible belongings, such as properties, tools and valuables, but also intangible assets, such as cultural habits, traditions, and values. Concerning communities, the term heritage also indicates any local and national features[4] recognised as particularly meaningful from a historical, cultural, or natural point of view. Historical heritage is generally geographically placed and associated with a person or a community. Examples of common natural heritage are islands, mountains, and forests. Cultural heritage is often intertwined with historical heritage and they both include tangible and intangible elements, such as archaeological sites, buildings and statues, or oral expressions, performing arts and social events.

The etymology of the word *heritage*[5] traces back to the Latin noun *heres*, heir, and the verb *hereditare*, to inherit. The Italian and French translations of heritage, respectively *patrimonio* and *patrimoine*[6], share similar etymologies and developments. From the Latin *patrimonium*, composed of

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[2] Since 1225 according to "Heritage, N., Sense 1.a." Oxford English Dictionary, Oxford UP, December 2023, https://doi.org/10.1093/OED/9391079025. Last access: 15.10.2024

[3] Since 1621 according to "Heritage, N., Sense 4." Oxford English Dictionary, Oxford UP, December 2023, https://doi.org/10.1093/OED/5778821977. Last access: 15.10.2024

[4] Since 1970 according to "Heritage, N., Additional sense." Oxford English Dictionary, Oxford UP, December 2023, https://doi.org/10.1093/OED/6071824639. Last access: 15.10.2024

[5] Sharing the root with the corresponding terms herencia (Spanish) and herança (Portuguese).

[6] The first evidence of the use of the French term "patrimoine" in the modern sense dates to 1790, when it appears in a petition to convince emigrants of the need to turn their heritage from family to national (Vecco, 2010).

the noun *pater* and the verb *monere*, the term indicates what belongs to the father and by extension to the family. At first, these terms, as well as *heritage,* denoted a form of private inheritance. Since the French Revolution, *patrimoine* began to included national assets and properties; later, this term acquired a cultural connotation, initially in institutional contexts, mainly to indicate goods and properties associated with history or fine arts, until modern usage, when both administrations and the public adopted this term to refer to testimonies of the past objectively and subjectively worthy of preservation (Vecco, 2010). A similar definition describes heritage as "all inherited resources which people value for reason beyond mere utility" (Stanford, 2017, p. 125). Terms, referring to goods privately or collectively inherited and figuratively extended to anything transmitted from one generation to another, are common throughout Europe, such as the term *Erbe* used in all the German-speaking countries, *arv* used in Denmark, Norway, and Sweden, as well as the Spanish herencia and the Portuguese herança. As the Latin *hereditare*, these terms find their roots in the ancient Greek word *kleros*, used to indicate the portion of land inherited from ancestors to share among family members *("**Κληρος**", 2008)*.

2.1.1 Development of the concept of heritage

The modern concept of heritage, understood as common goods and properties, is strongly linked to the development of nations, as heritage has played a significant role in defining a shared sense of identity (Graham & Howard, 2016). Indeed, until the end of the 19th century, heritage was primarily a national matter, and the interest in the preservation of historical and artistic monuments was limited to national domains (Konsa, 2013). An international approach towards heritage arose after World War I, with the Athens Conference (1931) on the restoration of historic buildings and especially after World War II, with the Hague Convention (1945), specifically focusing on cultural heritage protection in case of armed conflicts (UNESCO, 1954). Moreover, in the same years, the emergence of several international bodies engaged in cultural legacy protection and preservation reflects this trend (Konsa, 2013). The current approach to heritage denotes a collection of attitudes and connections with the past, marked by profound respect and affection for specific objects, locations, and customs believed to be representative of the past (Harrison, 2013). In this regard, it is worth noting that the Western approach toward history places significant importance on material heritage preservation, while other cultures prefer spirituality and expertise associated with the ability to create (Vecco, 2010). For this reason, the concept of heritage, after being extended from private to public and used to refer to historical and artistic goods, has been adapted to a more international and inclusive perspective, embracing intangible elements such as customs and traditions (Blake, 2002).

Protection measures

Historically, art and cultural heritage have been exploited for their pedagogical-persuasive value, to influence the masses, to convey religious or political messages, or for their economic-commercial value as a sign of power and social differentiation (Ainis & Fiorillo, 2015, pp. 3-5).

Most European countries began to legally define cultural heritage protection in the early 18th century, often due to concerns about losing important monuments of the past. For example, in Portugal the King Don João V defined the first measures to protect cultural heritage in the first half of the 18th century (Cunha Ferreira, 1993, p. 81). In Austria, Emperor Franz Joseph introduced the public preservation of architectural heritage in 1850 (Rampold, 2017, p. 99). England's sensitivity to heritage protection was probably influenced not only by the presence of a stable government, but also by disruptive historical events, such as Kings Henry VIII dissolution of churches and monasteries in 1530, the Civil War of 1640s (Stanford, 2017, p. 127). In France, revolutionary vandalism at the end of 18th Century was one of the main drivers for the birth and development of heritage protection, mainly based on the systematic and centralised construction of inventories for the development of the national identity (Prati, 2017, pp. 43-48). Spain first showed an aptitude for safeguarding cultural heritage with the establishment of the Academies of Fine Arts in the second half of the 18th century and followed the French model by developing a national catalogue of cultural heritage during the 19th century (Mileto & Vegas Lopez-Manzanares, 2017, pp. 65-66).

In Italy, among the pre-unification monarchies, one of the earliest legislative interventions aimed at safeguarding the built heritage was the decree of the Kingdom of Naples in 1822, prohibiting the demolition of buildings of noble architecture and establishing a control and supervisory commission (Frigo, 1986, pp. 14-16). With the unification of Italy, there was a concern to avoid overlapping the collective interest in cultural heritage with the violation of private property. For this reason, one of the first laws[7] related to the built heritage preservation allowed for the expropriation of ruined monuments if this was due to the owners' negligence[8]. Follow a series of regulations[9] aimed at the national cultural heritage preservation, up to the commitment of the Italian Republic to the protection and promotion of cultural heritage in the Constitution[10]. Ac-

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[7] L. 2359, 25.06.1865

[8] Guarino, C. (2020). La gestione dei siti del patrimonio mondiale culturale e naturale UNESCO: la reggia di Caserta [Master's thesis, Luiss Guido Carli]. Luiss Thesis, pp. 5-36

[9] L. 185, 12.06.1902; L. 363/1913; L. 1089, 1.06.1939

[10] Art. 9 "The Republic promotes the development of culture and scientific and technical research. It protects the landscape and the historical and artistic heritage of the Nation." (Italian version: "La Repubblica promuove lo sviluppo della

cording to current Italian regulations[11], cultural heritage consists of cultural and landscape assets, which may include monuments[12] and diffuse assets[13]. In Italy, competent national and regional authorities are responsible for the protection and valorisation of all public properties older than 70 years, after a confirmation of cultural interest[14], and private properties, after a declaration of cultural interest[15]. Moreover, regional authorities are responsible for reconnaissance and cataloguing[16], supervision, and inspection of local heritage[17].

In general, it is possible to notice how cultural heritage protection is strongly connected with the concept of conservation ensured by coherent and coordinated prevention, maintenance, and restoration activities (Trovò & Chiarelli, 2017, pp. 152-161). In particular *prevention*[18] is oriented to "limit risk situations related to the cultural asset in its context", *maintenance*[19] aims to "control the condition of the cultural property and to maintain the integrity, functional efficiency and identity of the property and its components" and *restoration*[20] involves "a series of operations aimed at the material integrity and recovery of the asset, and the protection and transmission of its cultural values".

Other countries also refer to specific categories in defining possible interventions on the built heritage. For example, according to Stanford (2017, p. 126), in England the main interventions are:

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cultura e della ricerca scientifica e tecnica. Tutela il paesaggio ed il patrimonio storico e artistico della Nazione.")

[11] D. Lgs. 42/2004, Capo I, Art. 10-11

[12] Notable examples of architecture traditionally studied for their historical, artistic, or architectural value.

[13] Minor architecture and areas between architectural assets, according to a new vision of history, open to the study of the whole society.

[14] D. Lgs. 42/2004, Capo I, Art. 12

[15] D. Lgs. 42/2004, Capo I, Art. 13-16

[16] D. Lgs. 42/2004, Capo I, Art. 17

[17] D. Lgs. 42/2004, Capo II, Art. 18-19

[18] D. Lgs. 42/2004, Sezione II, Art. 29, 2

[19] D. Lgs. 42/2004, Sezione II, Art. 29, 3

[20] D. Lgs. 42/2004, Sezione II, Art. 29, 4

- *conservation*, oriented to avoid loss or harm, accepting possible evolutions and changes and equally evaluating past phases and configuration of the building;
- *preservation*, aiming at the maintenance of the current state to extend the life of the building, avoiding any future transformation;
- *restoration*, focused on displaying and highlighting a specific past configuration of the building, considered as the most meaningful.

Canada has a very similar approach to conservation treatments[21], with a slight difference in terms, and distinguishes between:

- *rehabilitation*, involving the adaptation of the building to new uses and current standards;
- *preservation*, focusing on maintaining the building in good condition;
- *restoration*, referring to the accurate recovery of an historic phase.

International documents

The international awareness about the importance of protecting the cultural heritage rapidly increased during the two global conflicts, recognising it as a collective resource and expression of local, national, and international identity[22].

The first international documents in this direction are the Athens and the Venice Charter, respectively adopted during the First and the Second International Congress of Architects and Technicians of Historic Monuments. The *Athen Charter* (1931) consists of seven points, introducing the idea of a collective world heritage, promoting the protection of historical sites and surrounding areas, also through national legislation (ICOMOS, 2011). The *Venice Charter (1964)*, also known as the *Restoration Charter*, provides an international framework for the conservation and restora-

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[21] Canada's Historic Places. (2010). *Standards and Guidelines for the conservation of Historic Places in Canada. A Federal, Provincial and Territorial Collaboration. Link: https://www.historicplaces.ca/en/pages/standards-normes.aspx Last access: 04.08.2024*

[22] Especially during World War II there was a high concern about cultural heritage, both historical and contemporary, as well as tangible and intangible, as witnessed by special programmes such as the "Monuments, Fine Arts and Archives" and the "Emergency Rescue Committee", respectively recalled in the movie *Monuments Men*, by Geoge Clooney (2014), and in the miniseries *Transatlantic* by Anna Winger and Daniel Hendler (2023).

tion of monuments, not only as works of art but also as historical evidence (ICOMOS, 1964).

At the European level, international bodies adopted several documents to define policies for the protection and promotion of the built heritage, such as the *Amsterdam Charter*, the *Grenada Convention*, the *Krakow Charter*, and the *Leeuwarden Declaration*. In particular, the Council of Europe, with the *Amsterdam Charter*, recognise architectural heritage as an irreplicable expression of the wealth and diversity of European culture, referring not only to the most important monuments but also *to* groups of lesser buildings (Congress on the European Architectural Heritage, 1975). Ten years later, the member States of the Council of Europe included in the *Grenada Convention* the principles of integrated conservation to improve built heritage protection policies (Council of Europe, 1985). The *Charter* of *Krakow* acknowledged as heritage the values with which a community identifies itself (International Conference on Conservation, 2000). With the *Leeuwarden Declaration*, the European Union focuses on the adaptive reuse of the built heritage that, despite losing its original function, still represents a spatial and social landmark and confers identity to the environment (Architects' Council of Europe, 2018). This brief presentation of some of the main international documents on built heritage protection highlights two main actors: professionals and governmental bodies. On one side practitioners, such as "Architects and Technicians of Historic Monuments", express their concerns and offer their knowledge and expertise to technically guide built heritage conservation. On the other side, governmental bodies acknowledge the importance of built heritage as a common good and adopt policies to ensure its preservation.

2.1.2 Heritage stakeholders

The widespread interest in cultural heritage is expressed also through the development of a widespread network of institutions and associations from the international to the local scale. Firstly, the establishment of UNESCO (United Nations Educational, Scientific and Cultural Organization), in 1945, when twenty countries from all five continents acknowledged the importance of education and culture to ensure peace, justice and freedom among nations and committed "*to contribute to peace and security by promoting collaboration among the nations through education, science and culture in order to further universal respect for justice, for the rule of law and for the human rights and fundamental freedoms*" UNESCO Constitution (1945).

Examples of other international non-governmental bodies are the following, briefly presented in chronological order.

- ICOM - International Council on Museum (1946), "*committed to the research, conservation, continuation and communication to society of the world natural and cultural heritage, present and future, tangible and intangible"* (ICOM).

- ICA - International Council of Archives (1948), "*dedicated to the effective management of records and the preservation, care and use of the world's archival heritage through its representation of records and archive professionals across the globe*", with the belief that "*effective records and archives management is an essential precondition for (…) the preservation of mankind collective memory*" (ICA).

- IIC - International Institute for Conservation of Historic and Artistic Works (1950), founded to prevent and contrast the risk of meaningful historic and artistic works lost, with the strong belief that "*by looking after our cultural heritage and our own and others cultural identity we are helping to improve the richness and quality of life for everyone*" (IIC).

- ICCROM - International Centre for the Study of the Preservation and Restoration of Cultural Property (1959), an intergovernmental centre born to "*study and improve restoration methods*" and currently "*promoting an interdisciplinary approach to conservation*" (ICCROM).

- ICOMOS - International Council on Monuments and Sites (1964), a non-governmental body associated with UNESCO "*to promote the conservation, protection, use and enhancement of monuments, building complexes and sites*" (ICOMOS).

- WMF - World Monuments Fund (1965), "*devoted to safeguarding the world's most treasured places to enrich people's lives and build mutual understanding across cultures and communities*" (WMF).

- CIPA - International Committee for Documentation of Cultural Heritage (1968), originally "*Comité International de la Photogrammétrie Architecturale*", was created together with ISPRS (International Society of Photogrammetry and Remote Sensing) as International Scientific Committees of ICOMOS, to support "*the transfer of technology from the measurements sciences into the heritage documentation and recording disciplines*" (CIPA).

- DOCOMOMO - Committee for Documentation and Conservation of Buildings, Sites and Neighbourhoods of the Modern Movement (1988), with the mission of "*elicit responsibility towards this recent architectural inheritance*" (DOCOMOMO).

- TICCIH - The International Committee for the Conservation of Industrial Heritage (1999), with the goals to "*promote international cooperation in preserving, conserving, investigating, documenting, researching, interpreting, and advancing education of industrial heritage*" (TICCIH).

- CICOP Net, the Confederation of International Centres for the Conservation of Architectural Heritage (2012), to transform "*the static conception of heritage*" into a "*dynamic relationship with the territory and its belonging region, stimulating multicultural promotion processes*" (CICOP Net).

- The Blue Shield (2016), a fusion of ICBS - International Committee of the Blue Shield (1996), created by ICA, ICOM, IFLA[23] and ICOMOS, and ANCBS - Association of National Committees of the Blue Shield (2008) established to coordinate the work of the national committees (The Blue Shield).

[23] International Federation of Library Associations and Institutions, established in 1927.

All these associations conceived at a world scale find a supportive network also at lower levels, considering not only the European Union, but also national and local institutions. The European Commission fosters politics and programmes to support member states in protecting and promoting European cultural heritage. In the framework of several heritage networks, such as the European Heritage Alliance, coordinated by Europa Nostra, the following are some of the most meaningful bodies focused on the built heritage.

- E-FAITH - European Federation of Associations of Industrial and Technical Heritage, committed to research, safeguarding, interpretation and promotion of industrial and technical heritage (European Heritage Alliance, E-FAITH).

- EFFORTS - European Federation of Fortified Sites, active in the recovery, safeguarding and promotion of "*military heritage consisting in fortifications, dockyards and remarkable architectural assets*" as "*precious testimony to the collective memory*" and "*source of common identity for people across Europe*" (Declaration of intent to establish a European network of military heritage sites, 2014).

- EHHA - European Historic Houses Association stand for the private owners of historic buildings, their garden and their parks and is engaged in securing "*favourable measures for the conservation and the sustainable development of private historic houses*" (EHHA).

- FRH - Future for Religious Heritage (2011), an organisation "*working to protect religious heritage buildings across Europe*" (FRH).

At the national level, in Italy, the institution responsible for managing cultural heritage is the MiBACT *(Ministero per i Beni e le Attività Culturali e per il Turismo,* Ministry for Cultural Goods and Activities, and Tourism*).* Established in 1974, this Ministry combines the responsibilities and functions related to antiquities and fine arts, academies and libraries, state archives and discography, and the dissemination of culture[24]. The MiBACT includes central, peripheral, and advisory bodies. The General Directorate For Archaeology, Fine Arts And Landscape (Direzione Generale

[24] D.L. 657, 14.12.1974

Archeologia, Belle Arti e Paesaggio), one of the main central bodies, performs the functions and tasks relating to the protection of "*assets of archaeological interest, including underwater assets, historical, artistic and demo-ethno-anthropological assets, including wall paintings and decorative apparatus, as well as the protection of architectural assets and the quality and protection of the landscape*" (MiBACT, Direzione Generale Archeologia, Belle Arti e Paesaggio). Regarding the built heritage, advisory bodies include technical-scientific committees for archaeology[25], fine arts[26], contemporary art and architecture[27] and the historical heritage of World War I[28]. The Digital Library (Istituto Centrale per la Digitalizzazione del Patrimonio Culturale, Central Institute for Cultural Heritage Digitization), founded in 2020, coordinates and promotes digital programmes related to cultural heritage. Moreover, it is actively involved in the preserved assets management, cultural heritage interaction redesign and new values development (Digital Library). The Digital Library brings forward its mission with the support of some afferent institutions, such as the ICAR[29], the ICBAS[30], the ICCU[31] and the ICCD (*Istituto Centrale per il Catalogo e la Documentazione,* Central Institute for Catalogue and Documentation). In particular, ICCD coordinates and manages the General Catalogue of Cultural Heritage, including a specific section for "*architectural and landscape heritage*" (Catalogo Generale dei Beni Culturali). Another national public entity is Agenzia del Demanio (State Property Agency), entrusted with the care of the state's real estate assets and engaged in the digitization process of data on the built heritage of the state, through the UpDATE platform (Agenzia del Demanio, 2021).

At the national level, there are also some non-governmental associations and institutions focused on the built heritage, such as the AAA (*Associa-*

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[25] D.M. 455, 23.10.2018
[26] D.M. 456, 23.10.2018
[27] D.M. 572, 21.12.2018
[28] D.M. 31.10.2008
[29] Istituto Centrale per gli Archivi | Central Institute for Archives.
[30] Istituto Centrale per i Beni Sonori e Audiovisivi | Central Institute for Sound and Audiovisual Heritage.
[31] Istituto Centrale per il Catalogo Unico delle Biblioteche | Central Institute for the Unique Library Catalogue.

zione Archivi di Architettura - Architecture Archives Association), the ADSI (*Associazione Dimore Storiche Italiane* - Italian Historic Houses Association), the AIPAI (*Associazione Italiana per il Patrimonio Archeologico Industriale* - Italian Association for Industrial Archaeological Heritage), the ARCo (*Associazione per il Recupero del Costruito* - Association for the Recovery of the Built Environment), the IIC (*Istituto Italiano dei Castelli* - Italian Institute of Castles), but also wide-ranging no profit association such as *Italia Nostra* and *FAI (Fondo per l'Ambiente Italiano* - Italian Environmental Fund*)*, committed for the safeguard, preservation and valorisation of historical, cultural, artistic and natural heritage.

Superintendencies, the peripheral bodies of the MiBACT, are widespread at the local level, with headquarters in the main cities of each region. In Trentino, for example, the Superintendence cooperates with museums and territorial entities in the definition of recovery and redevelopment plans for cultural assets representing the territorial and cultural identity of local communities, moreover, supervise restoration works and the maintenance of cultural heritage assets of the entire Province of Trento. The website of this office includes a "*place of culture*" list including archaeological sites, castles and fortifications, churches, historical buildings, mountain huts and industrial buildings (Trentino Cultura).

2.1.3 Categories of built heritage

Built heritage can be identified and grouped according to different criteria. In Europe, considering those countries with more evidently closer cultural roots, according to Manfredi (2017, pp. 37-38) there are two main approaches in property to be protected identification: functional classification (e.g. England, Portugal, and Spain) and recognition of specific characters in the object (e.g. Austria, Germany and Italy).

Following this logic, we can identify the so-called "*operational definition of heritage: the series of mechanisms by which objects, buildings and landscapes are set apart from the everyday and conserved for their aesthetic, historic, scientific, social, or recreational values*" (Harrison, 2013, pp- 14-15).

Over time, Italian regulations identified diverse characters as worthy to be preserved, protected, and promoted. Considering built heritage, these characters include historical, artistic, monumental, demo-ethno-anthropological, and archaeological values[32].

According to current regulations, assets expressing political, military, literary, artistic, scientific, technical, industrial, and cultural history in general or as testimonials to the identity and history of public, collective, or religious institutions are also worth conservation[33]. Moreover, the norm considers as built heritage:
- assets relevant to the integrity and completeness of the national cultural heritage:
- rural architecture of historical or ethno-anthropological interest as evidence of the traditional rural economy[34];
- works of contemporary architecture of artistic value[35];
- the vestiges of the First World War[36].

Moreover, this norm puts under protection:

- all the public buildings, realized more than 70 years ago and whose author is not alive[37];

[32] D.L. 112/1998, Art. 148
[33] D.Lgs. 62/2008, Art. 2
[34] D.Lgs. 156/2006, Art. 2
[35] D.Lgs. 42/2004, Art. 11,1,e
[36] D.Lgs. 42/2004, Art. 11,1,i

- all the private properties, for which the competent ministry has established a declaration of cultural interest[38].

Similarly, at the international level, UNESCO acknowledges as heritage[39] monuments, groups of buildings of "*outstanding universal value from the point of view of history, art, or science*", as well as sites of outstanding universal value *from the historical, aesthetic, ethnological or anthropological point of view".* Beyond acknowledging these characters to identify world heritage buildings or sites, UNESCO declares that "*heritage is our legacy from the past, what we live with today, and what we pass on to future generations*" (UNESCO, 2023).

Figure 2.1 - Different examples of built heritage. On the left San Clemente archaeological site in Albenga (SV) - Case study of the Holistic Heritage Builing Information Modelling and Built Environment toward XR, coordinated by Prof. Brumana R. (Politecnico di Milano), June 2021; on the right CF1011 building in Roveto (TN) - Case study of the research project Metodologie BIM per una nuova indu-strializzazione degli interventi di riqualifi-cazione energetica del patrimonio edili-zio esistente, coordinated by Prof. Baggio P. (UniTrento), 2018-2019.

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[37] D.Lgs. 42/2004, Art. 12,1

[38] D. Lgs. 42/2004, Art. 13

[39] According to Art. 1 of the UNESCO Convention Concerning the Protection of the World Cultural and Natural Heritage: "architectural works, works of monumental sculpture and painting, elements or structures of an archaeological nature, inscriptions, cave dwellings and combinations of features (…), groups of separate or connected buildings which, because of their architecture, their homogeneity or their place in the landscape (…), *works of man or the combined works of nature and man, and areas including archaeological sites"*

This last most inclusive and transversal definition of heritage clearly expresses the object of interest of this research, that is not limited to a specific feature or time frame, according to Fernando Tavora' view of heritage, described as "not only what our predecessors left us, but the result of a permanent and collective creation" (Ferreira, 2017, pp. 88-89). Indeed, the research focuses on buildings inherited from the past and available in the present, that, if adequately preserved, will arrive to future generations. Some of the research case studies are included in local or national heritage catalogues, for their historical, artistic, or archaeological value. This kind of building asset not only presents interesting challenges in capturing, analysing and modelling their geometric features but also offers precious interaction occasions with heritage practitioners and stakeholders. Indeed, the geometry of these buildings is often more complex, due to the irregularity of their shapes, the craftsmanship of their elements and the effects of time and of atmospheric phenomena on their materials. In addition, the peculiarities of these assets often require the intervention and interaction of experts specialised in protecting and promoting cultural heritage, such as restorers, conservators, architectural history experts, and others, who need to dialogue on a common basis, generally a geometric frame that can host annotations from different field of knowledge (Torsello, 1988, p. 126). The research also includes contemporary architecture, expression of current aesthetics and performance standards, and buildings from the last century lacking valuable features, but still representative of a large portion of the building stock on the national territory. Most of this last asset, which we can indicate as *recent heritage*, was built during the post-war economic growth when the population rapidly increased and there was an urgent need for new spaces (Cnudde, 1991, p. 462). These buildings often present a low technological quality and require specific interventions to adapt to current performance standards, such as, for example, energy consumption, indoor comfort, and seismic resistance (Duran & Lomas, 2021). The transition to current standards represents a great opportunity and challenge for most AEC sector practitioners, requiring the integration of several information and the interaction among different technicians. Therefore, this category of buildings is also crucial to face and simulate issues helpful to a large group of practitioners and stakeholders.

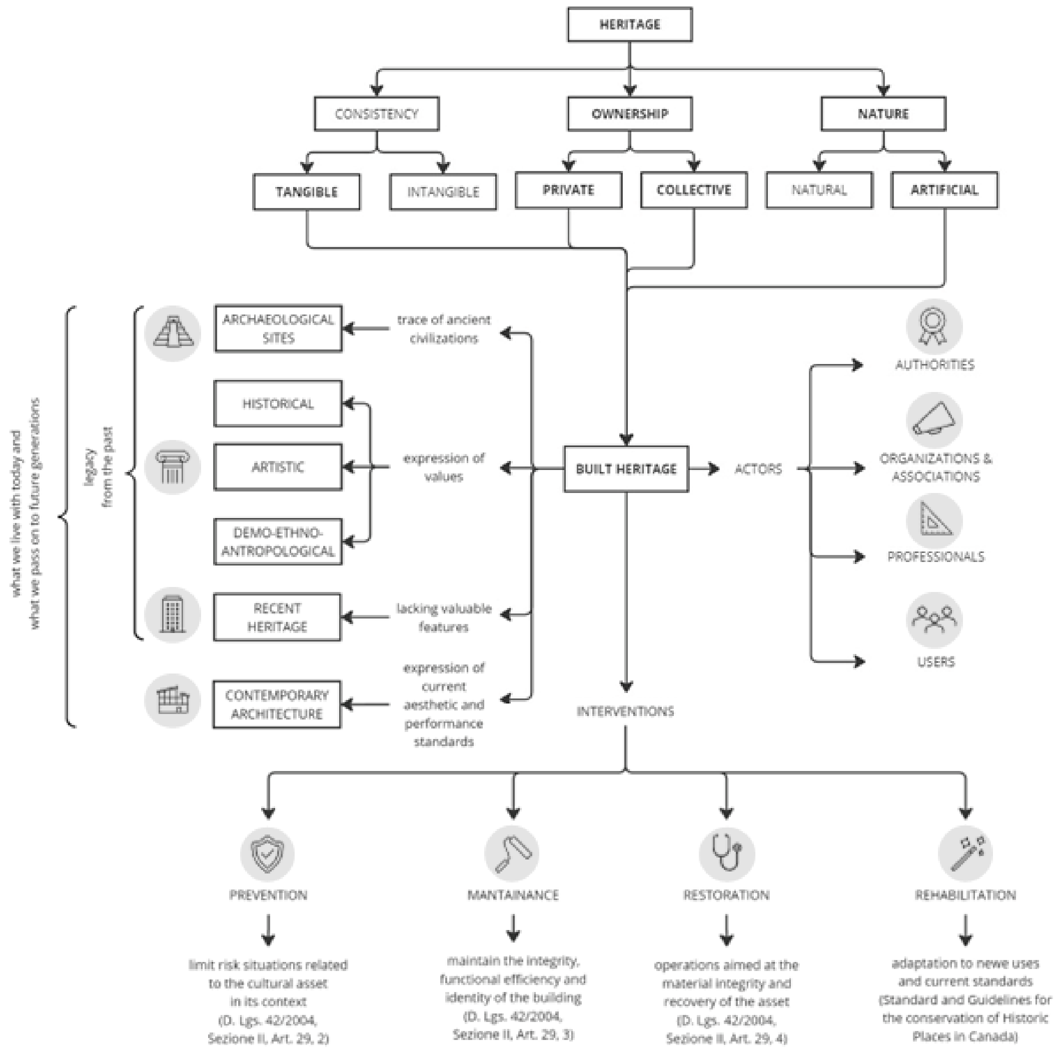

Figure 2.2 - Diagram collecting a synthesis of the analysis on Built Heritage.

2.2 Interface

Common in various fields of knowledge from science to technology, the term *interface* refers to a common element acting as a connector or separator between two entities ("Interfaccia", 1996). For example, in physical chemistry, it is used to indicate the separation surface between two phases of a system, in electronics, the element or channel connecting and adapting systems operating in different modes ("Interfaccia", 2024). Since the end of the 19th century, the term *interface* indicates a "surface regarded as the common boundary of two bodies" ("Interface N.", 2017). This definition perfectly reflects the Latin etymology of the term, a combination of the prefix "*inter"* meaning between and the term *facies*, meaning appearance, form, or surface. *Interface*, as a noun, also denotes a connection between devices enabling a joint function, a shared basis between two parties or disciplines, or even an interaction between two systems, partners, or organisations *("Interface N.", 2023).* As a verb, *to interface* means to set up a connection with something to enable a joint operation or to interact with someone or something ("Interface V.", 2023).

Generalising the definition from electronics, according to which interface enables connection and offers a communication channel to transfer information between two devices, the term interface evokes a dialogue between two parties. The two subjects of interaction could be both objects (e.g. a computer and its keyboard), both people (e.g. two colleagues), or a person and an object (e.g. a person using an object). In this third option, the human-object interaction has an impact and determines a modification on at least one of them or the surrounding environment[40]. Human-object interaction consists of three phases: knowledge acquisition through perception, selection of the activity to perform and activation of the interaction, during these phases the human body works as both a perception access for the mind and a bridge to the action (Anceschi, 1993 pp. 11-13).

[40] Ergonomics is the discipline that studies the human-machine-environment system to find optimal solutions adapted to the psycho-physiological capabilities and limitations of man.

2.2.1 Interface as object of design

A particular form of interface is the User Interface (UI), crucial in enabling the interaction between humans and machines[41]. It is possible to experience this kind of interface in everyday life, for example programming the washing machine or driving a car. From easy tasks to very complex activities, every time there are more alternatives to choose from, it is likely to deal with a user interface, supporting the selection of the desired option. Using buttons, levers, knobs and, for more complex activities, an entire device apparatus, it is possible to "set up a connection" with an object to perform a given activity. The more intuitive the interaction, the more effective the interface. To properly use a device, the user needs to own a correct model of the system, to forecast the necessary sequence of actions and possible answers of the system needed to perform the desired tasks (Bagnara & Broadbent, 1993, pp. 86-87). A well-designed interface includes a set of suggestions and constraints, which display the range of available alternatives and do not require explicit instructions (Polillo, 1993, pp. 76-78). The need to carefully design interfaces gains importance with the advent of electronic devices. Indeed, considering mechanical tools, most of the information is analogue and easily accessible, and the reactions of the system, responding to physical laws, facilitate the interaction (Susani, 1993, p. 195). Conversely, in electronic devices, the cause-effect relationship remains hidden among the internal mechanisms of the object and the number of controllers increases with the capability of the machine. The introduction of a microprocessor, elaborating instructions, makes several objects interactive and able to exchange information in real-time (Susani, 1993, p. 196) A further level of complexity is connected with the computer, which works both as meta medium since it embraces all the other media, and as meta-tool, extending simulation possibilities beyond the limits of physics, only subjected to the logical constraints and the user description ability (Polillo, 1993, pp. 46-47). Human-Computer Interface (HCI) offers multiple interaction modes, exploiting simultaneously different and complementary channels based on human senses and communication abilities

[41] Object or device consisting of a variable number of interconnected parts designed to perform given actions.

(Polillo, 1993, pp. 48-52). Most HCIs involve the use of physical input (e.g. keyboard, mouse, microphone, controller, touchscreen, graphics tablet, …) and output hardware (e.g. screen, printers, speakers, headphones, headset, glasses, …). According to the different hardware in use, it is possible to distinguish among standard, virtual, augmented, and mixed interfaces. These last three are part of Extended Reality (XR) technologies, which aim at enhancing human senses, through simulated environments or adding information to the actual space surrounding the user (Verma & Paul, 2022, p. 7). In Virtual Reality (VR) the user can experience a new form of immersive interface, where the scene and the interaction belong to the same environment (Anceschi, 1993, pp. 38-39). Augmented Reality (AR) adds real-time digital information, such as texts, static and dynamic images, audio tracks or 3D models, to the actual environment, with the support of mobile devices (e.g. smartphone or tablet) or specific AR glasses or headsets (Verma & Paul, 2022, pp. 5-6). Mixed Reality (MR) combines VR and AR technologies, overlapping digital elements on real ones and melting real and virtual realms (Verma & Paul, 2022, p. 6). In all these cases, HCI may interact with one or more human senses, especially sight, touch, and hearing, and, with the support of specific sensors, can detect and convert into inputs eyes, head, hands or in general body movements ("User Interface", 2024). One of the most common HCI, which exploits the visual and tactile channel, is the Graphical User Interface (GUI), introduced as a more user-friendly alternative to the Command Line Interface (CLI), which requires typing each command, as a sequence of words and symbols, through the keyboard ("Graphical User Interface", 2023). Each GUI can involve one or more interaction styles (e.g. menu selection, form filling, command input, direct manipulation, etc.) and components, such as windows, menus, icons, dialogue boxes, buttons, checkboxes, text boxes and others (Martinez, 2011, pp. 121-122). In most cases, GUI exploits a system of metaphors and symbols evoking a real environment, such as an office desktop hosting files, folders, and a trash bin (Anceschi, 1993, p. 30; Bagnara & Broadbent, 1993, p. 88; Montefusco, 1993, pp. 192-193). The interface metaphoric language can be very generic or highly specific according to the background and level of expertise of the users (Bernardelli, 1994, pp. 47-50). Computerised systems introduce a set of reactions, that the user perceives as arbitrary and unpredictable, for this reason, the human-computer interface exploits similarities with familiar environments (Bagnara & Broadbent, 1993, p. 87). A well-designed interface supports the user in becoming so familiar with the new environment, that the interface itself disappears in the background and the user is completely focused on the task to perform (Bonsiepe, 1993, p. 168). While the choice of symbols for the wider public should be based on the availability of the general cultural background, the design of interfaces for professional tools can rely on the specialised knowledge of the target group (Marrone, 2018). Furthermore, the system should ideally be able to adapt to the user's increasing capabilities. Although the design of an interface is always a special experience and optimal solutions cannot be defined a priori, cognitive ergonomics supports in the identification of critical points, such as (i) the translation of needs, interests and intentions into actions on physical variables, (ii) the evaluation of variables in terms of goals, (iii) the decomposition of main activities into phases and the observation of the relationships between phases as a function of experience, learning and practice (Bagnara & Broadbent, 1993, pp. 90-91).

2.2.2 From interface-ability to interoperability

Perception and action emerge as such crucial aspects of an interface, to distinguish between cognitive interfaces, or "interface to know", (e.g. book, radio, television, etc.), which exhibit and deliver knowledge and involve just minimum actions, and instrumental interfaces, or "interface to do" (e.g. hammer, photo camera, car, etc.), which require know-how and are focused on the performance of activities (Anceschi 1993, pp. 20-21). For example, looking at a book as a knowledge dispenser technology, it is possible to distinguish the cover as protective element and the binding as the rotation axis supporting the browsing fruition, typical of the codex and not of volumen based instead on scrolling through the entire roll to access information (Anceschi, 1993, pp. 17-19). Today, webpages combine the logic of a scrollable volume with the browsing option of the codex, through the introduction of the page menu and the "find" option. On the other hand, a photo camera, as image capture technology, belongs to the category of instrumental interfaces. Historically a photo camera required the specific knowledge of a photographer to be used, whereas today it is enough to press a button, yet the interface of a professional camera presents a whole range of options to offer more freedom to the user's creativity (Susani, 1993, pp. 211-213).

Moving the attention from human-object interface to interaction among people, we can still distinguish between communication purposes and joint operation needs. In this last case, not only the ability to interface, but also the ability to operate in conjunction among the involved parties, namely interoperability, is crucial. Indeed, the term "interoperability" refers to "the ability of two or more pieces (…) to operate in conjunction", or "to exchange and subsequently make use of data" ("Interoperability" N., 2023).

The Institute of Electrical and Electronics Engineering (IEEE) originally defined interoperability as "the ability of two or more systems or components to exchange information and to use the information that has been exchanged" (IEEE, 1991). Beyond these definitions more related to technological aspects, the interoperability has various domains and fields of application, such as electronics, defence, and regulation (Diallo et al., 2011). For example, the "Interoperability solution for public administra-

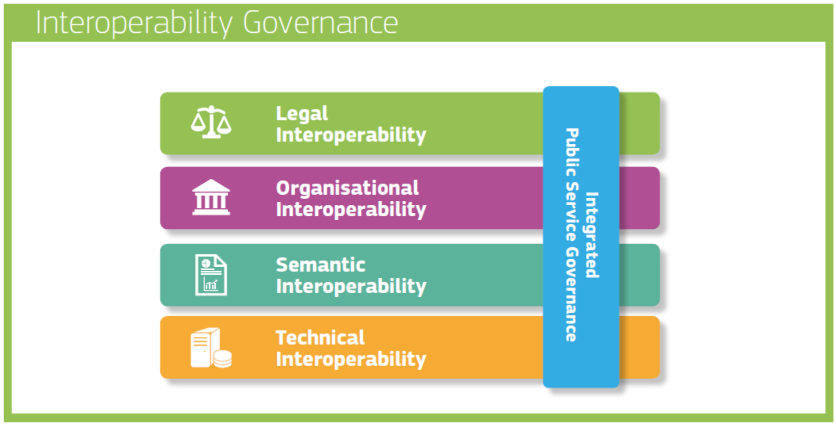

Figure 2.3 - The interoperability model proposed by the EIF: the four main layers are included in a background layer, the "interoperability governance", and are crosscut by the "integrated public service governance" component. Image from European Commission. (2017), *The New European Interoperability Framework*. p. 22. Retrieved from: https://ec.europa.eu/isa2/eif_en/ Last access: 15.10.2024

tions, business and citizens" (ISA^2) Programme released the new European Interoperability Framework (EIF) in 2017, offering recommendations and guidelines to guarantee interoperable digital public services across Europe (European Commission, 2017).

The EIF is structured in four "layers": legal, organisational, semantic, and technical interoperability (Fig. 6). Legal interoperability consists in overcoming possible issues related to legislation differences between member states (European Commission, 2017, p. 27). Organisational interoperability refers to business processes and relevant information exchange alignment and clear definition of the relationships between service providers and service consumers (European Commission, 2017, p. 28). Semantic interoperability prevents any ambiguities on semantic[42] and syntactic[43] aspects of the exchanged data (European Commission, 2017, p. 29-30). Technical interoperability relates to infrastructures and applications, such as interconnection and data integration, or communication protocols, linking systems and services (European Commission, 2017, p. 30-31). Several other international documents always emphasise tech-

[42] Data meaning and relationship.

[43] Data format and grammar.

nical interoperability, only sometimes organisational interoperability, while semantic and legal interoperability are rarely considered (Shehzad, 2021). In the last decades also within the AECO sector raised the interest in technical interoperability, mainly due to the widespread use of software to support various professional tasks, which do not always permit an optimal dialogue among each other. The attention was then shifted towards organisational and operational aspects, such as business processes, culture, and management of contractual issues (Grilo & Jardim-Goncalves, 2010). This led to the development of interoperability frameworks including multiple focal points beyond technical interoperability. For example, Poirier et al. (2014) suggest the combination of technological[44], organisational[45] and procedural dimension within a contextual[46] dimension. Muller et al. (2017) present a framework structured on business[47], process[48], service[49] and data[50] focuses. Golzarpoor et al. (2018) propose three interoperability layers: technical, concerning data transfer and exchange; information, including semantic and syntactic aspects; and organisational, related to coordination and workflow processes.

[44] Exchange of data and information within digital environments.
[45] Generation of information and knowledge, its management, and its exchange across the project network and throughout the project life cycle
[46] Norms, regulations, policies, markets, and cultures.
[47] Strategic and organizational aspects shared among stakeholders.
[48] Necessary requirements to manage design, building and operation.
[49] Need of coordinating external services (e.g. through common data dictionaries for products).
[50] Exchange among different software, platforms and systems in use by different stakeholders.

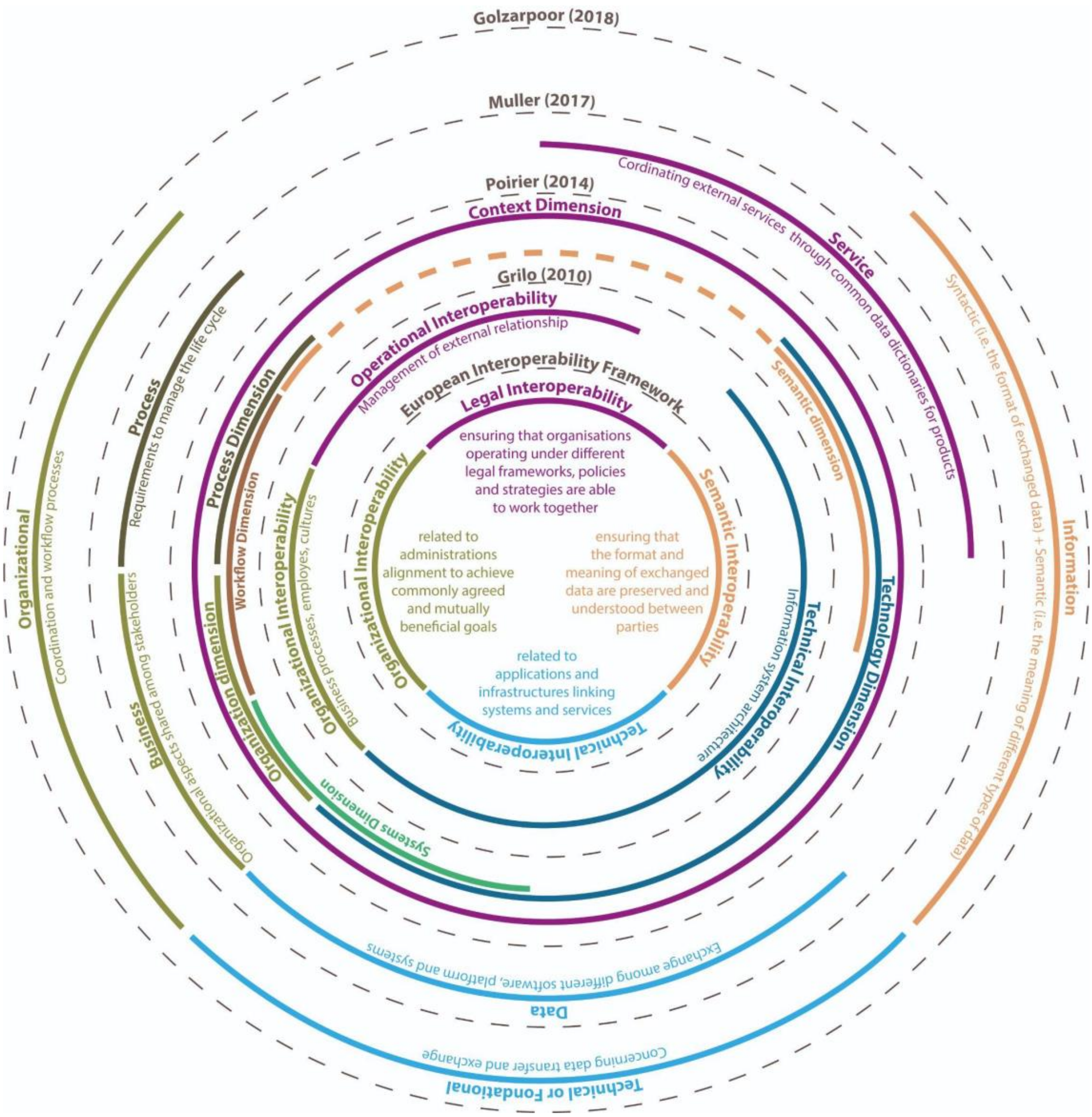

Figure 2.4 - Comparison of different interoperability frameworks. Image from Chioni, C., Barbini, A., Massari, G., & Favargiotti, S. (2021). Interoperable workflows: Information LIFE cycle AT landscape and architectural scales. AMPS Proceedings Series, 25, 234-243.

2.2.3 Interface as object of research

An interface is, therefore, something enabling an interaction between different parts, enabling them to communicate and/or work together. Contents communication and collaboration based on shared data are two of the main objects of investigation in this research. Furthermore, as a place of transition or moment of exchange on the border between different disciplinary fields, interfaces offer interesting lines of research on boundary crossing and interchange conditions between related or complementary disciplines (Ugo, 1993).

This research focuses on interfaces as tools that support different actors (e.g. researchers, practitioners, policymakers, stakeholders and interested people) to enhance their knowledge of specific aspects of the built heritage and to enable joint operations aimed at its conservation and promotion. In particular, the research looks at those practitioners, such as restorers, conservators, archaeologists, historians, designers, building components manufacturers and providers, construction companies and public bodies, who could greatly benefit from tools facilitating the sharing of their knowledge and expertise and the collaboration with each other. To understand how we imagine this kind of device, we need to delve into the possible meanings of the term model.

Interface design is not the focus of this research, but some forms of interface, as well as the principles for the design of a good interface may still be of interest in the analysis of the interactions among built heritage actors and in analysing how they organise and share information. Moreover, interoperability declinations and layers from technical, to process, to organisational and contextual aspects will be considered as a crucial tool to design and structure effective collaborative workflows among built heritage actors, especially within the AECO sector.

2.3 Model

The term "*model*" includes multiple meanings from conceptual to pragmatic and can be used both as a noun and a verb. As a noun it may refer to a representation, an object or output of an imitation process. In the past it was used to indicate drawings representing a project[51]. It was also used to refer to a summary[52] or a small portrait[53]. In its more pragmatic meaning, today it is used to refer to "*something which accurately resembles or represents something else, especially on a small scale*" ("Model, N., Sense I.2.a.", 2024), or to a "*three-dimensional representation of a person, thing or structure (both existing or projected), showing the component parts in accurate proportion and relative disposition*" ("Model, N., Sense I.4.a.", 2024). This definition can find specific declination according to different disciplines, such as maquette among artists and architects. In its more theoretical meaning, the term model refers to a conceptual or mental representation of a system or process, based on a simplified or idealised description or more rarely to an archetypal image. Ugo (1995) describes the model as a structure that enables to identify the relationships between words and things and among different disciplinary languages and theories, according to precise rules. Moreover, the term model is also used to literally indicate an object or a person "*serving as an object to be copied or depicted by an artist, sculptor, etc.*" ("Model, N., Sense II.11.a.", 2024), or to figuratively refer to an exemplar: "*a person, or a work, that is proposed or adopted for imitation*" ("Model, N., Sense II.9.a.", 2024), or a representative example of some quality: "*a person or thing eminently worthy of imitation*" ("Model, N., Sense II.10.", 2024).

The term model comes from the Latin "*modulus*" and in the classical Greek and Roman orders was used to indicate "*the unit of length by*

[51] Between 1570 and 1714 according to "Model, N., Sense I.1.a." Oxford English Dictionary, Oxford UP, March 2024, https://doi.org/10.1093/OED/1095522951. Last access: 15.10.2024
[52] Between 1626 and 1769 according to "Model, N., Sense I.1.c." Oxford English Dictionary, Oxford UP, March 2024, https://doi.org/10.1093/OED/7956099382. Last access: 15.10.2024
[53] Between 1605 and 1658 according to "Model, N., Sense I.3." Oxford English Dictionary, Oxford UP, March 2024, https://doi.org/10.1093/OED/2590505965. Last access: 15.10.2024

which portions are determined, usually equal to the diameter or the radius of a column at the base of the shaft" ("Modulo", 1996). This strong connection with the concept of measure is widely present both in pragmatic and theoretical architectural models, if we consider for example Palladian proportions or Le Corbusier's Modulor (Fig. 2.5). Moreover, engineers use models for thinking, calculating, analysing, predicting, controlling and communicating the project (Bertoline, 2016, p. 71). Similarly, architects consider the model as the oldest tool for project prefiguration (Scolari, 1998, p. 16). In general models supports the relationships among different disciplinary languages and different theories, even outside architecture (Ugo, 1995, p. 25-31).

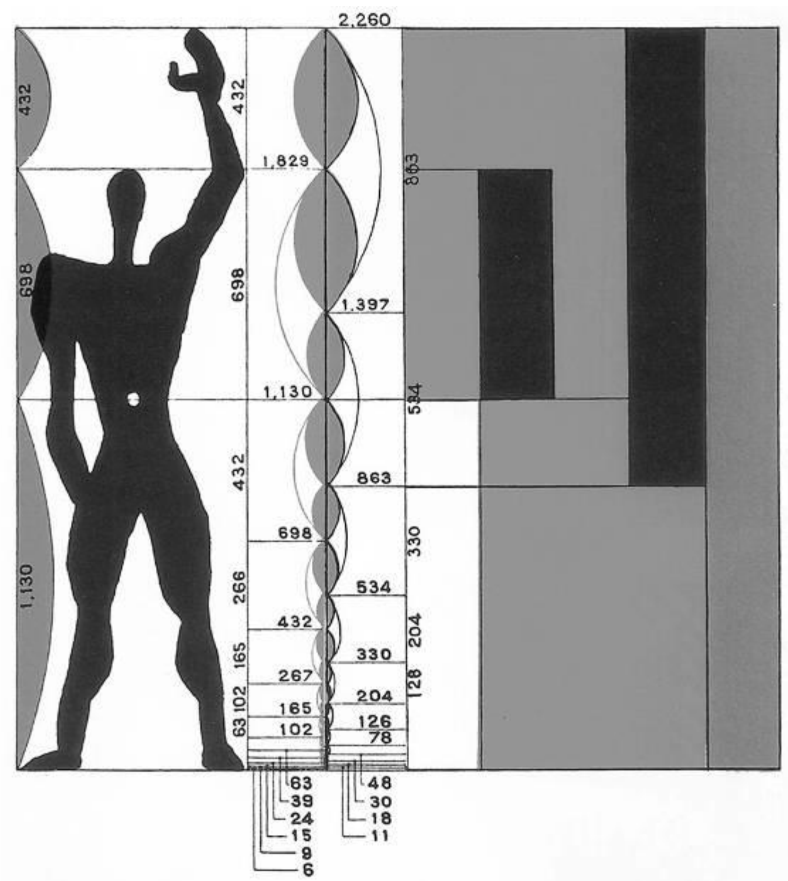

Figure 2.5 - Modulor of Le Corbusier (1948).

2.3.1 Model as representation

The term model is strongly connected to the concept of representation, intended both as conceptual-theoretical structure and graphic-visual element, respectively corresponding to the German terms Vorstellung, and Darstellung (Ugo, 2004, pp. 7-8). Considering theoretical representation, a model is generally used to describe, understand, and interpret a phenomenon, but also to simulate, explain and foresee a system[54]. A theoretical model can assume a very specific and scientific structure, such as in mathematics, or a narrative and ritual expressions, such as in myth. Mathematical models rationally abstract physical phenomena and experimental elements, maintaining relationships and the correspondence between terms (Ugo, 1994, p. 154). On the other hand, myths rely on metaphysical and meta-rational models, empowered through extraordinary creatures, events and places (Ugo, 1994, ibid).

Models are also intermediate structure, such as the balls of an abacus, able to represent just as well ideal operations, e.g. the sum "two plus three equal five", and the manual correspondence: concretely putting two glasses next to other three (Gioseffi, 2016, p. 8).

Considering a model as graphic-visual representation, it is crucial to recall the Latin etymology of the verb represent, meaning "to present to view, exhibit, show" ("Represent V.", 2024). Under this lens, a model can be the exposition of a thought to the judge of senses (Croset, 1987, p. 46). Architectural models recall the shape and some qualities, not only formal, of the object of representation (Migliari, 2002, p. 17). In architectural representation, models are geometric projections (i.e. perspective, axonometric, orthogonal projections) and in general the methods to transpose three dimensional objects onto a two-dimensional medium (Fasolo, 1994, p. 81). Architectural representation also includes three-dimensional models anticipating a constructive intention through a visual and tactile tool (Celant, 1987, p. 76), also known as "maquettes", a French term that comes from the Latin "macula" intended as first sketch ("Maquette" N., 2023). Maquettes cover a variety of functions involving

[54] Intended as a set of elements grouped in an organic whole with unitary functioning.

different stage, from the design to the realisation, including the communication of the project to the client, its presentation in front of approval authorities and its use as reference for the workers at the building site and as evidence of the architect's intentions (Ribichini, 2007, pp. 50-61). During the design phase maquettes are extremely valuable and effective in a wide range of applications: from the comparison of the first hypothesis, to the evaluation of compositional schemes, to the development of the design idea, to the validation of static behaviour, to the definition of functional or technical features, to the prefiguration of materials or decorations (Scolari, 1988, p. 16-30).

Generally, a three-dimensional model is not represented with the same dimensions as the real object, but on a smaller scale, because as a representation it must be fully accessible to view (Gioseffi, 2016, p. 8). Hence, models representing buildings or portions of territory present a reduced scale to avoid running into Borges' paradox[55] (Ugo, 1994, p. 152). In the opposite condition, where the object of representation is so small in real scale that it is hard to observe it (e.g. a construction detail), the model resorts to augmented scales (Guillerme, 1987, p. 30). Miniatures of buildings were common since ancient age in the form of votive models, of which we find traces among Mesopotamian, Egyptian, Roman and Etruscan archaeological evidence (Scolari, 1988, p. 16). In Greece, architects made models in wood or clay, to obtain the approval of a commission[56] for the construction of a building, fixing the forms and general outlines of the project to follow in the execution phase (Ribichini, 2007, pp. 52-53). The Greek model, called *παράδειγμα*[57] (*paradeigma*), was included in the overall cost of the work, and it is unclear whether its use was also common among the Romans or during the Middle Age due to

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[55] In the short story titled "Del rigor en la ciencia", written in 1946, Jorge Luis Borges describes an empire where was built a map of the same size of reality, with the aim to create the most rigorous example of cartography ("On Exactitude in Science", 2023, September 25)

[56] In the 4th century BC in Athens the Council of Five Hundred carried out this evaluation, later attributed to the Court (Aristotele, Costituzione degli Ateniesi. XLIX, in Giannantoni G. (ed.). *Opere*, Laterza, Bari 1984, vol. 11, p. 54.)

[57] For Aristotle this term also indicates an explanatory example, i.e. the use of a commonly known case to explain a less known or unknown one.

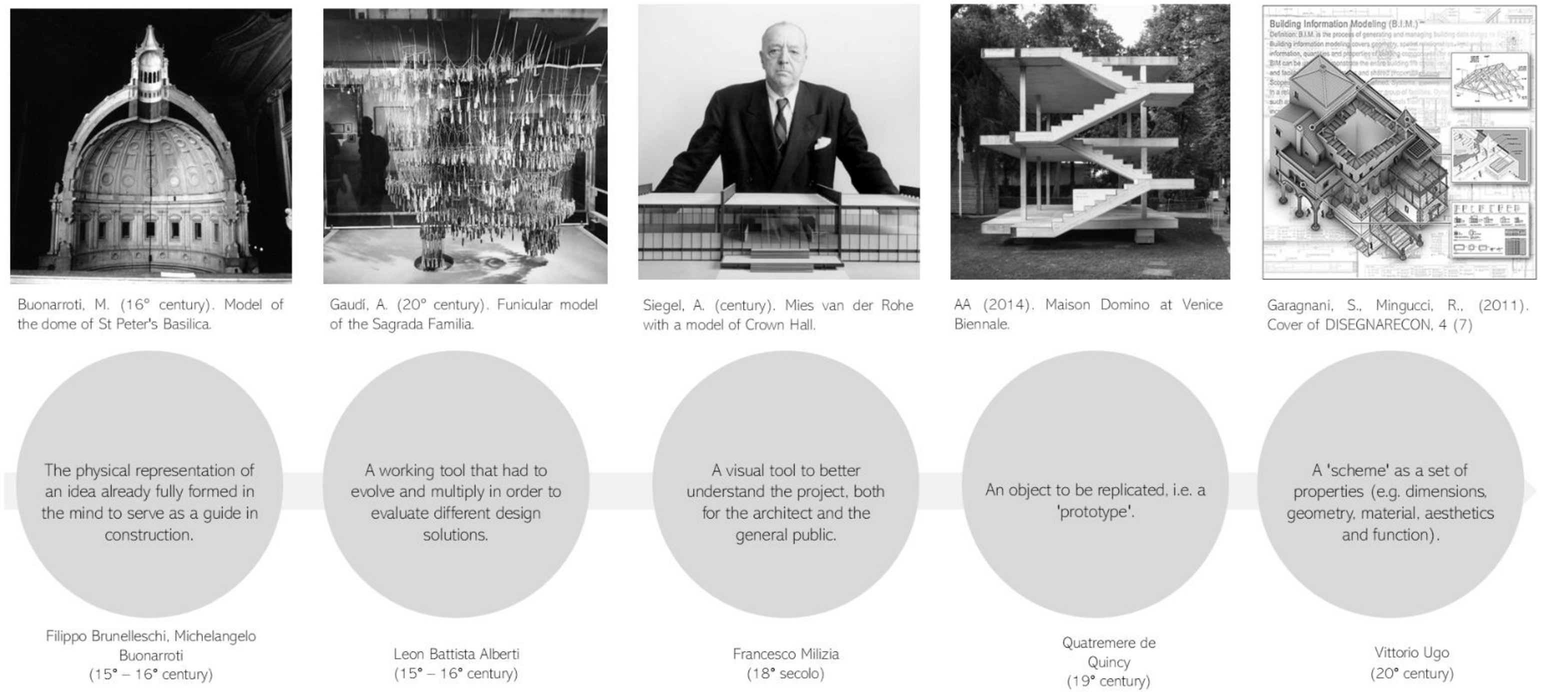

Figure 2.6 - Various points of view on model in architecture. Image from Barbini, A., Chioni, C., (2021). Reality VS Virtual Modelling. From Building to Landscape Heritage Representation. Conference on Cultural Heritage and New Technologies – CHNT (forthcoming).

the lack of specific information (Scolari, 1988, p. 16). Between the 6^{th} and the 14^{th} century in Italy it is quite common to represent those commissioning or financing the construction of a church holding a model of the building in their hands[58]. In central-northern Italy from the mid-14^{th} century onwards, there is evidence of the use of models, as small-scale reproduction of the formal and/or static qualities of a building, in the procedures of conception, approval and realisation (Pacciani, 1987, pp. 6-19). For the Renaissance architect, the model certified the originality of the solution in front of the citizens' committees and, unlike drawings, offered an understanding of the proposal at a single glance, without requiring any ability of abstraction (Scolari, 1988, p. 17). Filippo Brunelleschi made extensive use of undecorated architectural models with the aim of only illustrating the volumetric relationships of his concepts (Fasolo, 1994, p. 82). In the second half of the 15th century, the model tended to abandon its role as a pure presentation of the idea and assume a normative value during the realisation of the building (Scolari, 1988, p. 18). In *De re aedificatoria*, Leon Battista Alberti stresses the importance of models in architecture for technical purposes and to provide all useful indications in the executive phase, from structural dimensioning to the cost of construction (Ribichini, 2007, pp. 54-56). Unlike Brunelleschi and later Michelangelo, who used the models as representation of an idea already developed and shaped in their mind, Alberti used the model for the study and development of a design idea (Fasolo, 1994, p. 82). In addition, Alberti, and later the French architect Philibert De L'Orme promoted the use of simple and unadorned models to avoid illusions and amazement, only showing the concept of the architecture and presenting correct and consistent proportions and measurements (Novello Massai & Garzino, 1991, p. 43). At the end of the 15th century, many architects were sceptical of dimensional calculations based solely

[58] Some examples: Bishop Ecclesio, apsis of S. Vitale in Ravenna (521-531); Bishop Eufrasio, Basilica Eufrasina in Parenzo (543-554); Pope Onorio the 1^{st}, Church of S. Agnese (625-638); Arcivescovo Angilberto, Church of S. Ambrogio in Milano (830-840); Enrico Scrovegni, Scrovegni Chapel (1303). Retrieved from: "Committenza" Enciclopedia dell'arte medievale, Treccani https://www.treccani.it/enciclopedia/committenza_(Enciclopedia-dell'-Arte-Medievale)/ Last access: 15.10.2024

on the use of models, due to cracks and collapses in some buildings recently realised or under construction (Ribichini, 2007, p. 56). For example, Philibert De L'Orme points out that a small model does not always correspond to reality and Vincenzo Scamozzi compares the models to small birds, for which it is only possible to distinguish the species once they have grown up (Scolari, 1988, p. 22). The unreliability of the model has been the subject of several observations throughout history. Vitruvius, speaking of a war machine, pointed out that there is not always a correspondence between the full-scale realisation and the small-scale model (Ribichini, 2007, pp. 53-54). Palladio and other architects from the North of Italy in the 15th and 16th centuries regarded the model as deceptive and misleading (Puppi, 1987, p. 20). On the other hand, Brunelleschi intentionally exploited the vagueness of models both to avoid revealing all his secrets and to have more freedom in the realisation phase (Scolari, 1988, p. 18). After losing the component of technical prediction, the model becomes a tool for researching overall effects, the coordination of colours in various materials. From the 16th century, the use of models in different materials, from wax to wood and ivory, is evidenced by the many examples preserved throughout Europe (Pacciani, 1987, pp. 6-19). For example, Filippo Baldinucci suggests the use of wax for model for an easier and cheaper adaptations to client requests (Scolari, 1988, p. 22) and Antonio da Sangallo the Younger let his closer collaborators built a detailed model of St. Peter's Basilica in scale 1:30 using different wooden essences (Ribichini, 2007, pp. 56-58). Throughout the 17th and 18th centuries, the use of architectural models continued in Italy and the rest of Europe, although they have been largely lost, whereas in the 19th century they were apparently opposed in the programmes of the Ecole des Beaux-Arts, only to resume in the early 20th century when they were used in a wide range of applications (Fasolo, 1994, p 83). There are various examples of different use of models, for example, Renzo Piano exploited the model of the Rome Auditorium to solve a purely technical problem of acoustics and Antoni Gaudi realised several models of his architectures to solve structure-shape issues and considering the bidimensional representations not sufficient to describe his projects (Ribichini, 2007, p. 51). Using the model as a working tool, Le Corbusier realised a paper and wire sketch for the Ronchamp Chapel, whereas to anticipate the final result of his projects, Mies Van Der Rohe used rigorous and detailed models, such as the for the National Theater in Mannheim and the Bacardi offices in Santiago de Cuba (Fasolo, 1994, p. 82). In the 1970s with the rise of post-modern architecture, models are expressive objects and are enriched with new materials such as steel and onyx, marble and bronze and become stage sets and objects for collection (Celant, 1987, p. 76-77). In particular, Peter Eisenmann sees the model as an object that should enable the modernist condition of the architectural object to be realised, similarly to the other arts whose modernity is recognizable in the production of self-representational objects (Croset, 1987, p. 56; Bernal Lopez-Sanvincente & Camarero Julian, 2018).

Today tangible models are used not only for educational purposes and in architectural competitions, but also to promote inclusion among people with visual impairment. Indeed, tangible models can support in spatial orientation and to experience the characteristics of the real space in a scale-down form (Voigt & Martens, 2006), or to enter in contact with architectural and artistic heritage through tactile representations (Riavis, 2019).

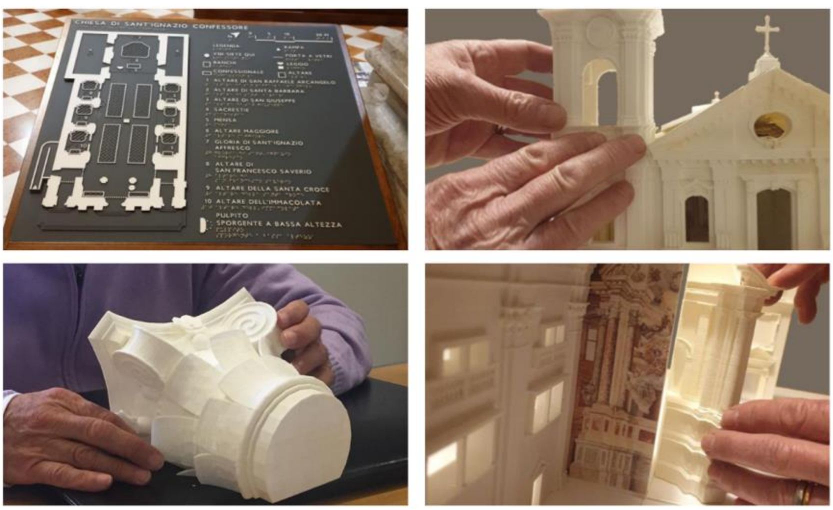

Figure 2.7 - Example of tactile models. Images from Riavis V. The Church of Sant'Ignazio in Gorizia between architecture and painting. Geometric analysis and restitution for tactile representation. EUT Editions University of Trieste 2020.

The *Modelli/Models* exhibition at Maxi in Rome (July 2012-April 2013), presenting 80 models of significant Italian architectural from the 20th and 21st century (Casciato & Valente, 2012), witnesses the wide interest in the subject of architectural models, as well as the 14th call of the *diségno* journal[59], *Analog Models*, in which the curators state that "advanced technologies while modifying the realisation process -speeding up its genesis, for example, with 3D printers- has not changed its configurative substance".

2.3.2 Digital models

The advent of informatics progressively extended the realisation of 3D models from the physical space, the realm of analogue supports, to virtual environments, relying on digital tools. Computers enable the development of 3D models and to observe them from various points of view (Migliari, 2003, p. 14). Digital 3D models have some similarities with physical ones in the representation and visualisation of the object but can also support further activities (Empler, 2006 pp. 13-14). The evolution from horizontal to vertical software application not only facilitate the development of a 3D model, but also the integration of various information in the form of parameters, which can involve both graphic and alphanumeric form (Lo Turco, 2015, p. 26). Horizontal modelling tools are based on the positioning and manipulation of geometric entities in a 3D virtual space, originally without considering the object to be modelled and subsequently integrating specific geometric constraints, called *features*, which can be dynamically adapted through parameters and are aimed at facilitating the development of specific objects (Bertoline et al., 2004, pp. 200-206).

On the other hand, vertical tools are based on a detailed deconstruction of building components which serve as modelling elements (Sacchi, 2016, p. 107). Each component relates with the others according to predefined rules, imitating the construction practice and its geometry, fixed or

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[59] Sdegno, A. & Cabezos Bernal, P. M. (2023). Analog Models. Call for papers diségno No. 14. In diségno. Retrieved from: https://disegno.unioneitalianadisegno.it/index.php/disegno/announcement Last access: 15.10.2024

parametrically adaptable to different needs, is semantically enriched with various information. The output of this process, known as Building Information Modelling (BIM), is an information model defined as "a virtual informative vehicle of building construction products and processes, including graphics, documental and multimedia elements" (UNI 11337-1:2017). For example, this kind of model can include a dynamic time parameter, normally frozen in traditional representation (Cocchiarella, 2010, pp. 38-39). Time is no longer associated to meaningful, isolated fragments, but can relate past, present, and future, even seamlessly through animations and real-time simulations (Soletti, 1992, p. 81). The information model is also considered as a multidimensional model, including other dimensions beyond geometry (3D), such as time (4D), costs (5D), life cycle and maintenance (6D), sustainability (7D), safety (8D), lean construction (9D) and construction industrialization (10D), intended as the different level of information that can be included within each component to simulate different phases of the construction process (NTI, 2023). This approach leads to the development of multidisciplinary models with variable levels of information, detail and accuracy. All these contents form an "immaterial simulacrum", not perceivable in its entirety but through individual representations that provide a partial description of it (de Rubertis, 1995, p. 13). Among the most common use of information models there is the generation of traditional 2D drawings and project documentation, the calculation of components quantities and geometric data (e.g. surface and volume), the transfer of data to automated production devices (e.g. 3D printing, laser cutter, CNC machines) and various analysis and simulation (Empler 2002, pp. 34-38). Information models can also be associated with infographic representation of the building process, intended as the combination of three-dimensional models and databases for the collection and management of data and the complex relationships between them (Sainz, 1995, p. 19). Moreover, these kinds of models are extremely powerful as collaboration tools and in facilitating integrated design processes (Sacchi, 2016, p. 107), since they support in overlapping and combining models associated with different disciplines (UNI 11337-1:2017). Transdisciplinary[60] collab-

[60] While a multidisciplinary and an interdisciplinary approach respectively refer to knowledge juxtaposition and to knowledge integration, a transdisciplinary approach, through an extensive knowledge integration, leads to the expansion of expertise for all the involved parties that can include researchers, specialists, stakeholders and others.

oration can involve any stage of the design process, such as simulation and validation of design solution, but also design definition. The parametric flexibility that characterises both alphanumeric data and geometry is a key element in supporting the development of design solutions shared among different actors and dynamically adapted to different points of view. Geometric and informative features can be implemented not only through parameters, intended as independent variables, coefficients or constants susceptible to change within a predetermined set, but also through algorithms, i.e. set of rules and operations for the creation of a virtual model or part of it, or can be driven from a preset goal, with the aim to explore the solution that better approximate the requirements, as in the case of generative modelling (Caetano et al., 2019, p. 287-300). These techniques can support, for example, the imitation of natural elements in the definition of a particular design shape (Omilli, 2023). Actually, the complexity of reality can be captured through a model, proceeding from an existing object to its simplification and vice versa from a scheme to its realisation (Musso & Torsello, 1995, pp. 14).

2.3.3 Model as imitation

In the exploration of the possible meanings of the term model, it is crucial the association with the Greek concept of μίμησις[61] (mimesis), intended as imitation. A model can be both the object and the outcome of an imitation process (Ugo, 2004, p. 20). As objects of imitation, models are selected as positive or negative examples, to follow or to avoid and include both conceptual and concrete applications. Archetypes are examples of conceptual and intangible models as objects of imitation, which try to capture certain aspects of reality and with which reality relates (Guagenti, 2010, p. 100). In the platonic philosophy archetypes are ideas, intended as immutable and transcended models behind things and according to Jung, archetypes are typical forms present in the collective unconscious, recognisable in traditional and folkloric expression of different cultures ("Archetipo", 1996). Within a theoretical framework, investigating the archaeology of architectural space Ugo (1991, pp. 145-209) identifies six archetypal forms capable of measuring architecture through architecture itself, three relate to the artificial component of architecture: the labyrinth[62], the hut[63], and the bridge[64], and the other three to its natural element: the forest[65], the garden[66] and the clearing[67]. The original hut is one of the most famous and recurring architectural archetype: from Vitruvius, to Filarete, to Marc-Antoine Laugier in its Essai sur

[61] With the concept of μίμησις Plato designates the resemblance of empirical things to the idea that constitutes their universal type and expresses disapproval of artistic products as imitations of things, themselves imitations of ideas. Aristotle, in the Poetics, interpreting μίμησις as a constructive procedure based on a set of shared techniques and values, re-evaluates this notion in art, considered as a representation of the artist's soul ("Mimesis", 2009).

[62] From the Greek term λαβύριον (laburion), the mole hole consisting of a system of underground tunnels.

[63] Associated with the human needs for shelter and protection.

[64] With the function of physically connecting spaces, but also conceptually connecting the natural and artificial components of architecture.

[65] Intended as inhospitable place, that can be domesticated, with the creation of a garden or a clearing.

[66] Made of natural element sorted, sampled and classified through the human action.

[67] Settlement fundamental condition related to the foundation of a building.

l'architecture assumed the primitive hut as an archetype of architectural quality, due to its inherent combination of natural and rational elements. Later, Quatremere de Quincy distinguishes three possible origins of architecture: the cave, the hut and the tent, associated to the three activities of primitive society, respectively hunt, agriculture and animal breeding. These archetypes, originally lacking any artistic or cultural component, but merely responding to the practical need of protection, became object of a metaphoric imitation ("architettura", 1842). According to this logic, the wooden frame hut represents the generative principle of Greek architecture, which had the widest spread among various cultures, and can be assumed as a fictitious canon to measure and interpret architecture in general ("capanna", 1842).

The canon, from the Greek κανών[68], as a reference ideal rule, is another form of model as an intangible object of imitation. The history of architecture includes several examples of canon, from Greek temples to Roman amphitheatres, all characterised by well-defined recursive elements, symmetries, and proportions, intended as repetition of a fixed module, used to relate different components to each other's and to the building as a whole. Also the Palladian architecture is an expression of a precise canon and follows a set of rules, ensuring proportions and harmonious relations among elements (Torsello, 1988, p. 121).

Another model as an object of imitation, is the prototype, that can be both tangible and intangible. Historically prototypes enable the close observation and study of a project, today they are normally developed as the first samples useful for the validation and refinement of a project and as reference for future realisations, but also to evaluate costs and construction time. Prototypes are often used for serial production of devices and machines but can be used also for building components. A prototype is often realised in real scale and can have different levels of similarity with the final object and include simplified elements, according to their purposes (Maldonado, 1987, pp. 57-58).

[68] Originally meaning cane and ruler, later also rule and norm.

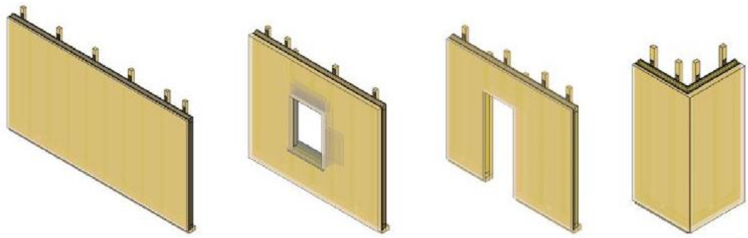

Figure 2.8 - Digital prototype of the Renew-Wall panel. Image from Barbini, A., Bernardini, E., Massari, G., & Roman, O. (2022c). Renew-Wall: innovazione e comunicazione di un processo edilizio tra impre-sa, professione e ricerca. ARCHITETTURA, URBANISTICA, AMBIENTE, 1025-1036.

The model, as outcome of an imitation process, can also present different levels and forms of similarities with its referent. For example, in homology, similarity is limited to structure, excluding form or function, in analogy, similarity involves structure and function, but not form, and in isomorphism, similarity related to forms and structure, but not necessarily function, as in the case of maquettes (Maldonado, 1987, pp. 59-60). However, it is crucial to distinguish between the passive, but still extremely accurate duplication of perceivable aspects, which leads to a copy of the original, and the analysis and critical interpretation, which consists in an imitation process. Between the 2nd and the 3rd century, the Platonic philosopher Maximus of Tyre distinguished between the technical and artistic component of an artist: αρετή (areté) and τέχνη (techne), respectively aiming at capturing aspects of perception or ideas (Ugo, 2004, p. 13). At the end of the 18th century, Quatremere de Quincy associated the term *model* with a practical execution of a copy identical to the original and the term *type* with an element that acts as a rule to the model (Ugo, 2004, pp. 14-15). At the beginning of the 21st century, the concept of model embedded not only the result of an imitation process but the entire journey of critical interpretation, also known as “meta-modelling” (Bianchini, 2022, p. 8). Therefore, the act of modelling can be a knowledge strategy and interpretation tool, extremely valuable in various fields of knowledge (e.g. physics, medicine, engineering, informatics, natural science, social science, philosophy, and others). For example, in historical and archaeological studies, a model can play a key role in reconstructing the original configuration of an object, building or settlement, based on the analysis of historical sources and available evidence, with possible implications in the field of education and tourism (Maldonado, 1987). In architectural survey, the process of knowledge of a building through the collection, organisation and interpretation of data leads to a knowledge model, which includes different forms of geometric models. Actually, according to Torsello (1988, p. 138), architectural survey itself is based on models, understood as intermediate elaborations, between a previous interpretive diagram and the next, which may be more general or more detailed, simpler or more complex. An example is the numeric model, based on a discrete description and consisting of point coordinates (Migliari, 2002, p. 24), belonging to a plane or to the 3D space, interrelated through measuring operations. The points can be very scattered and therefore hard to interpret without further information or developments, or highly dense, producing a cast of reality easily recognisable. This model can be further processed in different forms of continuous models, that can be based on lines, surfaces, or solid geometries. These continuous models involve an interpretation process of the collected data, which attributes meanings to the system of measured, classified and described data, to fill the gaps among the discontinuous structure of the numeric model. As anticipated, beyond geometric models, architectural surveys produce knowledge models, based on the cultural background of the surveyor, who develops a set of hypotheses on the object of study (Ugo, 1998, p. 19). This model is dynamically adapted to the feedback collected onsite through observations and measurements (Gioseffi, 1986, p. 60) and further refined through offsite data processing and registration through a synthetic language within a logic structure based on the acquired knowledge (Fasolo, 1995, p. 103). All these information, including a vast amount of technical, historical, and artistic data, can be registered not only in the mind of the surveyor and on analogue supports, but also on the magnetic memory of a computer, including flexible data update and integration (Empler, 2002, pp. 23-24). Indeed, computers memorise data according to logical structure independent from the way in which data are provided or will be recalled (de Rubertis, 1985, p. 20). The evolution and development of the knowledge model recalls one of the main features of the model according to Foucault, i.e. the fact that “once it is built, it tends to work on his own, progressively increasing its autonomy and influencing even the culture that produced it" (Ugo, 1994, pp. 154-155). Moreover, the knowledge model embodies all the features of the model both as visual representation, described as a working, validation and communication tool and as theoretical representation, described as description, comprehension and interpretation tool. New technologies are enabling and empowering all these new and traditional features, bringing new challenges and opening new issues on the possible strategies to adopt to move from reality to virtual modelling.

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3. THE RESEARCH QUESTIONS

The framework defined through the keyword investigation helps bring into focus the research object, purpose and tools.

The research object is the built heritage, witnessing ancient civilizations, cultural values or ordinary life settings. Built heritage includes the assets inherited from a newer or older past, available today and that we will pass on to future generations. The study of these assets within this research mainly relies on the knowledge of architecture and engineering without excluding the point of view of administrations, users and other stakeholders.

The research aims to explore interface alternatives to enable information access and facilitate data exchange for professional or other purposes. With the term interface, we refer to flexible boundaries, intended as the place where it is possible to transfer and exchange knowledge and skills. These boundaries are flexible also thanks to digital technologies that support adapting them to different needs and backgrounds.

The research tools are digital representation forms, specifically 3D digital models, intended as output of imitation processes integrating geometric and thematic information. Like conceptual-theoretical models describe and simulate phaenomena, these graphical-visual models simplify and interpret the continuum of built heritage through geometric primitives, serving as a basis on which to layer various analytical contents.

In some cases, modelling processes appear particularly challenging, such as for buildings with a high level of craftsmanship, presenting significant geometric irregularities, whose integrity has been compromised by the flow of time or whose information has never been systematically collected and structured (Chow & Fai, 2017). The scientific literature comprehensively documents several modelling strategies, encompassing potential workflows for direct and indirect data acquisition, processing, and integration (Percy et al., 2015; Banfi, 2016; Brumana et al. 2020). However, the potential that raw or structured data in the form of ordered and coherent information can offer as interface with existing buildings for multipurpose applications is still little explored. This research aims to define some possible criteria to determine the best approach to reduce the complexity of reality into accessible information and exchangeable data according to the case study and taking advantage of the currently accessible technologies.

Figure 3.1 - West façade photogrammetric reconstruction of Palazzo Pretorio in Trento showing an example of complex and stratified heritage of building. Elaborations by LAMARC.

Without abandoning the traditional techniques at the foundation of our current knowledge system, many modelling strategies heavily rely on digital technologies. Once professional and expensive tools, many of these technologies have become commonplace as "colloquial objects and virtual prostheses" (Anceschi, 1993). Both AECO sector practitioners and researchers widely acknowledge the advantages of digital technologies in data acquisition, processing and modelling. Among various technologies, BIM (Building Information Modelling) is particularly beneficial in the design and construction phase of large new buildings (Eastman, 2016), which often have regular geometries and recursive elements (Volk et al., 2014). These characteristics, not so common in most heritage buildings, take maximum advantage of a logic based on the parametric adjustment of standard types to specific requirements (Murphy et al., 2021; Fai et al., 2011; Brumana et al., 2013).

For many heritage buildings, according to the modelling purpose, it is still difficult to rely on automatic processes or artificial intelligence solutions for transforming survey data into a geometric model (Rafeiro & Tomé, 2020). In many cases, these processes may be expensive in terms of time and costs, requiring advanced hardware and software equipment beyond specialistic knowledge and skills (Chow, 2019). Since creating highly or less structured information on the built heritage may require considerable effort, primarily justified by design needs related to the AECO sector, this research proposes to explore how a built heritage geometric-informative model can support multipurpose applications beyond its original scope.

Moreover, BIM is also known for facilitating collaboration among AECO practitioners (Osello et al., 2013), but still, several professionals are not involved in the digitization process. Through the development of some case studies locally, the research investigates how built heritage models can provide an interface among professionals, facilitating collaboration processes and data exchange.

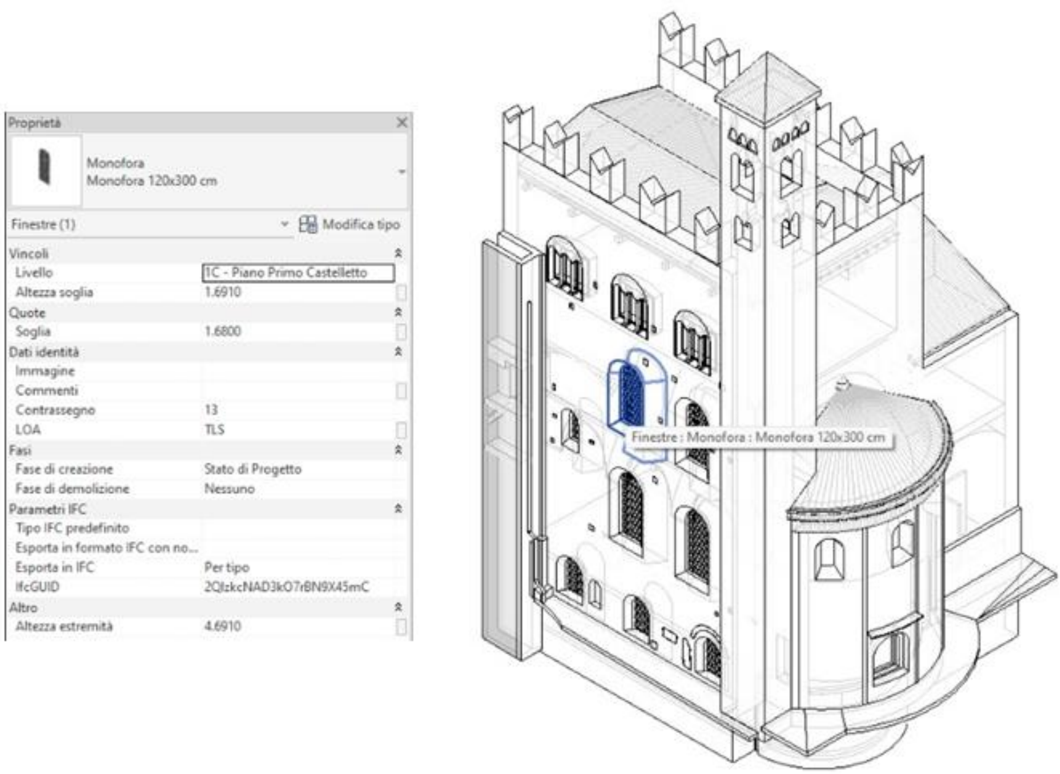

Figure 3.2 - HBIM reconstruction of the Castelletto of Palazzo Pretorio in Trento and some of the properties associated to the selected window.

Research questions:

How can models be developed and utilized as multifunctional interfaces to the built environment for accessing information and exchanging data?

1. How to reduce the complexity of built heritage into accessible information and exchangeable data? (chapter 4)
    a. How can different data acquisition strategies impact this process? (section 4.1)
    b. How is it possible to process the acquired data to develop an integrated and comparable dataset? (section 4.2)
    c. How different geometric modelling strategies support in the integration of the collected data? (section 4.3)
2. How can professional or generic users interface with the built heritage through a model? (chapter 5)
    a. Which criteria can influence the selection of a specific interface model? (section 5.1)
    b. How is it possible to define appropriate fruition solutions? (section 5.1)
    c. What is the point of view of local AECO professionals? (section 5.2)
3. How can users who operate on the built heritage interface with this research? (section 5.3)
    a. How can the purposes and priorities of the user support the selection of a Built Heritage Interface Model type? (section 5.3.1)
    b. How can the project peculiarities influence the selection of a modelling strategy? (section 5.3.2)
    c. How is it possible to facilitate collaboration among professionals? (section 5.3.3)

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4. FROM THE HERITAGE TO THE MODEL

The relationship between reality and its representation has fascinated humanity since the beginning of rational thinking[69]. The most common habit is to reduce the complexity of reality into rational schemes and models (Musso & Torsello, 1995, p. 2). Nowadays, developing virtual representations of architectural heritage is symptomatic of the broader trend toward digitisation that the AECO sector is crossing.

New technologies and processes progressively enable the integration of several kinds of data (geometric, alphanumeric, graphical, etc.) in virtual models to understand the past, represent the present, and design the future. Indeed, 3D virtual models facilitate the visualization of unusual or not perceivable points of view on the built environment, the reconstruction of destroyed or unbuilt spaces, and the anticipation of possible or planned transformations (Massari, 2011). These models enable both static configurations and the dynamic update of input and output data through sensors and actuators to connect physical elements with virtual environments, according to the logic of digital twins (Semerano et al., 2021). The connection between virtual and real environments is always more investigated and has different possible applications, such as management and conservation, alternative design solution simulation, data analysis, transformation project development, heritage valorisation and promotion.

Through literature review and case studies, this chapter explores different possible workflows available for the AECO sector professionals to collect and process data and develop 3D virtual models of the built environment. The literature review moves from the university libraries and online database resources. The selection of case studies tries to cover the various typologies of built heritage, from archaeological site to contemporary heritage, exploiting experiences developed within the LA-

[69] Some parts of this chapter are an updated version of Barbini, A., Chioni, C., (2021). Reality VS Virtual Modelling. From Building to Landscape Heritage Representation. Conference on Cultural Heritage and New Technologies – CHNT (forthcoming).

MARC[70] as educational or research activities. The aim is to investigate the current approaches to move from the complexity of reality to virtual modelling, highlighting the advantages and disadvantages of each solution and existing gaps. Despite new technologies offer wide options for data collection, elaboration, management, and communication, an informative selection, as well as the interpretation of acquired data, is still crucial to move from the complexity of reality to a functional virtual model, as illustrated by Jorge Luis Borges in the paradox of the 1:1 map of the Empire (Borges, 1999). Such an interpretative paradigm, reflecting the purpose of the model, its object and its reference framework, is a key element for the model development.

However, even the most advanced technologies and procedures for geometry acquisition, reconstruction, and semantic enrichment cannot entirely communicate a built heritage item or evoke an experience – sensory, emotional, perceptual – analogous to a fragment of real life (Menchetelli, 2019). Indeed, cultural heritage involves a large amount of data, already available in historical-archival documents or accessible through survey campaigns and diagnostic investigations or continuously generated through remote sensing technologies. Decreasing the volume of this massive amount of data enables to increase their informative value (Sultan et al., 2021). Therefore, intended as a logical structure of built heritage data, a model can support mindful decision-making processes.

Increasing attention on the built environment is expected both to avoid further loss of greenfield lands and to adapt the existing buildings to the current standards not only of seismic resistance, fire safety, and accessibility but also of internal comfort, energy consumption and environmental emissions, according to the logic of sustainable development and circular economy.

[70] LAMARC - Laboratory of Analysis and Modelling of Architecture Representation and Communication, integrated centre of scientific experimentation, professional work and educational activities coordinated by Professor Giovanna A. Massari and hosted within the Department of Civil, Environmental and Mechanical Engineering of the University of Trento

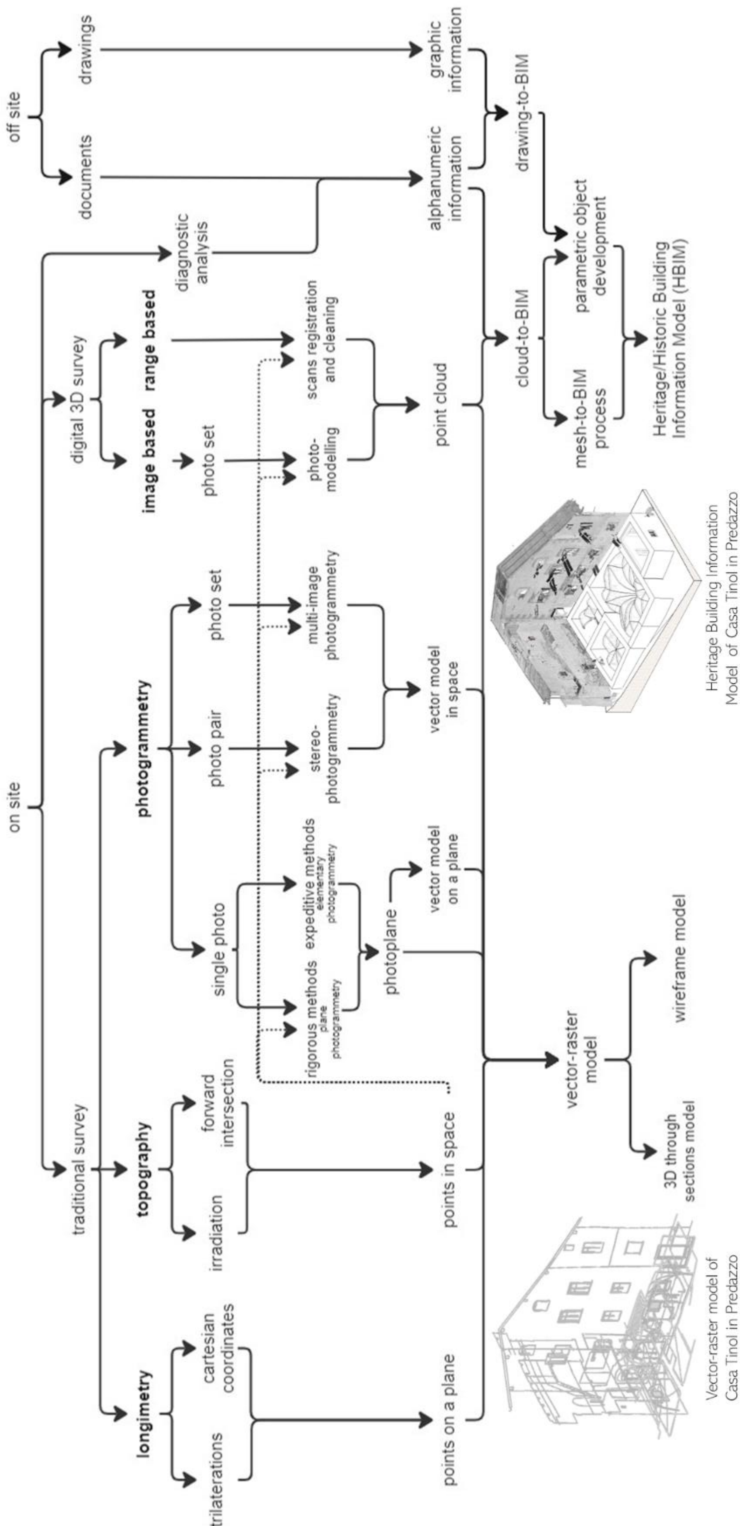


Figure 4.1 - Possible processes to develop a digital model of the built heritage starting from data acquisition.

Within the framework of Industry 4.0, the AECO sector is currently adopting various technologies that will facilitate the application of circular economy principles in the built environment (Sultan et al., 2021). In addition, raising awareness about the worth and vulnerability of built heritage is bringing the need to preserve and protect both material and immaterial witnesses from the past to transmit to future generations, also through extensive documentation and analysis of the building and the following development of thematic models, offering a synthesis of specific features.

The growing attention to the built heritage is shaping methods such as Historic/Heritage Building Information Modelling (HBIM) as possible alternatives to 2D and 3D geometric models, lacking structured ways of associating information to building components or spaces. Regardless of the method, a model generally reflects its object, purpose and target users, influencing graphic codes and level of details. Similarly, the selection among different data acquisition and processing techniques depends on the specific case study and the objectives of the analysis.

The structure of this chapter includes three main phases that mark the transition from the complexity of the built heritage to the synthesis of a knowledge model based on surveyed or documented geometries and incorporating thematic informative content. These contents can range from geometric detail to information on materials, building technologies, historical development, energy consumption, indoor comfort and many others and can take advantage of the involvement of different experts.

The three phases include:

- acquiring raw data, such as geometric data (coordinates, technical drawings, and others), material (texture, ruggedness, colour, mechanical features, etc.) and physical (temperature, moisture, CO_2 values, etc.) properties - section 4.1;
- processing the acquired data supporting the development of an integrated and comparable dataset (e.g. geometric data acquired with different survey techniques) - section 4.2;
- modelling the processed data in the form of information, reconstructing geometries and using them as a frame to communicate the results of the various analyses performed - section 4.3.

4.1 Acquisition phase

During the acquisition phase, all the data deemed necessary or helpful to perform a given analysis are recorded and collected. The acquisition typically follows a clear strategy, oriented at reaching precise goals, and has a clear structure facilitating the collaboration among all the involved specialists and the reuse of data for other purposes. The input of this phase is the complexity of reality, amplified by boundary conditions such as the accessibility to the object of investigation or the fragmentation of available sources. The output of this phase is raw data, intended as the data collected on the field, influenced by the peculiarity of different tools and sources. According to Musso & Torsello (1995, pp. 20-23), it is possible to classify acquisition techniques, distinguishing between direct and indirect, quantitative and qualitative, global and punctual, disruptive and non-disruptive, and active and passive approaches. Directly acquired data includes both geometric survey and diagnostic analysis, as they require some form of interaction between the observer and the object of study. Indirect data instead refers to bibliography, iconography and other historical-archival documentation. It is possible to describe phenomena according to qualitative or quantitative parameters, based respectively on feature description or measurement and counting. Some techniques support capturing a large amount of data simultaneously (e.g. photography, laser scanning, etc.), while others involve a selection of punctual data (e.g. traditional survey, topography, etc.). In addition, some techniques have specific requirements (e.g. illumination, temperature, etc.) to perform the analysis. Since geometric elements and principles are at the basis of each architecture or designed space (Musso & Torsello, 1995, pp. 4-6), this research mainly focuses on geometric and metric data. Moreover, geometry is a privileged code to think and analyse the built environment and represent it as a discontinuous entity through models (Torsello, 1988, p. 126). Nevertheless, some case studies also include diagnostic analyses and indirect documentation as information to associate with the geometric framework representing the object of investigation. However, the research does not include diagnostic analyses that could impact the material of the investigated building and be partially or extensively disruptive. The survey tools used in educational and research experiences belong to traditional and digital survey methods. All these experiences aim at recording intentional and accidental geometries (Torsello, 1988, pp. 126-131). Intentional geometries witness the intention of the mind who conceived, designed and realized a building and its cultural background (Torsello, 1988, ibid). These geometries can offer various insights into the construction techniques and the history and development of the building. Accidental geometries include irregular elements, depending on phenomena out of human control or intentions (Torsello, 1988, ibid). These geometries can display the state of conservation and the transformation of the building over time due to construction mistakes or incautious interventions, as well as environmental and atmospheric phenomena. A similar distinction also applies to indirect documentation, including design drawings and technical reports as direct records and pictures intended as intentional records and images representing a building as a background or the context of a historic event understood as accidental records.

4.1.1 Description, measurement, classification

Architectural survey requires a selection of values defined through three principal knowledge practices: description, measurement and classification (Massari, 1988).
A description is a form of representation based on words, in written or oral form, and it relies on the study of an object or phenomenon through direct observation or indirect documentation. Intended as an understanding and representation of the object of investigation, description is not only the final objective of architectural survey but also the preliminary activity of the knowledge process.
Mainly through direct observation, in the field of architectural survey, description supports the selection of peculiar characters meaningful for the analysis and identification of measurable properties. Measurement, focusing on a single property, defines its level of intensity in different objects (Cunietti, 1979, pp. 127-128).
Classification derives from comparing objects based on shared features and groups them into homogeneous classes (Monti, 1988, p. 29).
Description, therefore, includes preliminary proportioned drawings and schemes reducing the continuum of reality to a first discrete model as a result of a selective process. These first drawings can later host measurements and annotations of data collected onsite, confirming or denying the hypothesis formulated through observation.
Indeed, space analysis is performed through direct observation and with the support of science tools to analyse anything extremely small or big, too close or far away, composite, inaccessible or hidden (Torsello, 1988, pp. 115-116). These tools do not lead to a mere duplication of reality but to the development of a knowledge system accessible and usable by others (Ugo, 2004, pp. 14-15).
This interoperability derives from the scientific method, which involves objective and replicable procedures that can be verified or falsified (Popper, 1972, p. 421). The scientific method relies on mathematical language, which supports an objective description of a phenomenon and its comparison with others (Coiré, 1967, p. 91). For example, comparing measurements acquired with the same tool leads to defining the tool's precision. The comparison of measurements acquired with different tools, in the case of similar values, requires defining which instrument is

more accurate. In the case of distant values, the same comparison could lead to the identification of an error due to an instrument malfunction (*systematic error*), a distraction of the operator (*gross error*), or precarious measurement conditions (*accidental error*).
The acquisition of measurement can be oriented not only to comparison but also to the definition of hierarchies, to express a value scale and to produce knowledge. According to science, measure facilitates the description of heterogeneous geometries through inherent or anthropometric modules and neutral numbers, leading to the development of a numeric model. Indeed, numbers can describe phenomena by abstracting an intrinsic quality (counting) and artificially defining a comparable and classifiable quality (measuring). The complexity of the built environment often requires considering architecture itself as a measurement unit and referring to its philosophical meaning as the establishment of a relationship between a subject and an object and the ability to select quality before quantity (Massari, 1998).
Architectural survey is a measurable representation of measured built space and is strongly connected with the measurement techniques and tools chosen according to the peculiarity of each object of investigation. According to Roberto Masiero (1988) architectural survey is "representing though measurements" and "the surveyor simply expose what is clearly evident"[71]. It means that the object of investigation is the geometry of the built space directly observable or suggested by evident material trace, excluding entirely hidden elements (Ugo, 1994, p. 121), such as wall-embedded electric, hydraulic and mechanical systems. Beyond visibility, the other constraints of architectural survey concern the scale, excluding objects that require cartographic representations or chemical analysis to be described (Ippoliti, 2000, 9-10). Independently from its dimension, the object of investigation is available and perceivable in a continuous form but can be described, measured and classified just through a discretization. Different forms and levels of discretization can be reached through the adoption of different measurement methods and tools during the data acquisition process.

[71] "il rilevatore indica con un atto di ostensione ciò che è ben evidente [...] rilevare è semplicemente rappresentare prendendo le misure"

4.1.2 Measurements methods and tools

Data acquisition, and in particular measurement operations, involves the application of different methods and the employment of science tools. These methods and tools are selected and integrated according to the purpose of the architectural survey and the peculiarity of the object of investigation. Most of the methods available today, such as traditional direct survey, topography and photogrammetry, based on geometric, mechanical and optical principles, belong to the tradition of this discipline and are extensively documented in manuals[72] and scientific literature.

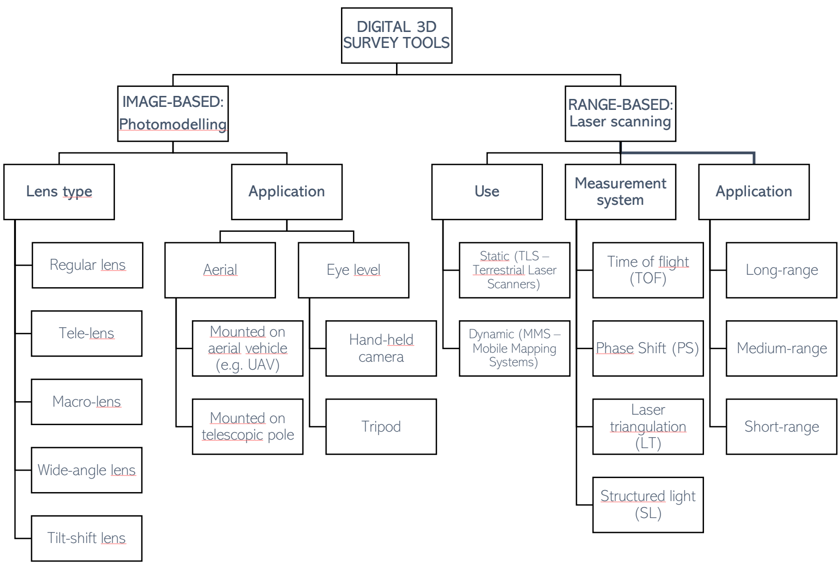


Figure 4.2 - Diagram presenting some possible classification of image- and range-based 3D digital survey tools.

[72] E.g.: Torsello, B. P. (1979). *Misura e conservazione: tecniche di rilevamento*. Venezia: CULVA; Thompson, M., Gruner, H. (1980). Foundations of Photogrammetry, Manual of Photogrammetry, American Society of Photogrammetry, Falls Church, Virginia; Ippoliti, E. (2000). *Rilevare: comprendere, misurare, rappresentare*. Roma: Kappa; Docci, M., Maestri, D. (2009). *Manuale di rilevamento architettonico e urbano*. Bari: Laterza; Historic England. (2021). Recording Heritage Technical Guidance.

These methods need an upstream orientation of the on-site activities and a preventive selection of the data to acquire and therefore are extremely helpful in educational experiences, since they require careful observation of the object of investigation (Barbini, 2024).
More recent methods based on electronic devices, such as digital cameras and laser scanning devices, support the development of 3D digital numeric models as a dense or sparse point cloud. These digital methods rely on optical 3D measurement techniques and support a massive data acquisition in a considerably short time. Therefore, preliminary activities are less focused on the selection of meaningful data but rather on possible context-related constraints (accessibility, visibility, illumination, etc.) and the device settings to optimize data acquisition according to the actual needs of the investigation, avoiding, for example, an excessive amount of data, difficult to store and process (Maragno et al. 2024). It is possible to distinguish between image and ranged-based digital survey methods.

Image-based techniques rely on passive sensors, capturing and recording the light emitted from the surrounding environment in the form of digital information, such as pixels, in the case of a digital photo camera used for photogrammetry (Fryer, 2007, p. 9). Transforming 2D images into 3D models, photo modelling derives 3D coordinates of the photographed surfaces through a mathematical model based on the collinearity principle[73]. The development of photogrammetry dates back to the mid-XIX century with the introduction of photography and the creation of stereoscopes for the fruition of a 3D scene from the combined observation of a couple of pictures (Ippoliti, 2000, pp. 123-125). Based on stereo image processing, deriving 3D information from at least two partially overlapping images, photo modelling does not autonomously produce metric data but only 3D geometries and colour information. To derive metric information from a set of photographs, it is always necessary to provide external information, such as the coordinates of at least three control points, for scaling and spatially referencing the produced

[73] According to the collinearity principle a given point on an object, the optical centre of the lens and the projection of that point on the photographic sensor lie on the same line.

3D model. Therefore, during the acquisition phase, it is crucial to correctly plan and complement a photogrammetric survey with some metric references (Fryer, 2007, p. 22). The necessary equipment of image-based survey, i.e. a digital photo camera, hand-held for eye-level applications or mounted on specific supports for aerial applications, is generally more affordable compared to range-based devices (Filippucci, 2010). On the other hand, while most laser scanners do not require highly specialized operators during the acquisition phase, the results of a photogrammetric survey mainly depend on the quality of the set of pictures collected on site (Filippucci, 2010). For this reason, the operators need to guarantee adequate scene overlapping among pictures and know how to correctly set the camera to ensure constant exposure and maximum sharpness.

Range-based techniques rely on active sensors, emitting energy, for example, in the form of a laser beam and detecting its reflection, such as in laser scanning devices, which derive spatial information in the form of a point cloud representative of the detectable surfaces. Laser scanning devices can be considered an evolution of total stations[74], able to rapidly measure and register tremendous amounts of data by projecting a laser beam on the surrounding space. A possible classification of laser scanners refers to their support. At the architectural scale, the most common supports are tripods, as in the case of Terrestrial or Static Laser Scanners, generally abbreviated as TLS. Other possible supports are vehicles, backpacks and other hand-portable holders, as in the case of Mobile Mapping System (MMS). Beyond the interest of this research in territorial applications, it is also possible to use aircraft, as in the case of Airborne Laser Scanners (ALS).
Another classification of laser scanners refers to the measurement system, which affects the extent of the detectable area, the acquisition speed, the noise level, the precision of acquired data and, therefore, the possible applications. Since the active laser sensors are based on a beam of light emission, measurement systems can exploit the properties of

[74] Electronic-optic tool, generally used on a tripod measuring the distance between the instrument and the collimated point, and angles between fixed horizontal and vertical directions and the point.

electromagnetic radiation, as in the case of Light Detection and Ranging (LiDAR) systems or geometric relationships (Vosselman, 2010, pp. 109-111). The most common measurement system for movable applications is Time-Of-Flight (TOF). This system exploits the known propagation velocity of the laser to estimate the transit time and evaluate the distance from an object by measuring the time it takes for the laser to hit the object and return reflected to the instrument (Vosselman, 2010, ibid). This system is suitable for medium and long-range applications, between 2 meters and 1 kilometre, but compared to other systems has a lower precision and acquisition speed and higher noise level (3DSYSTEMS, 2024). Static applications mostly use the Phase-Shift (PS) system, comparing the difference between the phase of the wave hitting the object and of the wave reflected to the instrument. This system has a high acquisition speed, a higher precision, a lower noise level and a high density of acquired data, which can be up to 0.6 mm between points at a distance of 10 metres (3DSYSTEMS, 2024), and therefore are suitable for medium-range applications.

Devices for close-range acquisitions mainly exploit geometric relationships, such as systems based on laser triangulation or structured light. The first one compares the angle of the reflected light with the angle of the emitted light, which is known as well as the distance between the emitting and receiving sensors. This system is generally easier to transport, and it is not excessively sensitive to environmental light (3DSYSTEMS, 2024). Structured light system project on the object a known light pattern, such as a grid or bars, and derives geometric and metric information on the object from the deformation present in the light pattern reflected from the object. Among the two, this second system is more accurate, can reach higher resolutions and has a lower noise level, but generally has a bigger size not easy to transport, requires preparation of the surface to survey and could require specific illumination conditions (3DSYSTEMS, 2024).

Static laser scanners often require more than one scan to survey the entire object of investigation, this imposes carefully plane stationing points

to avoid missing data and to integrate the survey with topographic data or GNSS[75] data to refer all the scans to the same reference system.
MMS generally include a laser sensor but also one or more cameras, advanced Inertial Measurement Unit (IMU) and GNSS to mathematically link the observed scan points in a unique spatial reference system, producing a single scan that integrates both static and kinematic acquisitions (Vosselman, 2010, pp. 293-295). However, topographic or GNSS data can be helpful to integrate separate acquisitions or MMS and TLS data.
A low-cost example of MMS, is the iPad Pro with LiDAR sensor, presenting lower performances than a professional MMS, but it is still useful for a wide range of daily and professional applications. The iPad Pro is a mobile device integrating the LiDAR sensor with two cameras and movement sensors which exploits computer vision algorithms to record the scene in detail. Despite presenting a lower resolution and a higher level of noise than professional instruments, this device reaches its best performances in a range of 5 meters.
The measurement accuracy of a laser scanner is affected by the distance from the survey object and its reflectivity. Indeed, accuracy decreases with the increase of distance and surface reflectivity, since objects with highly reflective surfaces, such as mirrors, glass and water are hardly detectable by the laser. These aspects influence the acquisition phase, requiring correctly planning the position of each scan for TLS and the itinerary for MMS, as well as integrating the survey with other techniques in case of surface with high reflectivity. Both traditional and digital 3D survey methods include professional and highly expensive tools, as well as low-cost devices, making metric and geometric data acquisition more accessible. In the following tables are presented the main tools used for the case studies presented in the next pages.

[75] Global Navigation Satellite System, example or GNSS are GPS (Global Positioning System) from USA, GLONASS from Russia, Galileo from Europe, IRNNS from India, Beidou from China, QZSS from Japan.

APPLICATIONS	INSTRUMENT		DESCRIPTION			OUTPUT DATA
			GENERAL FEATURES	SPECIFICATIONS		
Terrestrial photogrammetry		Canon EOS600D (LAMARC)	Digital Single Lens Reflex Camera	**Resolution**: 18.0 megapixel (5184×3456) **Sensor**: CMOS APS-C (22.3x14.9 mm) **Lens**: 18-55 mm **External memory**: SD 64 GB **Dimensions**: 133x100x80 mm (570g)	**ISO** 100-6400 **Aperture**: f/3.5-5.6 **Exposure time**: 30-1/4000 sec	Static and dynamic photographic images in digital formats
Aerial photogrammetry		3D Eye system equipped with Sony Alpha600 (LAMARC)	Mirrorless camera mounted on a telescopic pole stabilized by a gimbal controllable via the FeiyuON mobile app, and remotely operated via mobile	**Resolution**: 24.3 megapixel (6000x4000) **Sensor**: CMOS APS-C (23.5x15.6 mm) **Lens**: 16-50 mm **External memory**: micro-SD 32 GB **Dimensions**: 120x67x45 mm (344 g)	**ISO** 100-25600 **Aperture**: f/3.5-5.6 **Exposure time**: 30-1/4000 sec	
		DJI Spark LT (LAMARC)	Stabilized camera monted on an Unmanned Aerial Vehicle (UAV)	**Resolution** 12.0 megapixel (3968x2976) **Sensor**: CMOS 1/2.3" (6.17x4.55 mm) **Lens**: 25 mm **Flight autonomy**: 15 minutes **Dimensions**: 143x143x55 mm (300 g)	**ISO** 100-1600 **Aperture**: f/2.8 **Exposure time**: 2-1/8000 sec	
		DJI Mavic 2 Pro (by Francesco Giampiccolo)	Hasselblad L1D-20c camera mounted on an Unmanned Aerial Vehicle (UAV)	**Resolution** 20.0 megapixel (5472x3648) **Sensor**: CMOS 1" **Lens**: 28 mm **Flight autonomy**: 30 minutes **Dimensions**: 214×91×84 mm (907 g)	**ISO** 100-3200 (automatic), 1-12800 (manual) **Aperture**: f/2.8-f/11 **Exposure time**: 8 -1/8000 sec	
Spherical photographic shooting		Ricoh Theta V (LAMARC)	360 Spherical camera	**Resolution**: ~14 megapixel (5376x2688) **Sensor**: CMOS 1/2.3" (6.17x4.55 mm) **Lens**: minimum focal length 2 mm **Internal memory**: 19 GB **Dimensions**: 45x131x6.4 mm (121 g)	**ISO**: 64-3200 **Aperture**: f/3.5-5.6 **Exposure time**: 60-1/25000 sec	Static and dynamic panoramic images in digital formats
Topographic survey		Topcon GPT 1001 (LAMARC)	Total station equipped with three tripods, tribrach, adaptors, prisms with target and mini prisms	Telescope: Distance measurement: Measurement accuracy:	Lenght: 150 mm Lens 45 mm (EDM 50 mm) Magnification: 30x Non-prism mode: 100-130 m Miniprism: 2000 m Prism: 6000 m Non-prism mode: ± 10 mm Prism mode: ±3 mm	Horizontal and vertical angles and distance of each measured point

Table 4.1 - Survey tools used for LAMARC acquisition experience. Photographic and topographic tools.

APPLICATIONS	INSTRUMENT		DESCRIPTION		OUTPUT DATA
			GENERAL FEATURES	SPECIFICATIONS	
Range-based survey		Faro Focus CAM2 S150 (by Alberto Leoni)	Terrestrial Laser Scanner (TLS) mountable on a tripod and equipped with: - LiDAR sensor based on phase-shift system - dual axis compensator - height sensor - compass - color camera	**Range**: 0.6-120 m **Resolutions**: 122.000/244.000/488.000/976.000 pt/sec **Max relative accuracy**: 1 mm **Scanning autonomy**: 4.5 hours **Dimensions**: 230x183x103 mm (4.2 kg)	Point cloud
		Faro Focus 3D S120 (by Matteo Dallagiacoma)		**Range**: 0.6-120 m **Resolutions**: 122.000/244.000/488.000/976.000 pt/sec **Max relative accuracy**: 2 mm **Scanning autonomy**: 5 hours **Dimensions**: 240x200x100 mm (5 kg)	
		Geoslam ZEB Horizon RT (by Semprebon Lux)	Mobile Mapping System (MMS) hand-held/backpacked and equipped with: - LiDAR sensor based on TOF system - inertial navigation technology - SLAM tracking sensor - visible-light camera	**Range**: 100 m **Resolution**: 300.000 pt/sec **Relative accuracy**: 6 mm **Scanning autonomy**: 25 min **Dimensions**: 1.5 kg	
		Lixel X1 (by Novatest)		**Range**: 0.05-120 m **Resolution**: 320.000 pt/sec **Relative accuracy**: 2 cm **Scanning autonomy**: 60 min **Dimensions**: 138×90×381mm (1.9 kg)	
		LiDAR sensor iPad Pro 12.9" 5ª generation (LAMARC)	Movable scanning device equipped with: - LiDAR sensor based on direct TOF system - motion sensor - camera	**Range**: 5 m **Resolution**: 320.000 pt/sec **Relative accuracy**: 2 cm **Max battery autonomy**: 10 hours **Dimensions**: 261x215x6 mm (685 g)	

Table 4.2 - Survey tools used for LAMARC acquisition experience. Laser scanning tools.

4.1.3 Acquisition experiences

The collection of experiences illustrated in the following pages aims to expose some considerations on the data acquisition phase and to present the starting databases of some case studies that will be further analysed and discussed. As anticipated, all the case studies refer to experiences in which the LAMARC actively took part in the last few years. The case studies, presented in chronological order, are representative of all the categories of built heritage previously identified (Chapter 2.1) and cover a timespan from the first century B.C. to the 21st century, thus including an archaeological site, buildings expression of outstanding values (e.g. artistical, historical, demo-ethno-anthropological), as well as examples of recent and contemporary heritage.
The surveyed heritage is in Trentino Alto-Adige region, and the acquisition experiences started as collaborations between the University of Trento and local institutions or as part of regional, national or international research programmes.
According to the object size and peculiarities and the purpose of each survey, the acquisition phase required the employment of different tools, the involvement of human resources and variable time extensions. Moreover, acquisition experiences are mainly drive by three approaches, often mixed and combined: data accuracy, techniques integration and low-cost (Fig. 4.3). However, all the surveys include a topographic survey as a framework for integrating different metric data sources, from traditional to digital 3D surveys.
In addition to some images, representative of the acquisition phase, for each case of study, a synthetic table reports the heritage type, the research year and goals, indirect data source already available and data collected on site. Moreover, each table clarifies scale and object of the survey, adopted techniques and tools, operators and experts involved, and further developments.
In most cases, some LAMARC collaborators further processed the collected data and developed one or more models, testing data integration within a CAD environment and exploiting the potential of BIM environment, as illustrated in paragraphs 4.2.3 and 4.3.3.

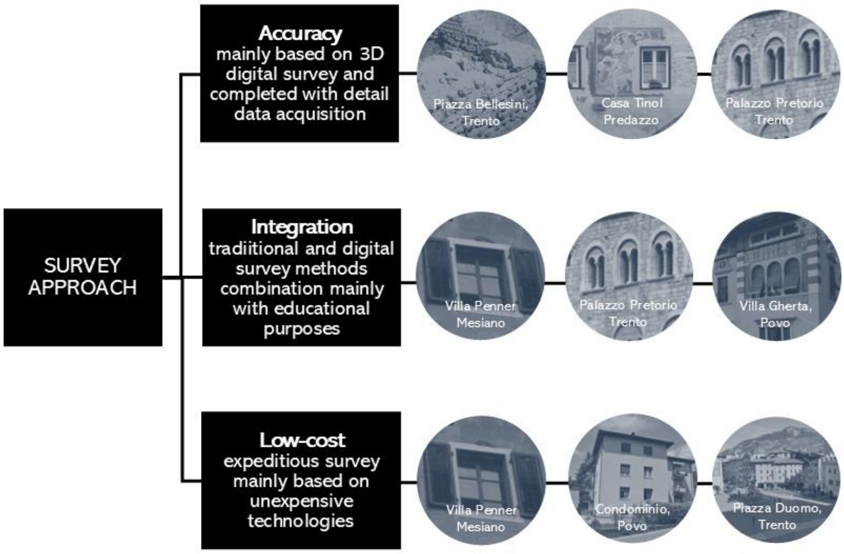


Figure 4.3 - Diagram presenting the main survey approaches adopted.

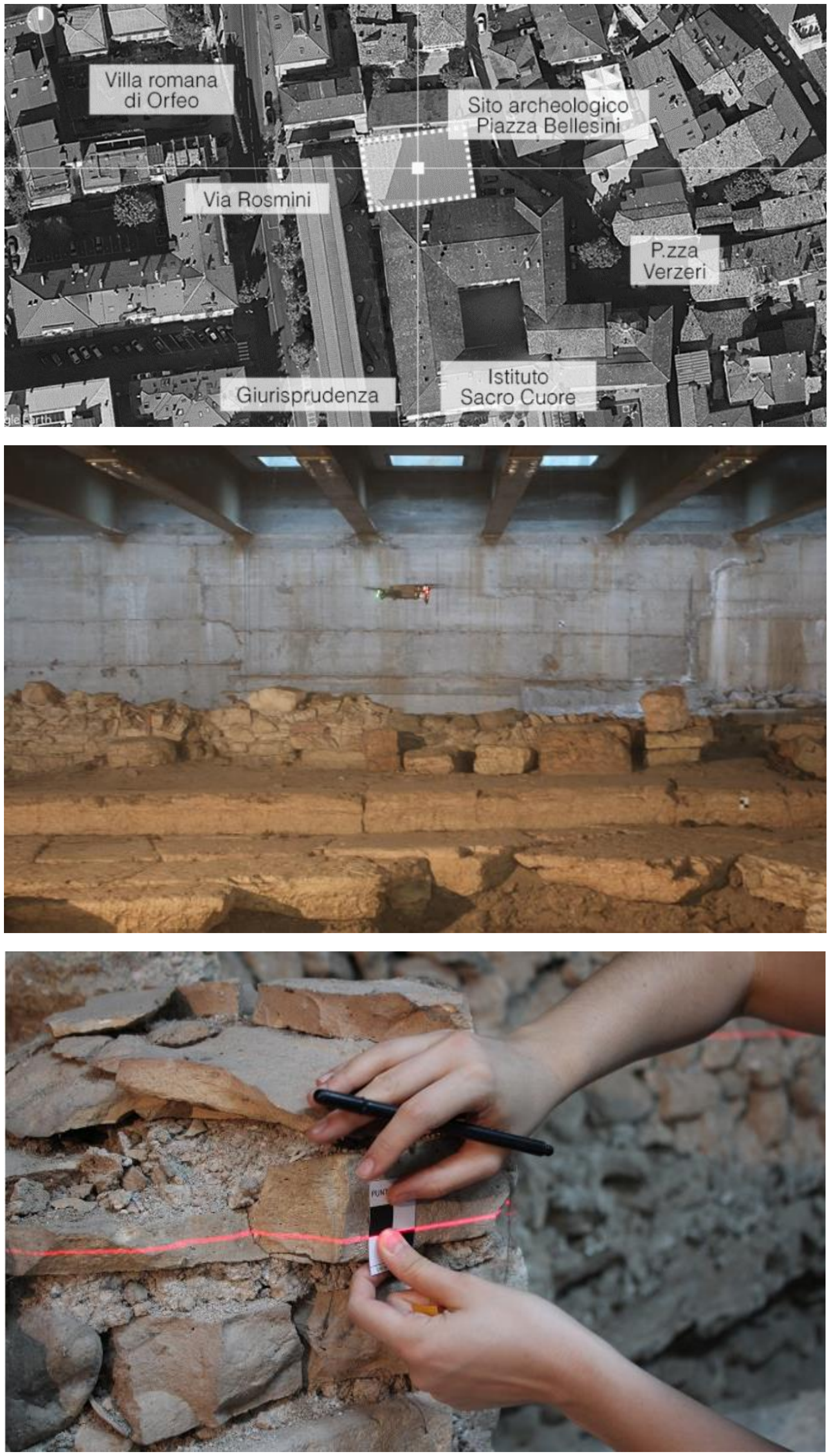


Figure 4.4 - Context of piazza Bellesini in the historic centre of Trento, drone survey and definition of a level plane. Images from Scoz, D. (2020-21). *Frammenti di Trento romana: un approccio HBIM per la conoscenza, il progetto e la rappresentazione del sito archeologico Piazza Bellesini*. Master Thesis in Building Engineering and Architecture, University of Trento.

Piazza Bellesini in Trento

Heritage type	Archaeological site (late 1st century B.C.)
Research years	2020-21
Research goals	Archaeological site documentation and communication Technical documentation for design and management
Available data	Historical-archival data: archaeological survey hand drawings (1994-97), iconography, bibliography. Design technical drawings of the nearby Law Faculty and the archaeological area coverage, by Emilio Pizzi for Mario Botta (2005).
Acquired data	Indoor and outdoor architectural survey. *Traditional methods: topographic (with **Topcon GPT 1001 Total Station**: 6 polygonal vertices and approximately 500 object points), photogrammetric (with **Canon EOS600D**), traditional direct and detail survey.* *Range-based digital 3D survey:* *- **Faro Focus 3D S120** TLS (12 scans).* *Image-based digital 3D survey:* *- terrestrial photogrammetry with **Canon EOS 600D** (174 internal pictures and 2 external pictures);* *- UAVs aerial photogrammetry with **DJI Mavic 2 Pro** (231 internal pictures and 111 external pictures) and **DJI Spark** (139 internal pictures and 21 external pictures).*
Working group	Architectural survey campaign: Francesco Castaldini, Matteo Dallagiacoma (laser scanner), Davide Giacomelli, Francesco Giampiccolo, Anna Maragno, Giovanna A. Massari (scientific coordination), Cristina Pellegatta, Starlight Vattano, Giulia Zantedeschi. Archaeologic advisory: Cristina Bassi Architectural advisory: Michela Favero
Further developments	Scoz, D. (2020-21). *Frammenti di Trento romana: un approccio HBIM per la conoscenza, il progetto e la rappresentazione del sito archeologico Piazza Bellesini*. Master Thesis in Building Engineering and Architecture, University of Trento. Supervisors: Prof. Giovanna A. Massari, Prof. Maurizio Fauri and Arch. Michela Favero. Processing phase - see pages 110-111 Modelling phase - see page 134

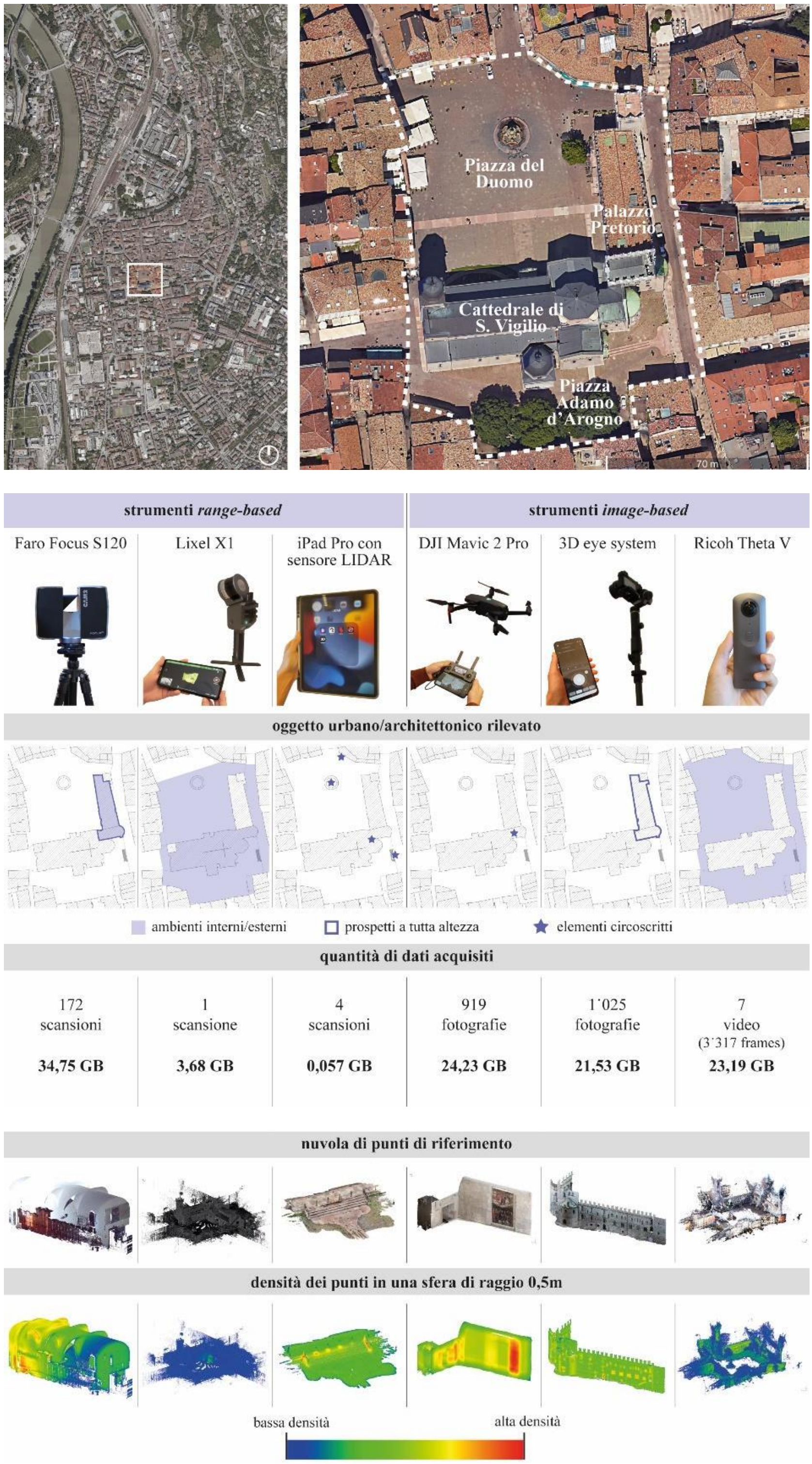
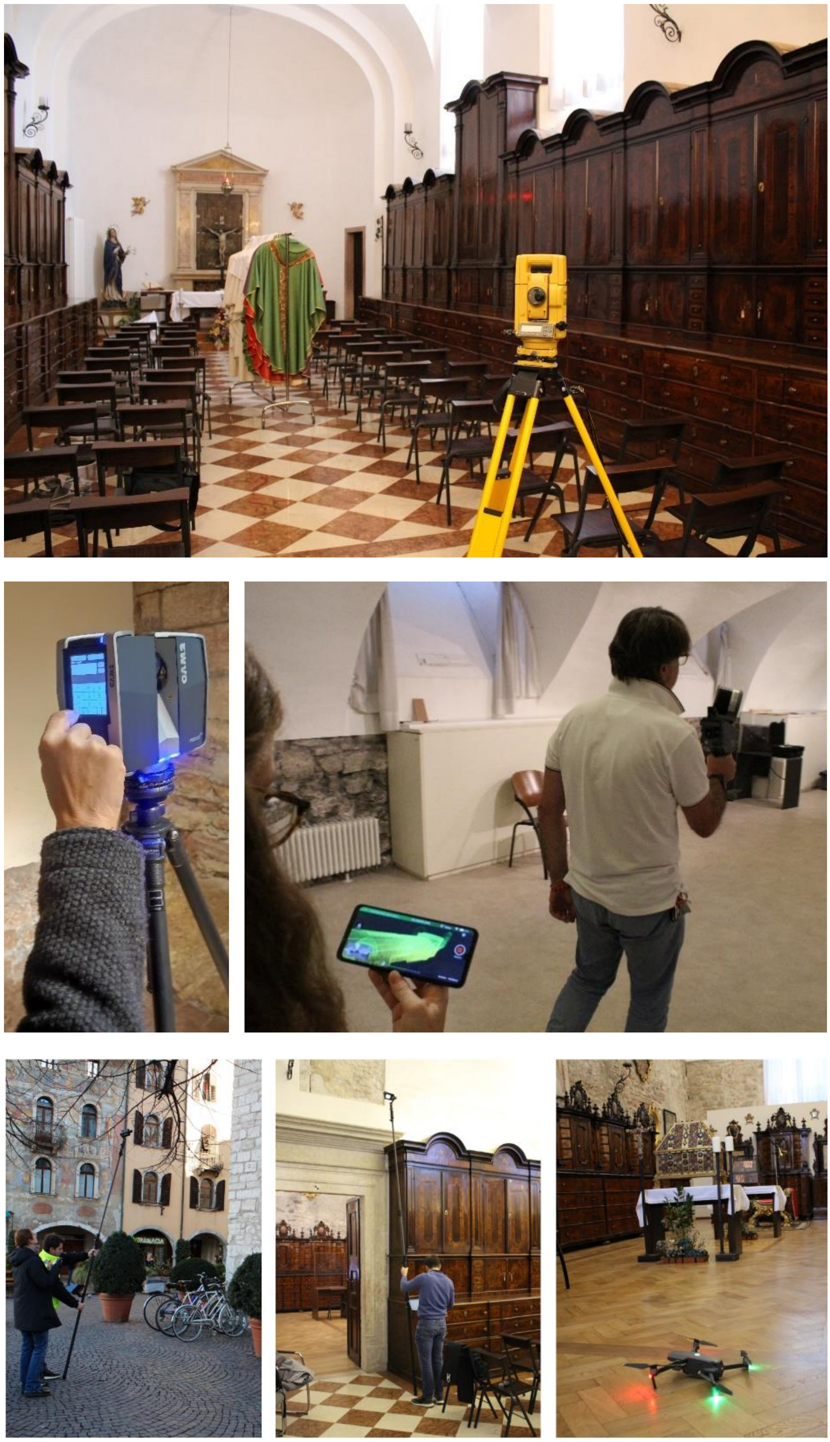


Figure 4.5 - Context of piazza and Piazza D'Arogno and synthesis table of employed range- and image-based survey tools for different urban areas and single objects, survey data quantity and output point cloud example and density. Images from Marago, A., Barbini, A., Bernardini, E., Chioni, C., Massari, G. A. (2024). La misura per la dismisura dei dati da rilievo digitale 3D. Il caso del centro storico di Trento. *UID 2024 Conference Proceedings.* (forthcoming).

Piazza Duomo and Piazza d'Arogno in Trento

Heritage type	Historic urban space (12th century)
Research years	2023-24
Research goals	Urban space documentation and communication
Available data	Archival documents: historical iconography and bibliography. LAMARC raw and processed survey data: - ***Faro Focus CAM2 S120*** *TLS (34 scans);* - ***Lixel X1*** *MMS (1 scan);* - ***3D eye system*** *aerial photogrammetry with* ***Sony Alpha 2000*** *camera (593 pictures).*
Acquired data	Low-cost urban survey. *Range-based digital 3D survey:* - ***iPad Pro*** *LiDAR sensor (3 scans).* *Image-based digital 3D survey:* - *terrestrial photogrammetry with* ***Ricoh Theta V*** *360° camera: (7 videos -3317 frames).*
Working group	Urban survey campaign: Ambra Barbini, Chiara Chioni and Anna Maragno Survey methodological supervision: Giovanna A. Massari from the University of Trento-DICAM Architectural history supervision: Cristiana Volpi Technical and instrumental support: LAMARC Archival support: staff of the Archivio Storico del Comune di Trento (ASCTn)
Further developments	- Maragno, A., Barbini, A., Bernardini, E., Chioni, C. (2024). *Other stories. Virtual reconstruction of different design hypotheses for Piazza d'Arogno in Trento*. In eXplora Conference Proceedings (forthcoming); - Maragno, A., Barbini, A., Bernardini, E., Chioni, C., Massari, G. A. (2024). *La misura per la dismisura dei dati da rilievo digitale 3D. Il caso del centro storico di Trento*. In UID Conference Proceedings (forthcoming). Fruition phase - see pages 156-157

Figure 4.6 - Indoor and outdoor survey activities in Palazzo Pretorio. From top to bottom: topographic survey, range-based survey: TLS (links) and MMS (right), aerial photogrammetry with telescopic pole (links and centre) and drone (right). Images from LAMARC presentation for the Workshop organized by the Museum Diocesano Tridentino on the 1st of December 2023.



Palazzo Pretorio in Trento

Heritage type	Historical building (16th century)
Research years	2021-23
Research goals	Investigation of the building history and development
Available data	Archival documents: historical iconography and bibliography. Architectural survey processed data (e.g. Torsello).
Acquired data	Indoor and outdoor architectural survey. *Traditional methods: topographic (with **Topcon GPT 1001 Total Station**: 54 polygonal vertices and approximately 1500 object points), photogrammetric, traditional direct, detail and thematic survey (as part of educational activities).* *Range-based digital 3D survey:* *- **Faro Focus CAM2 S120** TLS (172 scans);* *- **Lixel X1** MMS (1 scan for the Chapel of S. Giovanni, the Cathedral of St. Vigilio and surrounding urban area);* *- **iPad Pro** LiDAR (9 scans for hardly-accessible areas).* *Image-based digital 3D survey:* *- **NikonD750** camera (55 pictures);* *- **3D eye system** with **Sony Alpha 2000** camera (351 internal and 593 external pictures);* *- UAVs with **DJI Mavic 2 Pro** (499 internal pictures).*
Working group	Architectural survey campaign: Architectural Survey course students (A.Y. 2021-22), Barbini A., Bernardini E., Chioni C., Canale M., Di Valerio S., Giampiccolo F., Gottardo G., Leoni A. (laser scanner), Maragno A., Massari G. A. (scientific coordiantion) and Sarti G. Archival experts: Cagol F. and Iseppi R. Restoration experts: Aldrighettoni J, Anderle M., Gentilini G. and Quendolo A. Archaeology experts: Cavada E. and Possenti E.
Further developments	- *Workshop* by Museo Diocesano on 1.12.2023; - Barbini, A., Giampiccolo, F., Maragno, A., Massari G. A., Pellegatta, C., (2024). Innovation and tradition: integrated practices in the architectural survey of Pretorio Palace in Trento. *SCIRES-IT, 2024(1), 45-62.*

Processing phase - see pages 116-117
Modelling phase - see pages 135-138
Fruition phase - see pages 153-156

Figure 4.7 - From top to bottom: main façade of Casa Tinol, stone wall and survey activities: topographic survey and level plane definition. Images by LA-MARC acquired during the first acquisition phase in September 2021.

Casa Tinol in Predazzo

Heritage type	Historical building (16th century)
Research years	2021-23
Research goals	Technical documentation for restoration activities Virtual historical phases reconstruction
Available data	Restorer photographic and report documentation, previous architectural survey drawings, cadastral documents, historical bibliography.
Acquired data	Indoor and outdoor architectural survey of the vaulted basement floor and of the two main façades. *Main survey campaign at the beginning of the restoration activities (07.09.2021):* *Traditional methods: topographic (with* ***Topcon GPT 1001 Total Station****: 5 polygonal vertices and 276 object points), photogrammetric with* ***Canon EOS600D*** *(23 internal pictures and 48 external pictures) and traditional direct survey.* *Range-based digital 3D survey:* - ***Faro Focus CAM2 S120*** *TLS (16 scans);* *Photographic documentation during the restoration activities*: - ***Hasselbladt H4D-60*** *(9 external pictures) on 11.01.2017;* - ***Canon EOS600D*** *(63 internal pictures and 3 external pictures) on 08.02.2022;* - ***Hasselbladt H4D-60*** *(12 internal pictures) on 04.03.2022;* - ***Canon EOS600D*** *(101 internal pictures and 26 external pictures) on 28.03.2023.*
Working group	Architectural survey campaign: Barbini A., Bernardini E., Chioni C., Leoni A. (laser scanner), Maragno A., Massari G. A. (scientific coordiantion) and Pellegatta C. Restoration activities: Silvia Invernizzi History of art expert: Giovanni Dell'Antonio
Further development	- Third edition of the ViC-CH project on the 22-24th September 2023 in Predazzo; - Presentation event of results of the ViC-CH project in Predazzo on the 27th of September 2023.

Processing phase - see pages 112-114
Modelling phase - see pages 135-138
Fruition phase - see pages 148-152

Figure 4.8 - From top to bottom: location of Villa Penner, collage of pictures representing some details of the buildings and the main survey campaign with students. Images from Gaspari, A. (2020-21). *L'applicazione di tecnologie immersive alla metodologia HBIM per la gestione e condivisione del progetto*. Master Thesis in Building Engineering and Architecture, University of Trento.

Villa Penner in Mesiano

Heritage type	Historical building (16th century)
Research years	2020-21
Research goals	Technical documentation for design and management
Available data	Archival documents: historical iconography and bibliography.
Acquired data	Indoor and outdoor architectural survey *Traditional methods: topographic (with **Topcon GPT 1001 Total Station**: 11 polygonal vertices and approximately 300 object points), photogrammetric, traditional direct, detail and thematic survey (as part of educational activities).* *Range-based digital 3D survey:* *- **Faro Focus 3D S120** TLS (21 outdoor scans);* *- **iPad Pro** LiDAR (indoor scans).* *Image-based digital 3D survey:* *- terrestrial photogrammetry with **Canon EOS 600D** and other reflex cameras (indoor pictures for each group);* *- UAVs aerial photogrammetry with **DJI Mavic 2 Pro** (roof and outdoor pictures).*
Working group	Architectural survey campaign: Architectural Survey course students (A.Y. 2020-21), Marco Canale, Matteo Dallagiacoma (laser scanner), Andrea Gaspari, Franscesco Giampiccolo (photogrammetry), Giovanna A. Massari (scientific coordiantion), Giacomo Sarti, Starlight Vattano Architectural advisory: Michela Favero
Further development	Gaspari, A. (2020-21). *L'applicazione di tecnologie immersive alla metodologia HBIM per la gestione e condivisione del progetto*. Master Thesis in Building Engineering and Architecture, University of Trento. Supervisors: Prof. Giovanna A. Massari and Prof. Mario C. Dejaco, co-supervisor Arch. Michela Favero. Processing phase - see pages 110-111 Fruition phase - see page 133

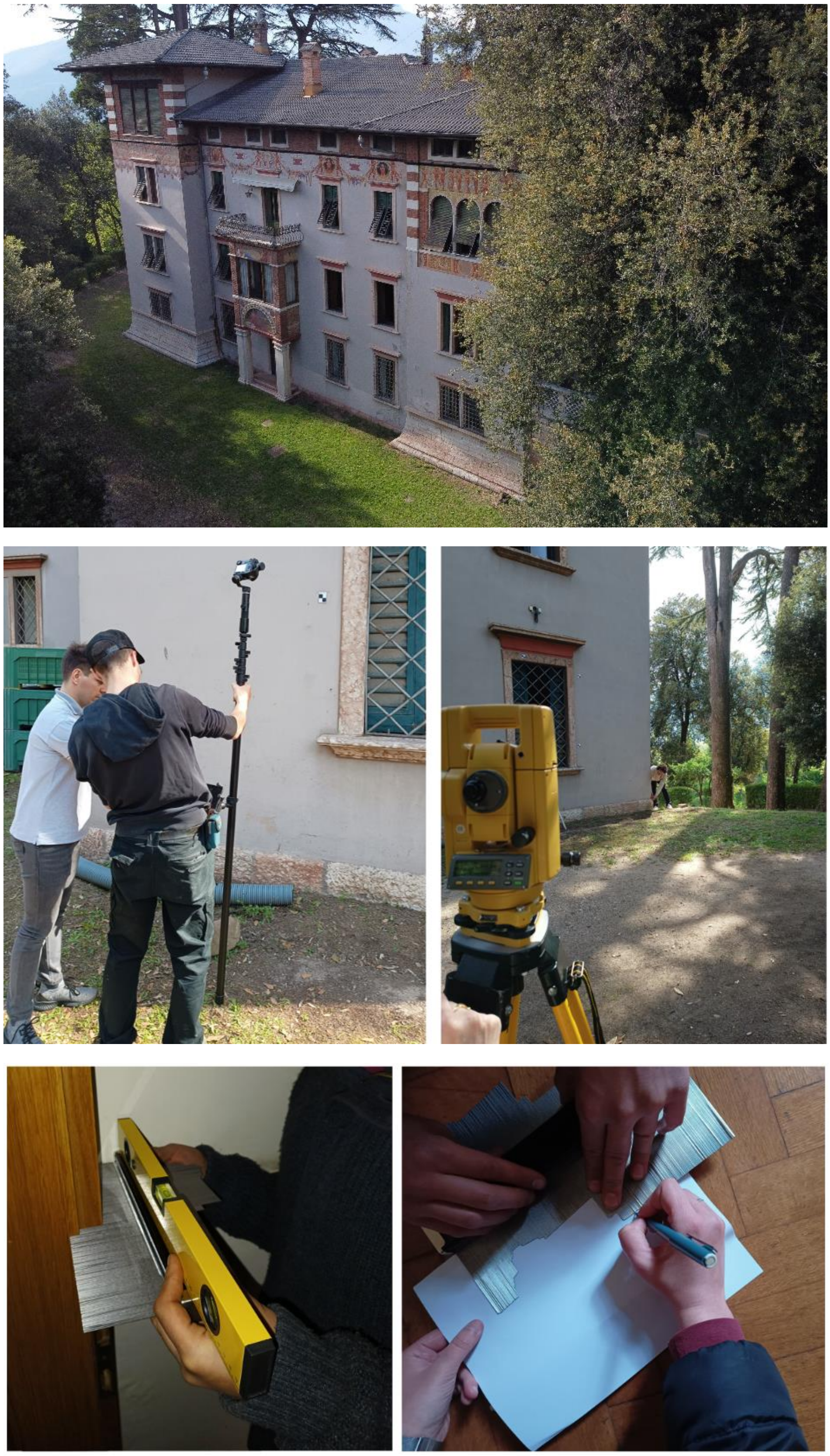


Figure 4.9 - From top to bottom: drone view of Villa Gherta, survey campaign with students including aerial photogrammetry, topographic survey and detail survey. Images by LAMARC.

Villa Gherta in Povo

Heritage type	Historical building (20th century)
Research years	2022-23
Research goals	Technical documentation for design and management
Available data	Previous architectural survey drawings, photographic documentation, iconography and bibliography
Acquired data	Indoor and outdoor architectural survey. *Traditional methods: topographic (with* ***Topcon GPT 1001 Total Station****: 17 polygonal vertices and 336 object points), photogrammetric (with* ***Canon EOS 600D****: 433 pictures; with* ***Canon EOS 6D****: 377 pictures), traditional direct, detail and thematic survey (as part of educational activities).* *Range-based digital 3D survey:* - ***Faro Focus CAM2 S120*** *TLS (33 scans);* - ***iPad Pro*** *LiDAR (integrative indoor scans).* *Image-based digital 3D survey:* - *terrestrial photogrammetry with* ***Nikon D750*** *camera (85 pictures);* - ***3D eye system*** *aerial photogrammetry with* ***Sony Alpha 2000*** *camera (335 pictures);* - *UAVs aerial photogrammetry with* ***DJI Mavic Mini*** *(85 external pictures).*
Working group	Architectural survey campaign: Architectural Survey course students (A.Y. 2022-23), Ambra Barbini, Marco Canale, Margherita Gallio, Gregorio Gottardo, Franscesco Giampiccolo (photogrammetry), Giovanna A. Massari (scientific coordiantion), Giacomo Sarti Architectural advisory: Umberto Anesi, Fabio Campolongo, Stefano Gialanella, Michela Favero, Alessandro Pasetti Medin, Alessandra Tiddia
Further development	- Villa Gherta: un sogno liberty a Trento guided tour on the 24th of May 2023; - Restoration feasibility study cured by the Architecture Division of the Estates Directorate of the University of Trento (ongoing); - Gottardo, G., Master Thesis in Building Engineering and Architecture, University of Trento. Supervisors: Prof. Giovanna A. Massari (ongoing).

Figure 4.10 - From top to bottom: view of the residential building in Povo, survey campaign with LIDAR sensor, total station, MMS and telescopic pole. Images by LAMARC.

Residential building in Povo

Heritage type	Recent heritage (20th century)
Research years	2022-ongoing
Research goals	Comparison of different expeditious and low-cost survey workflows to support the technical documentation for energy retrofitting based on prefabricated panels.
Available data	Design technical drawings and reports. Architectural survey processed data (from ***Faro Focus 3D S120*** *TLS and UAVs aerial photogrammetry).*
Acquired data	Outdoor architectural survey. *Traditional methods: topographic (with* ***Topcon GPT 1001 Total Station****: 4 polygonal vertices and approximately 100 object points) and photogrammetric (with* ***Canon EOS 600D*****: 142 pictures) survey.* *Range-based digital 3D survey:* - ***iPad Pro*** *LiDAR sensor* (50 scans using the Scaniverse free application).* - ***GeoSLAM Zeb Horizon*** *MMS* (1 scan);* *Image-based digital 3D survey:* - ***3D eye system*** *aerial photogrammetry with* ***Sony Alpha 2000*** *camera (802 pictures).*
Working group	Architectural survey campaign: Ambra Barbini, Elena Bernardini, Rudy Faitini (MMS), Gregorio Gottardo, Giovanna A. Massari (scientific coordiantion), Giacomo Sarti and Desiré A. Vallenari
Further development	Building renovation through a modular prefabricated system based on timber, developed as a retrofit kit (see Renew-Wall project - pages 161-164) to improve energy efficiency, indoor comfort and architecture aesthetics of existing buildings.

* Used from both the ground level and from a lifting platform.

Figure 4.11 - From top to bottom: view of the University library in Mesiano, available project drawings and layout of the floor heating system MMS and telescopic pole. Images from Murer, J. (2022-23). *Analisi energetiche e rappresentazione delle informazioni: il caso studio della BUM*. Master Thesis in Civil Engineering, University of Trento.

BUM - Biblioteca Universitaria Mesiano

Heritage type	Contemporary architecture (21th century)
Research years	2022-23
Research goals	Energetic and HVAC system analysis and simulation Diachronic sensor data visualisation
Available data	Design technical drawings and reports. Indoor sensor data: *t*emperature, moisture and carbon dioxide every 15 minutes from 13.07.2023 to 11.01.2023
Acquired data	Design drawing validation campaign: on site sample measurements through traditional direct techniques.
Working group	<u>HVAC systems experts</u>: Paolo Baggio and Alessandro Prada <u>Architecture analysis and modelling advisors</u>: Ambra Barbini and Giovanna A. Massari
Further development	Murer, J. (2022-23). *Analisi energetiche e rappresentazione delle informazioni: il caso studio della BUM*. Master Thesis in Civil Engineering, University of Trento. Supervisors: Prof. Paolo Baggio, Giovanna A. Massari and Alessandro Prada Modelling phase - see page 132 Fruition phase - see pages 158-160

Among the illustrated case studies, it is possible to distinguish three main approaches, often mixed and combined:
- the attention to accurate data acquisition;
- the reduction of time and budget, leading to expeditious and low-cost surveys;
- the integration of traditional and digital methods.

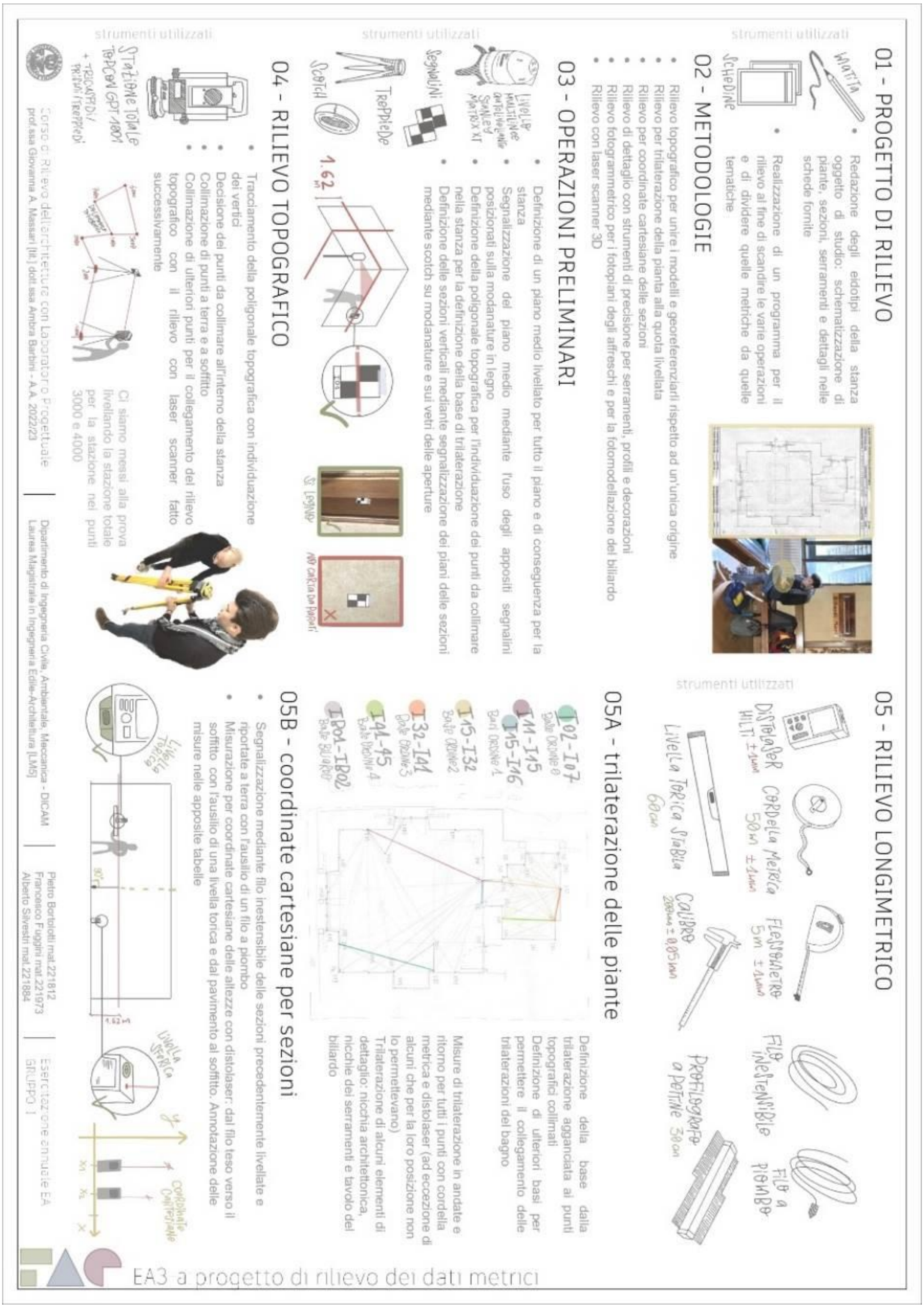
Several acquisition experiences (e.g. Palazzo Pretorio, Villa Penner, Villa Gherta) are part of the educational activities of the Architectural survey course. These acquisition campaigns last 3-4 days for 20-30 hours, and each group of 2-3 students is required to survey a small portion of the building using different tools and techniques. Students are provided with sheets for data acquisition covering main topics (e.g. context and architecture hand drawings to support traditional survey operations) and a collection of survey equipment (Figure 4.4-4.5) to use autonomously or with the support of the teaching staff or experts. After the presentation of the case study, the educational activities generally include:
- a first inspection of the entire building, focusing on the assigned space;
- the elaboration of proportioned hand drawings in perspective or axonometric projection to describe and understand the case study at different scales and levels of detail and in orthogonal projections to host future measurements and annotations;
- the definition of a survey project to clarify the techniques and tools to use for different data collection;
- the definition of shared horizontal and vertical planes to use as reference for all the traditional direct survey acquisition and for the subsequent development of a 3D for sections model[76];
- a traditional direct and details survey of each assigned space, paying particular attention to all the visible building components (e.g. walls, doors, windows, structural elements, decorative apparatus);
- a photographic survey for plane photogrammetric elaborations and the documentation of the space and the acquisition activities;
- a topographic survey, to define a reference framework for the integration of all the other acquired geometric and metric data;

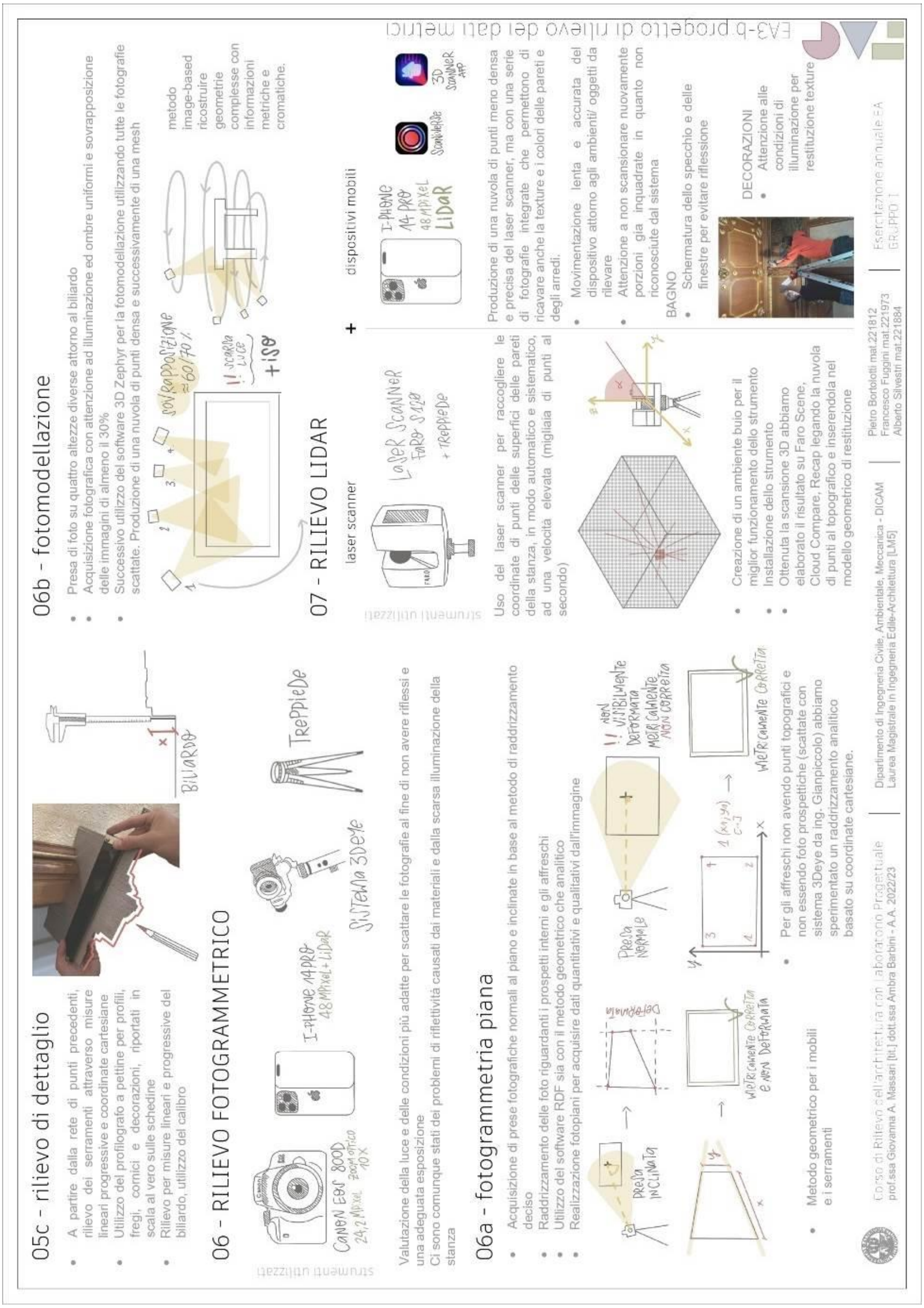
[76] This step is common to all surveys for which the creation of a 3D model via sections is planned.

- a range-based survey, using a TLS eventually completed with an MMS, to produce a dense point cloud of all the accessible spaces;
- an image-based survey, using UAVs or other aerial photogrammetric systems, to produce a dense point cloud also including non-directly accessible spaces (e.g. outdoor higher levels, roofing surfaces);
- a thematic survey analysing materials, construction technologies, conservation conditions and eventual presence of degradations.

Traditional surveying maintains a key role, especially at the scale of detail and material investigation, thanks to the tactile component of its operations. These experiences aim to develop a critical approach to built heritage analysis, considering its peculiarity and complexity, acknowledging the importance of expertise integration and working as a team. Despite this being the first survey experience for most students, the collected data generally have good quality and accuracy, thanks to the redundancy of the acquisition processes and the involvement of teaching staff and experts, who acquire some of the data during demonstrative sessions (topographic, range-based and image-based survey). For example, in the case of the topographic survey, the teaching staff defines a closed polygonal for the station points, places the tripods, defines the settings of the total station and coordinates measurement operations. During these activities, students elaborate station point monographs, select detail points and annotate measured points on sketches or photographs. The sheets used for data acquisition and conservation, completed with bibliographic and iconographic sources that complete the survey, support keeping memory of analysed parts, adopted procedures and involved operators. This approach facilitates the interoperability among operators and integration of data acquired by different groups in a wider database that could be helpful for future analysis of the same building.

Figure 4.12 - Students elaborations of the architectural survey project for one room of Villa Gherta in Povo (next pages).


01 - PROGETTO DI RILIEVO
strumenti utilizzati
MATITA
SCHEDINE
Redazione degli eidotipi della stanza oggetto di studio: schematizzazione di piante, sezioni, serramenti e dettagli nelle schede fornite
Realizzazione di un programma per il rilievo al fine di scandire le varie operazioni e di dividere quelle metriche da quelle tematiche
02 - METODOLOGIE
Rilievo topografico per unire i modelli e georeferenziarli rispetto ad un'unica origine
Rilievo per trilaterazione della pianta alla quota livellata
Rilievo per coordinate cartesiane delle sezioni
Rilievo di dettaglio con strumenti di precisione per serramenti, profili e decorazioni
Rilievo fotogrammetrico per i fotopiani degli affreschi e per la fotomodellazione del biliardo
Rilievo con laser scanner 3D
03 - OPERAZIONI PRELIMINARI
LIVELLO MULTILINEE AUTOLIVELLANTE STANLEY MATRIX XT
SEGNALINI
TREPPIEDE
SCOTCH
Definizione di un piano medio livellato per tutto il piano e di conseguenza per la stanza
Segnalizzazione del piano medio mediante l'uso degli appositi segnalini posizionati sulla modanature in legno
Definizione della poligonale topografica per l'individuazione dei punti da collimare nella stanza per la definizione della base di trilaterazione
Definizione delle sezioni verticali mediante segnalizzazione dei piani delle sezioni mediante scotch su modanature e sui vetri delle aperture
1.62 m
SI LEGNO
NO CARTA DA PARATI
04 - RILIEVO TOPOGRAFICO
STAZIONE TOTALE TOPCON GPT 1001
+ TRICUSPIDI/ PRISMI/TREPPIEDI
Tracciamento della poligonale topografica con individuazione dei vertici
Decisione dei punti da collimare all'interno della stanza
Collimazione di punti a terra e a soffitto
Collimazione di ulteriori punti per il collegamento del rilievo topografico con il rilievo con laser scanner fatto successivamente
Ci siamo messi alla prova livellando la stazione totale per la stazione nei punti 3000 e 4000
05 - RILIEVO LONGIMETRICO
DISTOLASER HILTI ±1mm
CORDELLA METRICA 50m ±1mm
FLESSOMETRO 5m ±1mm
FILO INESTENSIBILE
FILO A PIOMBO
LIVELLA TORICA STABILA 60cm
CALIBRO 200mm ± 0,05mm
PROFILOGRAFO A PETTINE 30cm
05A - trilaterazione delle piante
I02-I07 Base Ordine 0
I11-I15
I15-I16 Basi Ordine 1
I15-I32 Base Ordine 2
I32-I41 Base Ordine 3
I41-45 Base Ordine 4
IB01-IB02 Base Biliardo
Definizione della base dalla trilaterazione agganciata ai punti topografici collimati
Definizione di ulteriori basi per permettere il collegamento delle trilaterazioni del bagno
Misure di trilaterazione in andate e ritorno per tutti i punti con cordella metrica e distolaser (ad eccezione di alcuni che per la loro posizione non lo permettevano)
Trilaterazione di alcuni elementi di dettaglio: nicchia architettonica, nicchie dei serramenti e tavolo del biliardo
05B - coordinate cartesiane per sezioni
Segnalizzazione mediante filo inestensibile delle sezioni precedentemente livellate e riportate a terra con l'ausilio di un filo a piombo
Misurazione per coordinate cartesiane delle altezze con distolaser: dal filo teso verso il soffitto con l'ausilio di una livella torica e dal pavimento al soffitto. Annotazione delle misure nelle apposite tabelle
LIVELLA TORICA
LIVELLA SFERICA
COORDINATE CARTESIANE
1.62 m
90°
y
x
x1
x2
EA3 a progetto di rilievo dei dati metrici
Corso di Rilievo dell'architettura con Laboratorio Progettuale
prof.ssa Giovanna A. Massari [tit.] dott.ssa Ambra Barbini - A.A. 2022/23
Dipartimento di Ingegneria Civile, Ambientale, Meccanica - DICAM
Laurea Magistrale in Ingegneria Edile-Architettura [LM5]
Pietro Bortolotti mat.221812
Francesco Fuggini mat.221973
Alberto Silvestri mat.221884
Esercitazione annuale EA
GRUPPO 1


05c - rilievo di dettaglio
A partire dalla rete di punti precedenti, rilievo dei serramenti attraverso misure lineari progressive e coordinate cartesiane
Utilizzo del profilografo a pettine per profili, fregi, cornici e decorazioni, riportati in scala al vero sulle schedine
Rilievo per misure lineari e progressive del biliardo, utilizzo del calibro
BILIARDO
06 - RILIEVO FOTOGRAMMETRICO
strumenti utilizzati
CANON EOS 800D
24,2 MPixel
ZOOM OTTICO 10X
I-PHONE 14 PRO
48 MPixel + LIDAR
SISTEMA 3DEYE
TREPPIEDE
Valutazione della luce e delle condizioni più adatte per scattare le fotografie al fine di non avere riflessi e una adeguata esposizione
Ci sono comunque stati dei problemi di riflettività causati dai materiali e dalla scarsa illuminazione della stanza
06a - fotogrammetria piana
Acquisizione di prese fotografiche normali al piano e inclinate in base al metodo di raddrizzamento deciso
Raddrizzamento delle foto riguardanti i prospetti interni e gli affreschi
Utilizzo del software RDF sia con il metodo geometrico che analitico
Realizzazione fotopiani per acquisire dati quantitativi e qualitativi dall'immagine
PRESA INCLINATA
DEFORMATA
PRESA NORMALE
!! NON VISIBILMENTE DEFORMATA METRICAMENTE NON CORRETTA
METRICAMENTE CORRETTA E NON DEFORMATA
METRICAMENTE CORRETTA
Metodo geometrico per i mobili e i serramenti
Per gli affreschi non avendo punti topografici e non essendo foto prospettiche (scattate con sistema 3Deye da ing. Gianpiccolo) abbiamo sperimentato un raddrizzamento analitico basato su coordinate cartesiane.
06b - fotomodellazione
Presa di foto su quattro altezze diverse attorno al biliardo
Acquisizione fotografica con attenzione ad illuminazione ed ombre uniformi e sovrapposizione delle immagini di almeno il 30%
Successivo utilizzo del software 3D Zephyr per la fotomodellazione utilizzando tutte le fotografie scattate. Produzione di una nuvola di punti densa e successivamente di una mesh
SOVRAPPOSIZIONE ≈60/70%
!! SCARSA LUCE
+ISO
metodo image-based ricostruire geometrie complesse con informazioni metriche e cromatiche.
07 - RILIEVO LIDAR
laser scanner
+
dispositivi mobili
LASER SCANNER FARO S120
+ TREPPIEDE
I-PHONE 14 PRO 48 MPIXEL LIDAR
SCANIVERSE
3D SCANNER APP
Uso del laser scanner per raccogliere le coordinate di punti delle superfici delle pareti della stanza, in modo automatico e sistematico, ad una velocità elevata (migliaia di punti al secondo)
Creazione di un ambiente buio per il miglior funzionamento dello strumento
Installazione dello strumento
Ottenuta la scansione 3D abbiamo elaborato il risultato su Faro Scene, Cloud Compare, Recap legando la nuvola di punti al topografico e inserendola nel modello geometrico di restituzione
Produzione di una nuvola di punti meno densa e precisa del laser scanner, ma con una serie di fotografie integrate che permettono di ricavare anche la texture e i colori delle pareti e degli arredi.
Movimentazione lenta e accurata del dispositivo attorno agli ambienti/ oggetti da rilevare
Attenzione a non scansionare nuovamente porzioni gia inquadrate in quanto non riconosciute dal sistema
BAGNO
Schermatura dello specchio e delle finestre per evitare riflessione
DECORAZIONI
Attenzione alle condizioni di illuminazione per restituzione texture
EA3-b progetto di rilievo dei dati metrici
Corso di Rilievo dell'architettura con Laboratorio Progettuale
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Esercitazione annuale EA
GRUPPO 1

A similar approach is also extended to research activities aimed at achieving high metric accuracy or at optimising time and costs, taking the maximum advantages from 3D digital survey techniques and limiting traditional surveys to all the necessary measurements for specific integrations or validations. For all the architectural survey experiences, the connection between the topographic survey and the other acquisition techniques guarantees a unified and shared referencing of data, making it possible for them to be compared or mutually integrated, depending on the needs and purposes of the survey.

Given the limitations of different tools, such as the reliability range and accuracy of different laser scanning devices, it is often necessary to integrate different range and image-based survey techniques to collect accurate and complete geometric and metric data on the object of investigation. For example, UAV aerial photogrammetry successfully integrates TLS data for the survey of roofing surfaces and the 3D eye system, based on a camera mounted on a telescopic pole and controlled remotely through mobile devices, results particularly strategic in all the cases when regulations forbid the use of UAVs.

Considering acquisition experiences oriented to the optimisation of time and budget, not requiring the highest metric and geometric accuracy there are at least three alternative approaches:

- the use of professional tools, such as MMS or aerial photogrammetric systems, that generally have a lower price compared to a TLS and require shorter acquisition time;
- the adoption of non-professional tools, such as the LiDAR sensor of the iPad Pro for point cloud acquisition or a digital photo camera for plane photogrammetry applications, requiring a lower budget, but reaching a lower level of accuracy;
- the high reliability of project drawings or previous surveys, possibly validated with some on-site measurements, for all the cases when accuracy is not a requirement.

In general, the analysed acquisition experiences highlight the importance of clarifying the purpose of the survey in terms of levels of detail, grade of accuracy, expected processing and modelling operations, as well as uses and users of the model. Another crucial aspect of a successful acquisition phase is the awareness of the specificities of the object, including visibility and accessibility conditions, safety and comfort, and other boundary conditions that can arise during the site inspection and the survey planning phases. All this information contributes to the selection of the most appropriate techniques and tools, the involvement of all the necessary experts and operators and the preparation of all the necessary equipment. To summarise, the peculiarities of the object and the purpose of the survey strongly influence methodological and technical choices for the acquisition phase.

Beyond all the necessary measurements, during the acquisition phase it is crucial to acquire:

- redundant data to validate and compare different acquisition techniques;
- meta data, such as sketches and photos documenting the survey campaign, to keep memory of the entire acquisition phase and support operators who did not take part in the acquisition phase to work autonomously on the processing or modelling phase, as well as to make the collected data usable in the future;
- indirect data, such as archival documents, bibliography and historical iconography or oral testimonies, to support the interpretation of the building during data processing and model development.

Moreover, indirect data are crucial in all the cases when the acquisition phase not always require extensive survey campaign, for example when geometric accuracy is not a requirement. In these cases, it is possible to relay on project drawings or previous survey data, limiting the on-site operations to photographic documentations and sample measurements.

4.2 Processing phase

At the end of an architectural or urban survey campaign, a set of heterogeneous raw data is available and needs to be transformed to exploit it for the development of a geometric model. The processing phase concerns the transformation of raw data into an integrable data set, understood as a structured archive of processed data, open to further processing and investigation and that allows comparison and integration. To obtain an integrable data set, it is necessary that data collected in different shapes and formats, such as distance measurements, pictures or coordinates of points in space, are transformed into comparable, coherent and consistent shapes and formats, enabling, overlap, comparison and integration of different survey methods. This phase is extremely crucial in preserving the level of accuracy obtained during the acquisition phase and can involve different workflows, from simple digitization processes to complex calculations requiring adequate hardware and software equipment. These workflows are often not equivalent in terms of time and cost. On one hand, traditional methods, especially traditional direct surveys and topography, are more selective during the acquisition phase and this facilitates a seamless and time-effective processing phase. On the other hand, digital 3D survey methods involve a massive data acquisition, requiring longer time during the processing phase both for the exclusion of unnecessary data and for the critical interpretation of the collected data. Notwithstanding the peculiarities of each acquisition technique, the processing phase can be driven by various priorities, such as accuracy maximisation, time efficiency or cost limitation. For most of the case studies considered in this research, accuracy played a crucial role. However, some low-cost and expeditious workflows have also been tested to assume the point of view of heritage actors, who may need more accessible alternatives. Especially in the case of a 3D digital survey, there are very specific software solutions, often sold in a package together with the acquisition system, that can require a significant investment in terms maintenance cost for the software licence or its updates, as well as the availability of adequate hardware and trained operators. University laboratories are often equipped with high-performance workstations and many times software licences are available for free or more affordable for research and educational activities, but this is not the case for many small and medium enterprises or non-professional users. To reduce the gaps between academia and general users, for each acquisition technique has been reported at least a FOSS (Free and Open Source Software) solution (Table 4.3).

Methods	Input data	Output data	Proprietary software	FOSS alternative
Traditional direct survey	Distances	Point on a plane	Autodesk AutoCAD	LibreCAD
Topography	Angles and distances	Point in space	GEOPRO Meridiana	Total Open Station
Geometric plane photogrammetry	Single photo	Photo-plane	Acca Fotus, Meridiana Office PhotoMetric, Adobe Photoshop	RDF, Hugin, Gimp
Analytical plane photogrammetry			Meridiana Office PhotoMetric	RDF
Laser scanning	Set of scans	Point cloud	Faro Scene/Leica Cyclon, Autodesk Recap	Cloud Compare
Photo-modelling	Set of photos	Point cloud	Agisoft Metashape, 3Dflow 3DF Zephyr	ARC3D, MeshLab, AliceVision Meshroom,

Table 4.3 - Input and output data of different survey methods associated to FOSS and proprietary software that can support the processing phase.

The high performances of proprietary software may not always be necessary and cost limitation could be extremely valuable for approaching new workflows and enhancing interoperability and collaborations among professionals. For this reason, despite often using proprietary software during the processing phase, some of the workflow also included free or low-cost solutions.

Despite survey data processing is not the primary focus of this research, this chapter reports some of the workflow tested and adopted for the case studies previously presented, as necessary intermediate step between the acquisition and the modelling phase.

4.2.1 Traditional survey data

In some cases, the adoption of low-cost procedures is particularly easy and does not necessarily result in a loss of accuracy of the acquired data or significant differences in processing time.
Traditional direct survey can be extremely accessible for users with lower budget given the possibility to use low-cost tools and applications during both the acquisition and processing phase. After calculating the arithmetic mean of the repeated measurements and excluding the less reliable values, it is possible to proceed with the graphic restitution of the acquired data. The distance measures acquired through traditional direct survey can be easily processed in paper or digital format. In the first case all that is required is paper, pencil, compass and ruler. In the second case any CAD (Computer Aided Design) software can support in defining the reciprocal position of points on a plane.
Photogrammetry investigates the relationship between reality and its representation in central projections exploiting geometric principles and determines the dimension and shape of objects analysing images registered on a film or electronic support (Paris, 2014, p. 32). In the case of plane photogrammetry there are expeditious and rigorous methods. For expeditious methods it is crucial to distinguish between photos taken with the optical axis of the camera orthogonal to the mid-plane of the object, and photos taken with the optical axis at various angles to the object. In the first case, it is possible to proceed by scaling from a known measurement, using any CAD software. In the second case, it is possible to identify the vanishing points both manually, through a graphic procedure, or digitally, using a dedicated software[77]. This software, including a package for the geometric rectification, require indicating horizontal and vertical lines on the picture to identify the vanishing points of the perspective and a horizontal and vertical measure to correctly scale the rectified picture. In both cases, after the calibration of the photographic camera and the correction of the optical distortions it is possible to associate sample measurements with the photograph.

[77] E.g.: Acca Fotus (link), Meridiana Office PhotoMetric (link)

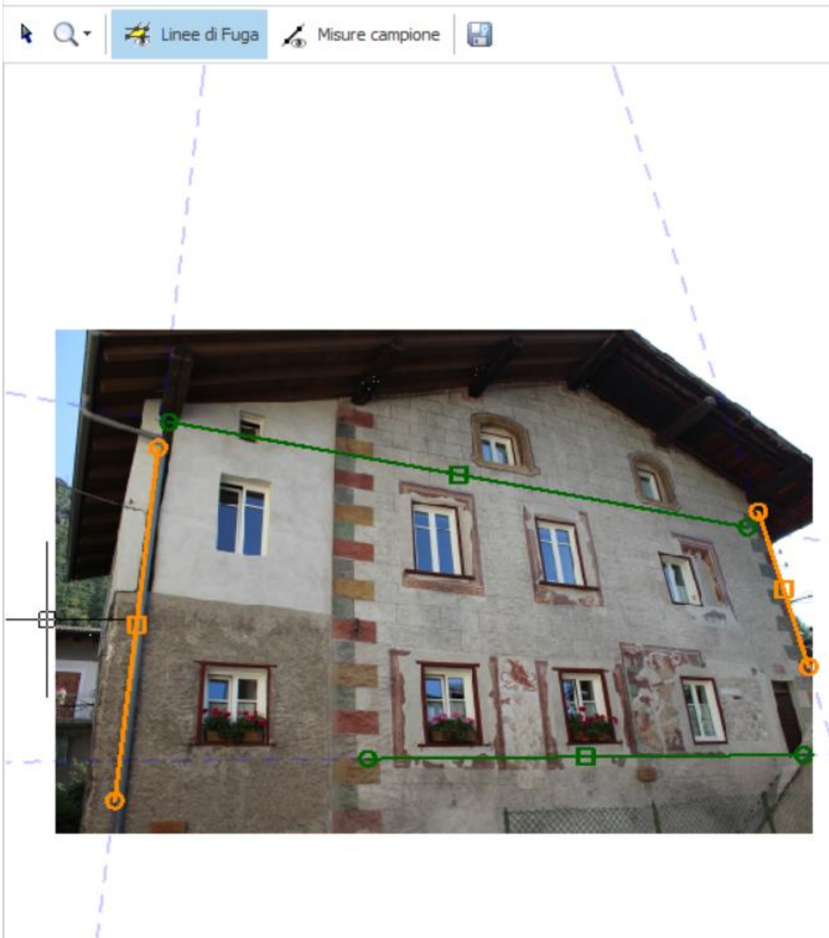


Figure 4.13 - Example of a software for picture rectification (Acca Fotus).

In the case of rigorous methods, the photographic image is straightened through the recognition of homologous points, by matching image-points to points whose coordinates are known. In this case a strong perspective system is not required, but it is necessary to know the XY coordinate on the mid-plane of the object of at least four points. These points need to be easy to identify on the picture and well-distributed on the perimeter of the surface to rectify. A dedicated software[78], including a package for the analytical rectification, recomputes the position of each pixel according to matched homologous points. Some of the software, including both geometric and analytical rectification packages, require indicating

[78] E.g.: Meridiana Office PhotoMetric (link), RDF (link)

the pixel resampling value, expressing the metric content of each pixel and therefore the metric reliability of the rectified picture. Moreover, the metric accuracy of the rectified and/or scaled image can be assessed through redundant measurements belonging to the same object plane of the photograph.

Topographic data require a dedicated software[79] to transform the measured polar coordinates into 3D cartesian coordinates, which can be exported both in a graphic format accessible with CAD software and in a tabular format accessible with a word processing software. For both formats it is possible to distinguish polygonal and detail points, and each point is associated to the name registered during the acquisition phase and generally reported on detail hand-drawings and/or on photographs. In the case of points acquired from multiple A further processing of the topographic data in the CAD format that may be helpful during the modelling phase is the organization of points into different layers, that can assume different colours or switched on and off for easier visibility.

4.2.2 3D digital survey data

The processing phase is particularly crucial for image and range-based data, which can follow different digital workflows, always based on the use of one or more dedicated software.

Photo-modelling is a digital technology, that, starting from raster images, enables the creation of a 3D point clouds (Filippucci, 2010). The input data is a set of photographs, and the algorithms embedded in the software leads to the creation of a numeric model, that generally presents more accurate colour data compared to laser scanners. In fact, while laser scanners are generally equipped with a lower resolution camera, photo-modelling processes are based on set of high-resolution photos. To correctly scale the model, that does not contain metric data but only the 3D coordinates, it is necessary to refer the point cloud to highly accurate measurements, generally acquired through total station or GPS.

The photo-modelling process is based on algorithms able to identify the internal orientation of the camera (Structure from Motion – SfM), the

[79] E.g.: GEOPRO Meridiana (link),

relative and absolute external orientation of the pictures (collinearity equations) and to produce a dense cloud (Multi View Stereo – MVS).
The digital procedure to obtain a point cloud requires to identify homologous points, intended as natural (e.g. the corner of a window-frame) or artificial (e.g. a target) points visible in different pictures. To obtain a scaled point cloud it is necessary to associate 3D coordinates to at least 3 Ground Control Points (GCPs). According to the complexity of the object to model, GCPs are generally more than 3 and well distributed both on the borders and in the middle of the photographed object. The first output is a sparse point cloud that can be further processed into a dense point cloud. From the dense point cloud, it is possible to obtain orthophotos of the object, representing 2D surface of the building. Moreover, most of the software in use for photo-modelling support the creation of a mesh model from the dense point cloud.
While a dynamic laser scanner directly produces a point cloud, the outputs of TLS are available in the form of separate scans that combined with each other return a point cloud. Each scan is correctly scaled but does not share the same reference system with the others, for this reason they need to be registered and aligned to obtain the complete point cloud of the surveyed object (Vosselman, 2010). To align the scans, it is necessary to match equivalent point in different scans. Most of the software for the scans' alignment include both automatic and manual alignment options. Manual alignment often includes the possibility to refer the point cloud to a topographic survey, associating the 3D coordinates of GPS or total station points with each scan. Most software for laser scanning data management also enables filtering and cleaning processes, adjusting the density of points in each scan and removing unnecessary data. FOSS alternatives for point cloud management can support all these processes, even though the purchase of both dynamic and terrestrial laser scanners often include proprietary software for data processing and management.

4.2.3 Processing experiences

For all the processing experiences a preliminary crucial step has been the systematic and structured organization of all the collected data. This involved the creation of digital folders for the processing operations, kept separately from the raw data to keep trace of the entire workflow.

Different procedures for the processing of survey data have been analysed, considering directly developed case studies, research activities in collaboration with other colleagues or supporting students in their master thesis or during educational activities. For most of the case studies this phase has been exploited to test and compare different procedures.

Piazza Bellesini

Raw data	Processing software	Processed data
Topographic data (Topography)	GEOPRO Meridiana Office 2011	Scattered point in .dwg format.
Trilateration and cartesian coordinates (Traditional direct survey)	AutoCAD 2020	Point on single planes in .dwg format integrated with topographic data
Single pictures (Photogrammetry)	RDF geometric and analytic method	Rectified pictures in .jpg integrated with topographic data
Set of pictures (Image-based survey)	Photomodelling and scaling with Agisoft Metashape Cleaning with Recap PRO	Dense point cloud in .rcp format
TLS scans (Range-based survey)	Registration with Faro Scene Cleaning with Recap PRO	Point cloud in .rcp format

Comparing the two point clouds with the topographic survey in CloudCompare it was possible to notice that the point cloud from image-based survey has a lower level of accuracy compared to the point cloud from TLS but a better visual aspect. Data from laser scanners have a much lower colour quality and are much more affected by differences in illumination (Figg. 4.14-15). The processed data set has been integrated first in Autodesk AutoCAD (Fig. 4.16) and then in Autodesk Revit.

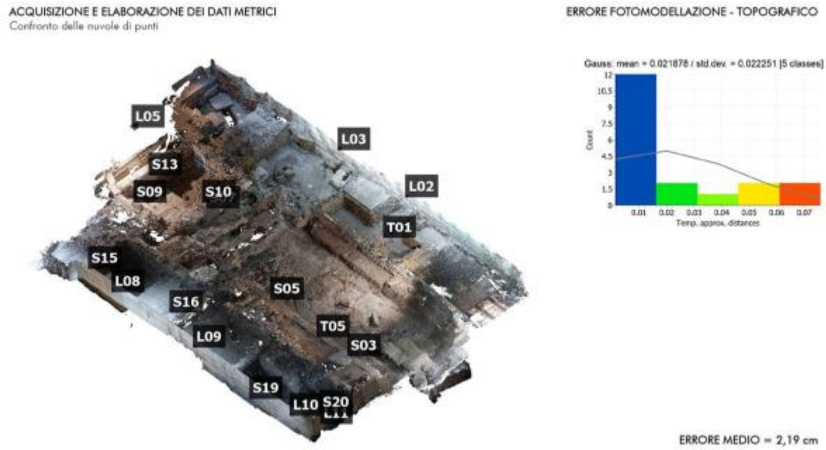


Figure 4.14 - Image-based and topographic data comparison (Scoz, 2021).

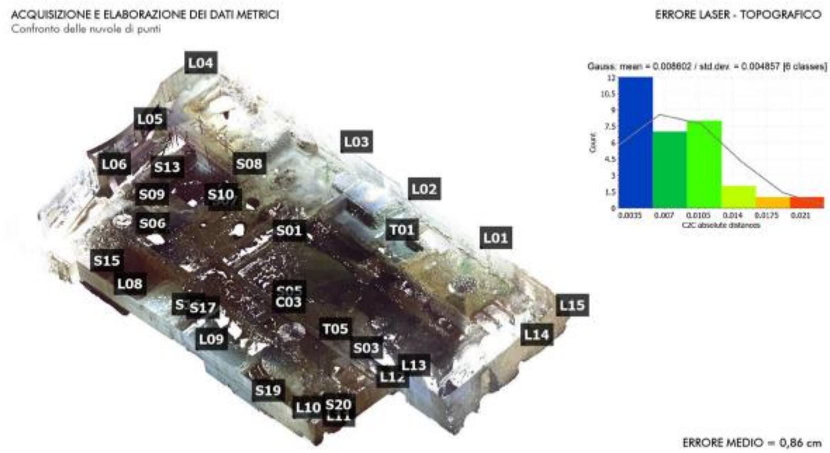


Figure 4.15 - Range-based and topographic data comparison (Scoz, 2021).

Figure 4.16 - Integration of the various point cloud in AutoCAD (Scoz, 2021).

Villa Penner

Raw data	Processing software	Processed data
Topographic data	GEOPRO Meridiana Office 2011	Scattered point in .dwg format.
Trilateration and cartesian coordinates (Traditional survey)	AutoCAD 2020*	Point on single planes in .dwg format integrated with topographic data
Single pictures (Photogrammetry)	RDF geometric and analytic method*	Rectified pictures in .jpg integrated with topographic data
Set of pictures (Image-based survey)	Photomodelling and scaling with Agisoft Metashape Cleaning with Recap PRO	Dense point cloud in .rcp format
TLS scans (Range-based survey)	Registration and cleaning with Recap PRO (automatic process)	Point cloud in .rcp format
Scans from iPad PRO	Cleaning with Recap PRO	Point cloud in .rcp format
* Educational activities of the Architectural Survey course (A.Y. 2020-21)		

After overlapping and aligning the point clouds obtained from different acquisition tools based on control point of known coordinates, the metric reliability of the dense point cloud from image-based survey (most of the external walls) and of the point cloud acquired with the LIDAR sensor of the iPad PRO (a small portion of the external wall) has been evaluated by comparing both of them with the point cloud from TLS. Despite the dimensions of the two point clouds are not comparable, the distance between these two point clouds and the TLS point cloud is in the order of a couple of centimetres (Fig. 4.17). While this result is quite good for the iPad PRO scans, the point cloud from image-based survey is generally expected to have a lower distance from the TLS point cloud (Fig. 4.18). Such a high distance between these two point clouds is probably influenced by different window settings (open/closed) during acquisition with the two techniques that took place in different days.

Topographic, photo-plane and traditional direct survey data have been processed by small groups of students and then integrated in a single CAD environment (Fig. 4.19).

Figure 4.17 - TLS and image-based point cloud comparison (Gaspari, 2021).

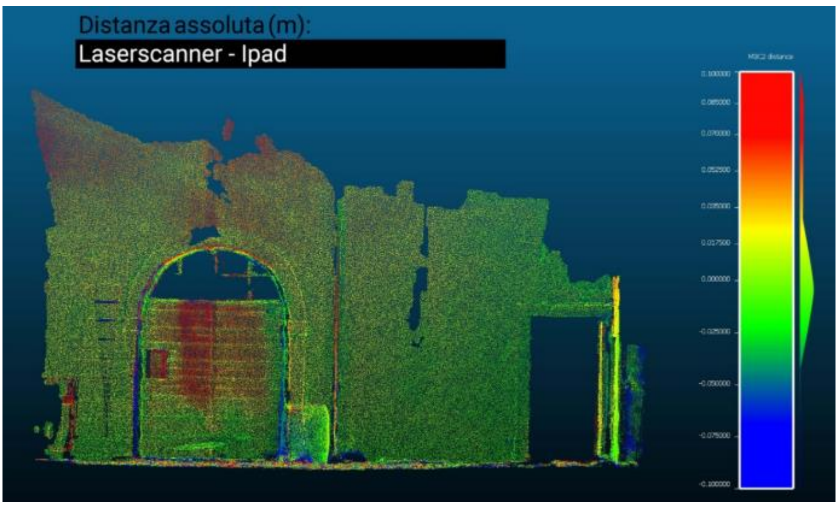


Figure 4.18 - TLS and iPad PRO point cloud comparison (Gaspari, 2021).

Figure 4.19 - Integration of students processed data (Gaspari, 2021).

Casa Tinol

Raw data	Processing software	Processed data
Topographic data	Geopro Meridiana Office 2011	Scattered point in .dwg format.
Trilateration and cartesian coordinates (Traditional survey)	AutoCAD 2020	Point on single planes in .dwg format integrated with topographic data
Single pictures (Photogrammetry)	RDF geometric and analytic method	Rectified picture in .jpg integrated with topographic data
TLS scans (Range-based survey)	Registration and cleaning with Recap PRO	Point cloud in .rcp format

The CAD file containing the processed topographic survey data, has been analysed to check and calculate the average position of points measured from different stations. Then points have been organised into layers distinguishing among: points belonging to the levelled plane and to the internal or external walls (Fig. 4.20).

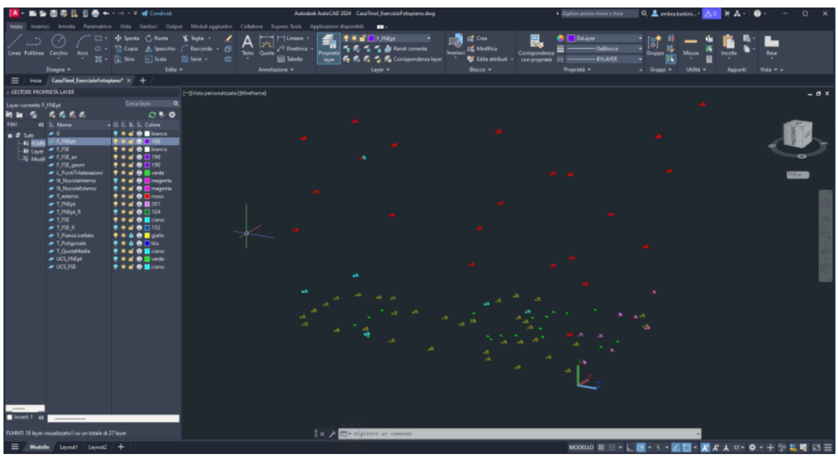


Figure 4.20 - Organization of topographic data in different layers.

Plane photogrammetry has been directly tested for the photographic documentation, acquired multiple times during the restoration works. Most of the pictures have been taken with the optical axis of the camera orthogonal to the mid-plane of the object and could just be scaled through a reference measure. However, since a topographic survey has also been performed, for some of the façades, the results of expeditious and rigorous method have been compared. The stone façade on the North-East of the building resulted particularly interesting from this point of view. On this portion of façade have been placed 8 targets randomly distributed on the stones, whose 3D coordinates are known thanks to the topographic survey. As first attempt, the distance between two yellow points at the extreme sides of the wall was chosen as reference measure to scale the picture, but none of the other topographic points in red matched the targets in the photo (Fig. 4.21).

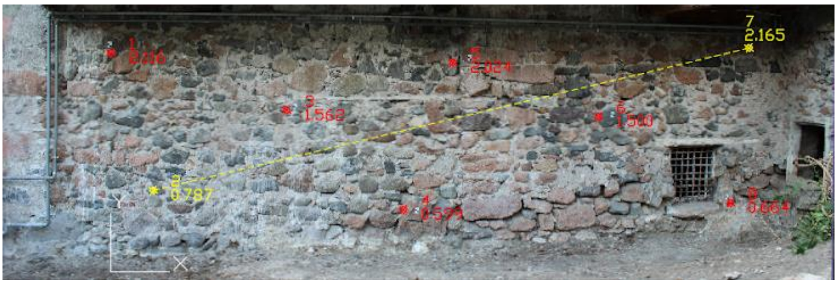


Figure 4.21 - Picture scaled according to the expeditious procedure using as reference measurement the distance between points 2 and 7.

This result can be attributed to the vertical discontinuities that can be noticed between targets 4 and 5. Therefore, assuming that the external surface of wall belongs to two different planes and that the picture has been taken with the sensor parallel to the left portion of the wall, a second attempt of scaling has been made. In this case has been assumed as reference measure the distance between two yellow points at the extreme sides of the left portion of the wall (Fig. 4.22). In the scaled image it is possible to notice how the other points in green in the left portion of the wall match the target, as well as the closer point 5 (Fig. 4.22). Instead, most of the points of the right side of the wall don't match the target and the farer are the points from the left side of the wall the higher is the error.

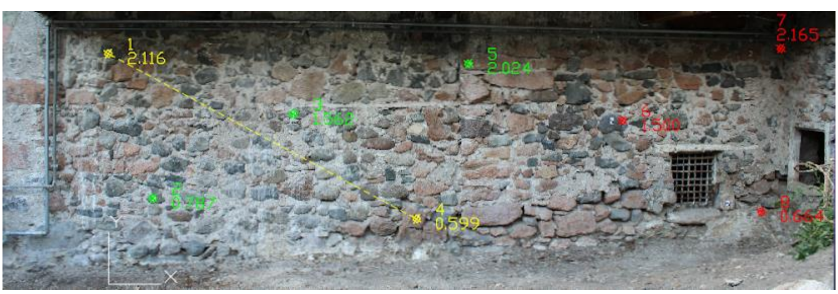


Figure 4.22 - Picture scaled according to the expeditious procedure using as reference measurement the distance between points 1 and 4.

These expeditious procedures have been compared with the output of rigorous method using the free educational software RDF and using the coordinates of all the target points to perform an analytical rectification process. In this case all the topographic points match the target on the rectified picture, overcoming the perspective deformation of the right side of the wall (Fig. 4.23).

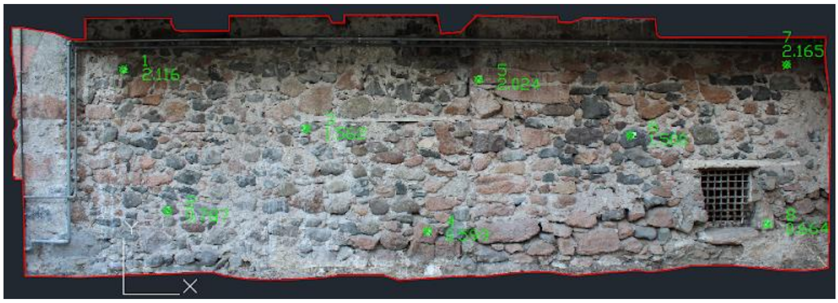


Figure 4.23 - Picture scaled according to the rigorous procedure with the RDF software (analytical method).

The fact that the walls belong to two different planes confirms the hypothesis that the building was constructed in different phases. Indeed, it is assumed that a second room was attached to an initial core, corresponding to the area on the right side. In this case the result of the analytical method was compatible with the purpose of the processing phase, but to obtain a higher level of accuracy it would be possible to define two mid-planes and process separately the two portions of the wall and join them after the rectification and/scaling process in a photo-mosaic.

After testing and comparing two registration and alignment procedures with CloudCompare (FOSS), the 16 scans have been processed using the automatic option of Recap PRO, that resulted the most time effective and reliable option. Indeed, the manual scans registration and alignment with CloudCompare (FOSS), tested only for a small portion of the building, permits the registration of the single scans with the topographic survey, but results extremely time consuming. The automatic scans fine alignment with CloudCompare (FOSS), is possible only for scans with large overlapping areas and this was not the case for most scans. Moreover, importing Faro scans directly in CloudCompare causes the loss of the RGB value associated to each point.

Palazzo Pretorio

Raw data	Processing software	Processed data
Topographic data	GEOPRO Meridiana Office 2011	Scattered point in .dwg format.
Trilateration and cartesian coordinates (Traditional survey)	AutoCAD 2020*	Point on single planes in .dwg format integrated with topographic data
Single pictures (Photogrammetry)	RDF geometric and analytic method*	Rectified pictures in .jpg integrated with topographic data
Set of pictures (Image-based survey)	Photomodelling and scaling with Agisoft Metashape Cleaning with Recap PRO	Dense point cloud in .rcp format
TLS scans (Range-based survey)	Orientation with Faro Scene Cleaning with CloudCompare Conversion in Autodesk compatible format with Recap PRO	Set of scans in .rcp format
Scans from iPad PRO	Cleaning with Recap PRO	Point cloud in .rcp format
* Educational activities of the Architectural Survey course (A.Y. 2021-22)		

Given the large overlapping of most TLS scans the automatic fine alignment with CloudCompare (FOSS) was successfully tested (Fig. 4.24). This alignment option requires two main steps:

1. manual gross alignment of two scans using the "Translate/Rotate" command,
2. automatic alignment of the two scans using the "Finely registers already (roughly) aligned entities (clouds or meshes)".

This test confirms the possibility to effectively use a FOSS alternative for the alignment of TLS scans, but as anticipated this option causes the loss of the RGB data. The workflow adopted for TLS data processing includes three main steps (Fig. 4.25):

1. Registration: association of each scan to topographic data to have a common reference system among all scans using Faro Scene, the proprietary software associated to the Faro TLS, fa-

cilitating the selection of the topographic point within the scans through the visualisation of an immersive panoramic picture;

2. Cleaning: removal of areas of the scan that are unreliable because they are too far away from the instrument or produced by reflective surfaces with CloudCompare;
3. Integration: use of Autodesk RecapPRO to convert of each scan in .rcp file format, compatible with AutoCAD and Revit, where all scan are integrated and automatically aligned thanks to the association to topographic data in the first step.

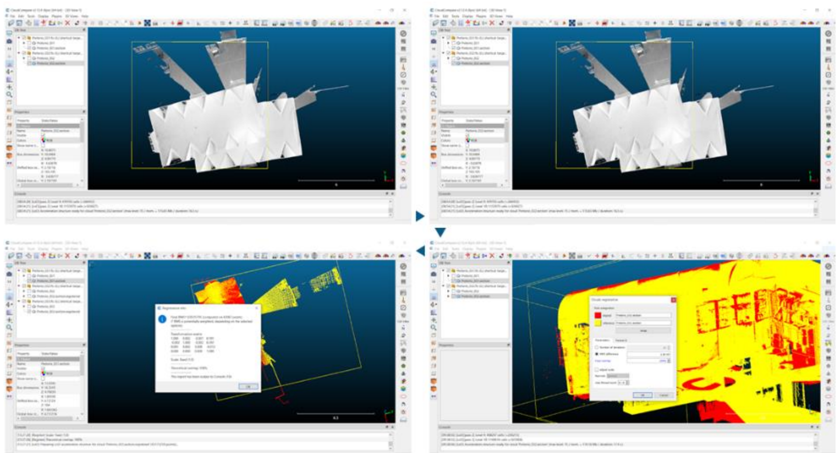


Figure 4.24 - Scans alignment process based on CloudCompare.

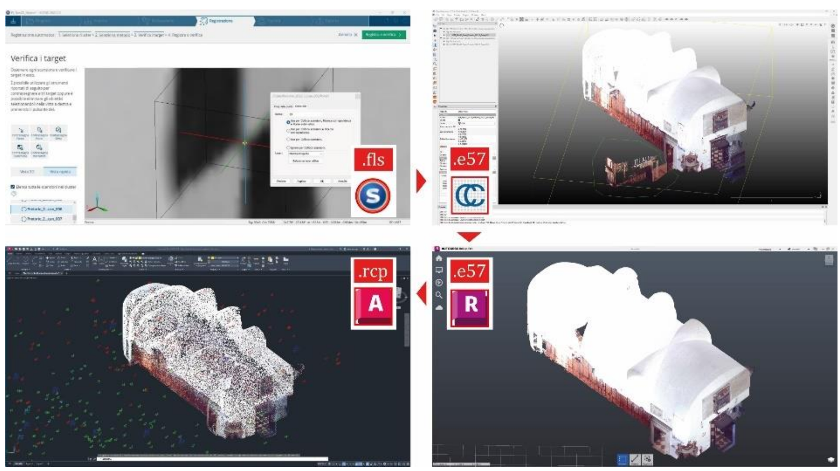


Figure 4.25 - Workflow adopted for TLS data processing. Image from Barbini, A. Giampiccolo, F., Maragno, A., Massari, G.A., Pellegatta, C. (2024). Innovation and tradition: integrated practices in the architectural survey of Pretorio Palace in Trento. SCIRES-IT, 2024(1), 45-62.

4.3 Modelling phase

Once built heritage data are collected and processed it is possible to transform the integrable dataset into an informative model. The output of these phase is information, intended as the result of an interpretative and knowledge process, available as documentation of a given analysis and for communication among specialists and/or with generic audience, according to different representation forms.

The main challenges of heritage modelling concern:

- the management of the huge amount of available data, especially in the case of a digital 3D survey, the processing of which is often time consuming and requires the interpretation of an expert for the development of a functional virtual model (Volk et al., 2014);
- the collaboration of many experts on the same project leading to interoperability issues, including different aspects, such as the employed technologies, the workflows adopted by different organizations, the coordination among professionals and the introduction of a common normative framework (Chioni et al., 2021).

Capable of evoking the shape and more than just the formal qualities of an object, models support in understanding what is represented through the measurement of dimensions (Migliari, 2003, p. 17). Moreover, they can assume different shapes and include different types of contents, ranging from pure geometry to geometric-informative models, up to informative visual models independent from a 3D structure.

Geometric models are often used to understand spaces from a technical point of view, to simulate given building features and its effect on the surrounding (Migliari, 2003, p. 14). Furthermore, they can be used as a frame to enrich with information associated to fundamental geometric entities, such as points, lines, surfaces or volumes. Traditional digital modelling tools, such as 2D and 3D CAD, and solid modellers, can achieve a high degree of detail and accuracy in the representation of geometric features, but only a partial and loosely structured integration of information, defined from time to time, e.g. using layers, patterns or colours. Building Information Modelling (BIM) often involves greater approximations in geometric modelling but enables the structured association of very large and heterogeneous information sets with geometric elements that are functionally, semantically and topologically defined with respect to a specific construction project. Both geometric and informative attributes can have different levels of specificity, completeness and detail, ranging from symbolic and indicative to very specific contents. According to UNI 11337-4:2017 the combination of geometric and informative attributes, defines the Level of Development (LoD) of a model and/or its components. The LoD is related to the purpose and use of the model and often refers to different phases of a building life cycle from conceptualisation to design, to construction, to maintenance. The UNI 11337-4:2017 includes seven levels of LoD, using letters from A to G, while the UK system use numbers from 1-7 and the USA system has six levels as displayed in Table 4.4.

LoD USA	LoD UK	LoD Ita
	LOD 1 - Preparation and Brief	**LOD A** - oggetto **SIMBOLICO**
LOD 100 - Concept	**LOD 2** - Concept	**LOD B** - oggetto **GENERICO**
LOD 200 - Design Development	**LOD 3** - Developed Design	**LOD C** - oggetto **DEFINITO**
LOD 300 - Documentation	**LOD 4** - Technical Design	**LOD D** - oggetto **DETTAGLIATO**
LOD 350 - Construction	**LOD 5** - Construction	**LOD E** - oggetto **SPECIFICO**
LOD 400 - Construction	**LOD 6** - Handover	**LOD F** - oggetto **ESEGUITO**
LOD 500 - Facilities	**LOD 7** - Mantainance	**LOD G** - oggetto **AGGIORNATO**

Table 4.4 - Comparison of different systems for the measurement of the level of development.

A set of information can also be visually communicated without a 3D geometric model, e.g. through tables, graphs, diagrams, or by spatially referencing various forms of informative contents, such as captions, written notes, images, audio, video and more, on bidimensional visual media, such as maps, elevation drawings, plane or panoramic[80] photograph.
According to the application it could be more convenient to have a high geometric accuracy and visual fidelity or to privilege semantic richness and parametric flexibility (Radanovic, 2020). Generally, the highest visual fidelity is expected in organizing and integrating into a model a set of data collected through an accurate and meticulous architectural survey. As previously discussed (Chapter 4.1), architectural survey returns measured and measurable data in a given time frame, observing, analysing and interpreting the visible aspects of reality. However, in some cases, it is also possible to reach a high visual fidelity beyond some of the most

[80] Some fruition forms of spherical or cylindrical panoramic photographs can give the illusion of being inside a three-dimensional space, even though they are two-dimensional elements.

common features of an architectural survey. Indeed, especially some photographic applications can be strategic in reaching a high visual fidelity beyond dimension, time and human eye.

Figure 4.26 - Panoramic images used for a virtual tour. Grotta Buontalenti at the Uffizi, available at: https://www.uffizi.it/mostre-virtuali/grotta-buontalenti Last access: 15.10.2024

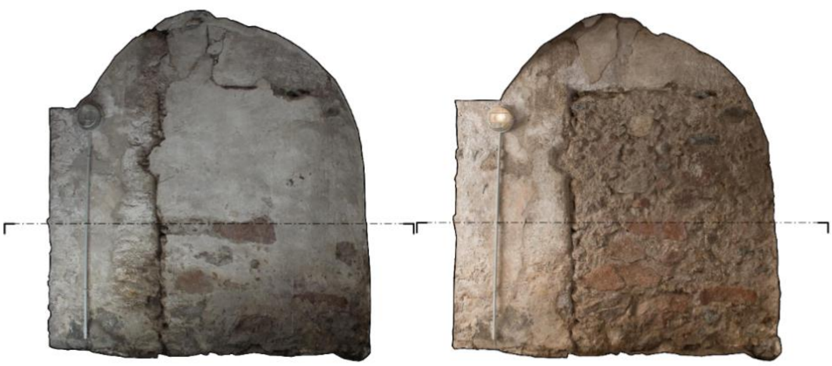


Figure 4.27 - Comparison of two photo planes of the same wall, captured at the beginning (07.09.2021) and during (07.02.2022) the restoration works at Casa Tinol in Predazzo. Pictures and elaborations by LAMARC.

Cylindrical and especially spherical panoramic pictures are a perfect example of such a high visual fidelity that can give the illusion of a 3D space, despite being a 2D object, lacking any measured or measurable content (Fig. 4.26). An architectural survey generally captures a snapshot of the building with an appearance, configuration, degradation level associated with a given time laps. By combining multiple photographic documentation of the same object at different time, it is possible to reach a good visual fidelity representing the object beyond a single time frame (Fig. 4.27). In a similar way exploiting gigapixel photography, it is possible to reach such a high visual fidelity, that not even human eye would be able to catch some of the captured details (Fig. 4.28).

Whilst acknowledging the communicative potential of purely informative models, this chapter focuses on models with a geometric basis. Indeed, the models considered in this section are both descriptive and predictive, transforming the collected data on the built heritage into a recognisable shape, with the aim to support the communication of specific information on a building and the elaboration of data for further analysis and investigations (Bertoline, 2016, p. 71). First the different types of 3D geometric models are investigated, and then the focus is on Heritage Building Information Models and the analysis of different strategies for their creation and development, both from historical archival sources and from a 3D digital survey. Having then identified some limitations in the creation of irregular and complex geometries in the BIM environment, two solutions are proposed that can be exported and extended to similar case studies.

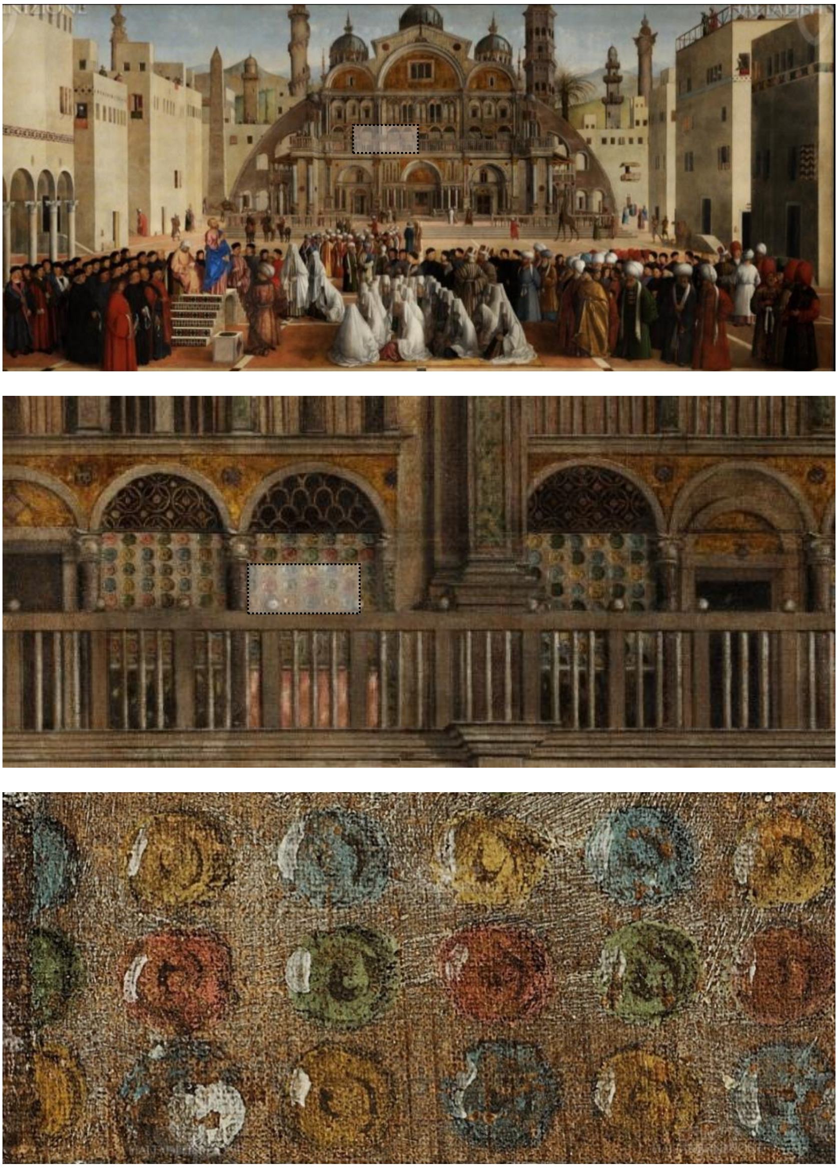


Figure 4.28 - Example of 3 levels of zoom obtained through Gigapixel photography showing the Predica di san Marco ad Alessandria d'Egitto (1504 – 1507) Olio su tela di Gentile Bellini e Giovanni Bellini (347 x 770 cm), Pinacoteca di Brera – Milano, Images from: Haltadefinizione

4.3.1 3D geometric models

As physical models, 3D digital models can represent an object with different possible purposes, such as:

1. description and visualization, that in the case of heritage building can anticipate transformations, offer unusual or inaccessible points of view and reconstruct space never realized or not accessible due to transformation or loss (Massari, 2012);
2. production of traditional 2D drawings for project documentation (Fasolo, 1991);
3. transfer of geometric data to automatised production systems, such as 3D printers or CNC cutting machines (Barbini, 2022).

To graphically describe a building, it is necessary to rely on geometric primitive entities, such as points, lines, surface and solids (Bertoline, 2016, p. 109). It is possible to distinguish between discrete and continuous models. Discrete models are based on points or lines and continuous models are based on surface or solids. Bidimensional geometric primitives, such as points, lines, circles and arcs, can be combined and used to create complex and 3D shapes (Bertoline, 2016, p. 109).

Starting from an architectural survey, point based models require the lowest modelling effort. Indeed, the first output of most survey techniques is a set of points on a plane, in the case of traditional direct survey, in the 3D space with a low density, in the case of topographic survey or with a high density, in the case of digital 3D survey. All these outputs can be considered as point based models and have a higher visual fidelity (Fig. 4.29), the higher the density of the point cloud. The geometric accuracy of these models can be extremely high and is directly related to the acquisition and processing phase. On the other hand, the information richness of these model is generally quite low, unless exploiting the semantic segmentation of the point cloud to associate information to each segment of the point cloud. Moreover, these kinds of models do not enable any detail richness, indeed even point clouds with the highest density rapidly loose resolution from a closer observation and make it difficult to distinguish the shapes of individual components, unless connecting points belonging to the same edge, plane, surface or object through line, surface or solid based models.

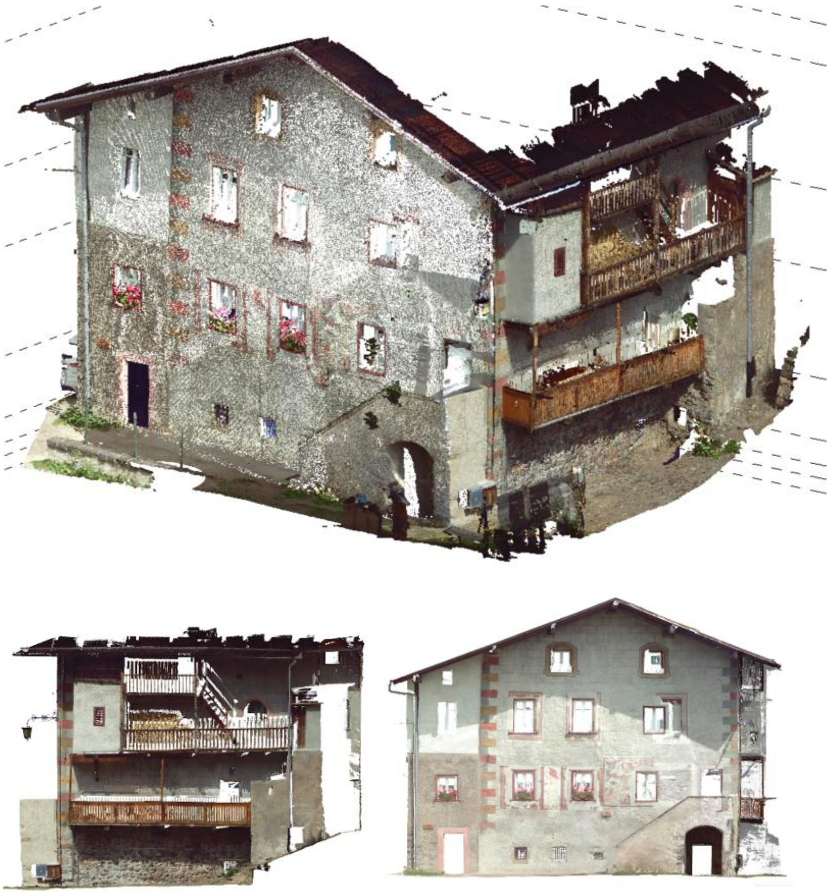


Figure 4.29 - Point cloud model of Casa Tinol in Predazzo. Elaborations by LA-MARC.

By connecting the points belonging to the same edges it is possible to obtain a wireframe model. Despite being complex to develop[81], a wireframe model can reach a good geometric accuracy and detail richness, but generally has a lower visual fidelity and it is hardly integrable with non-graphical information. Wireframe models require the observer to identify volume consistency and other shape-related properties from simple contour lines (Empler, 2006, p. 32). Moreover, they require the adoption of some visual tricks to guarantee the correct perception of the model (e.g. linear edges of a cylinder), but some of them may cause

[81] For example, a wireframe model can be directly obtained from a point cloud only for building with simple and regular shapes, while for more complex shapes it is necessary to extract the edges from a surface or solid base model.

ambiguity and imprecision (e.g. Necker cube), for example due to the removal of hidden edges (Bertoline, 2006, p. 139).
By connecting the points belonging to the same horizontal or vertical plane it is possible to develop a 3D model via sections (Fig. 4.30)., obtained through the redrawing of profiles extracted from a point cloud and completed with the projections of visible parts in front of (thin lines) and behind (dotted lines) the section plane (Fig. 4.31).

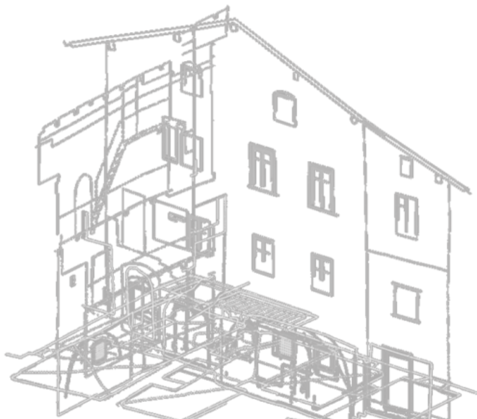


Figure 4.30 - 3D model via sections of Casa Tinol in Predazzo. Elaborations by LAMARC.

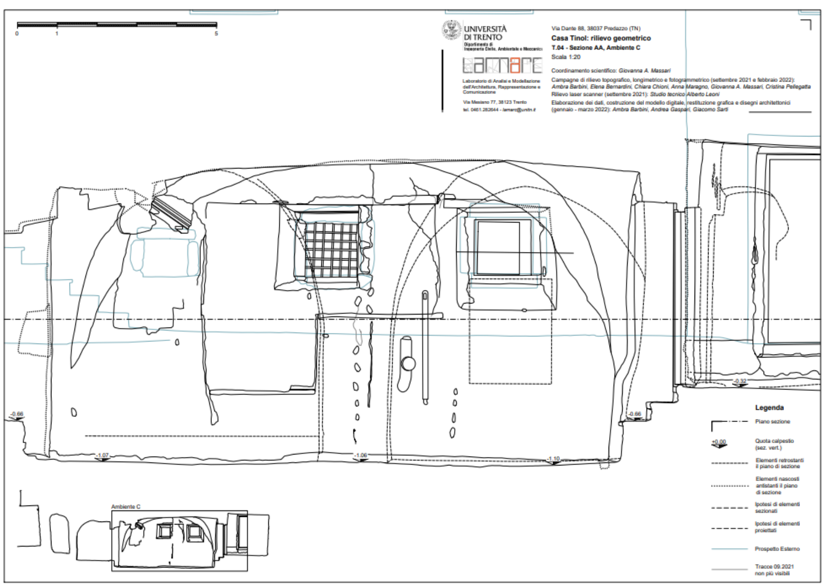


Figure 4.31 - Section drawing in 1:20 scale extracted from the 3D model via sections of Casa Tinol in Predazzo. Elaborations by LAMARC.

Integrating photo planes (Fig. 4.32) within a 3D model via sections it is possible to obtain a vector-raster model, from which the technical drawings in orthogonal projection can be retrieved. While as a whole this kind of model has the lowest visual fidelity, since it is difficult to recognise the shapes of the represented building (Fig. 4.30). On the single 2D planes it is possible to reach a high geometric accuracy and detail richness. In addition, each plane can host a mapping of some information, such as materials or degradations.

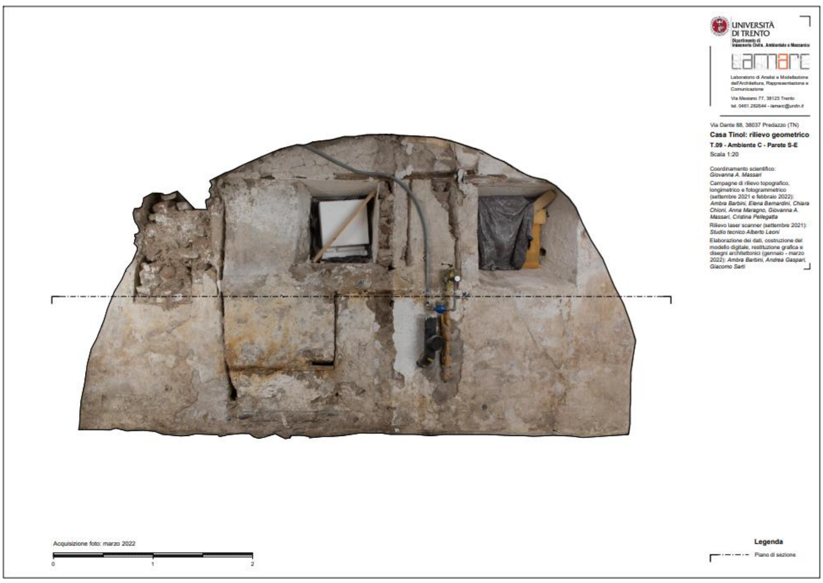


Figure 4.32 Photo plane view extracted from the vector-raster model of Casa Tinol in Predazzo. Elaborations by LAMARC.

However, 2D drawings offer a single static view on the object, while 3D models enable the user to choose the point of view from which observe and study the model (Empler, 2006, p. 12). In particular, 3D models via sections are not only more difficult to understand for users who are not familiar with architectural drawing codes, but also require defining in advance the most meaningful section planes. Moreover, recognising and interpreting the geometries of the point cloud can be particularly laborious and time-consuming, especially for complex geometries.

These critical issues were confirmed both by the analysis of some case studies and by some research experiences for which a 3D model via sections was used. For example, in the case of Casa Tinol the involved

stakeholders expressed difficulties in reading and understanding the highly detailed 2D views, extracted from the 3D model via sections. Moreover, this kind of model was not particularly suitable for the reconstruction and visualization of the historical development of the building. In the case of Palazzo Pretorio, the extension and the complexity of the building made it difficult to select a reasonable number of representative sections useful to support all the subsequent study on the historic development of the building. In the case of the archaeological site of Piazza Bellesini, the 3D model via sections was not very effective because the object of study has extremely complex geometries, and the manual redesign of each profile took a long time, and it was difficult to integrate with non-graphical information. This led to the development of a Heritage Building Information Model, based on the development of a surface-based model exploiting mesh and NURBS surfaces.
Supporting in representing in detail the feature of external faces of objects, surface-based models offer a high visual quality but often prevent from the calculation of the main geometric properties, such as the area or volume of the intersection between two objects and do not support in the integration of information (Empler, 2006, p. 16). It is possible to distinguish between polygonal meshes and free forms surfaces. A polygonal mesh is made of vertices and plane polygonal faces, generally triangles or quadrangles, and permits the simplification of complex surfaces. Free form surfaces exploit quadratics or cubic faces, to guarantee the continuity of the surface, that can be dynamically modified. NURBS (Non-Uniform Rational B-Splines), is a mathematic representation able to accurately represent any kind of geometry, from primitive surfaces, such as sphere, cylinder and cone, to ruled surface, such as hyperbolic paraboloid and free form geometries.
Both NURBS and mesh surfaces can reach a high visual fidelity and geometric accuracy, but require a higher geometric approximation compared to 3D models via sections, with a lower detail richness. While some surface-based models can be obtained directly from the processing of architectural survey data (e.g. mesh from photogrammetric survey), 3D solid models are generally developed exploiting different possible operators, such as topological, geometric, transformation, Boolean and assembly operators (Empler, 2006, p. 18). Solid models can be

classified into two main approaches that are often mixed and combined within 3D modelling software CSG and B-rep (Bertoline, 2016, p. 122). Constructive Solid Geometry (CSG) models support in the development of complex geometries through Boolean operations among simpler solids and are exploited for the construction and transformation of the model (Empler, 2006, p. 31). Boundary representation (B-rep) models are based on the representation of boundaries, such as vertices, edges and faces, and support various operations such as visualization and measurement (Eastman., 2016, p. 85). Solid-based models can reach high visual fidelity and geometric accuracy, but often require a higher approximation of detail compared to surface models and as all the other 3D geometric models does not support a high information richness.

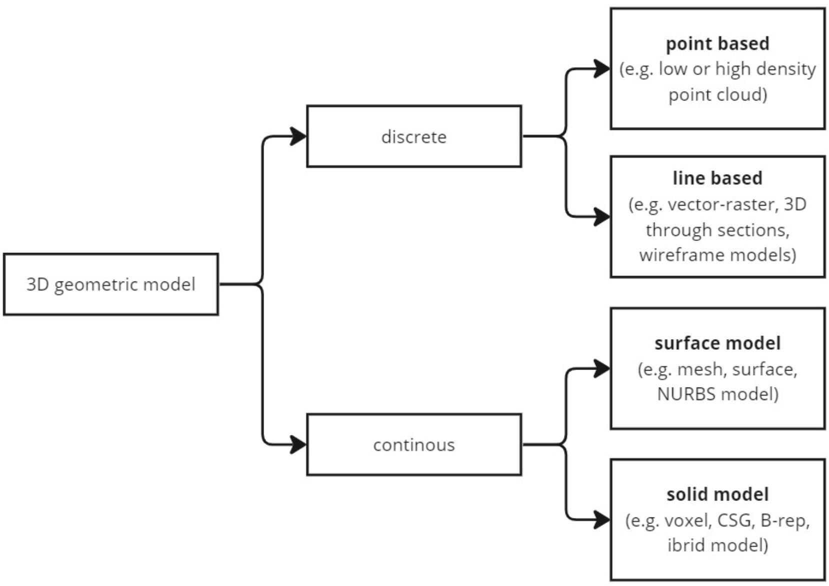


Figure 4.33 - Diagram presenting different types of geometric models.

4.3.2 HBIM - Heritage Building Information Modelling

Whilst 3D geometric models include a set a procedure for the restitution of the geometries only, HBIM refers to the restitution of geometries developed according to a construction logic (ontological model) associated with information (semantic model). This means that HBIM enables the integration of data coming from different sources, for example combining the complexity of the geometrical shapes with the information from the historical archive with the construction technology analysis (Brumana et al., 2020).
Considered as new paradigm for the design, documentation, and digital management of existing assets, HBIM supports the communication between data in different formats, facilitating exchange and collaboration opportunities among many actors (Chioni et al., 2021). The idea of adopting BIM processes, not only for the management of building life cycle but also for the intervention on the existing asset, is particularly relevant in Europe and especially in a country, like Italy, with a very rich history and a high presence of built historical heritage (Adami, 2018).

Mostly known as Heritage Building Information Modelling, the H of the acronym HBIM originally stood for Historic, mainly referring to a library of parametric historic building components developed from past manuals, treatises and data sheets (Murphy et al., 2007). This approach is associated to the concept of forward modelling (Yang et al. 2018; Yang, et al. 2019; Murphy, 2013), indicating the a priori modelling of building components, mainly based on documental source and then parametrically adapted to the actual feature of the building. This approach takes advantage of the parametric flexibility that characterize BIM authoring environments and generally leads to the development of a library of parametric objects, through which it is possible to virtually reconstruct the building object of modelling (Maiezza & Tata, 2019). The main challenges connected with this approach lay on the difficulties to adapt the objects of the parametric library to the real condition of the physical object, often including degradation and irregular geometries (Maiezza & Tata, 2019). A possible strategy to avoid accepting an excessive approximation of real geometries can rely on the adoption of a parameter numerically controlling the distance between the model and the real geometry of the building, exploiting a point cloud (Qattrini et al., 2016) and the adoption of a threshold value, beyond which is recommended to follow another modelling approach (Apollonio et al., 2017).

The other most common approach to HBIM is reverse modelling, which involves the generation of geometries directly from reality, using point clouds to recognize and inform building components (Yang et al. 2019; Lopez et al., 2018). This approach often requires the semantic segmentation of the point cloud and the subsequent extraction of meaningful geometric primitives to create the model of each building component, requiring a longer modelling time. Reverse modelling ensures greater adherence to reality and provides greater geometric accuracy at the expense of parameterisation and the possibility of reusing created elements to model other buildings in the future.

For both forward and reverse modelling it is possible to associate textual, numerical, graphical and documental data, through the creation of dedicated parameters, to each building component, reaching a high level of information richness. The selection of the best modelling approach generally depends on the expected use and purpose of the model, as well as the peculiarity of the object to model. Moreover, in most of the case the two modelling approaches are mixed and combined together. For example, when a 3D digital survey is not available and the model is based on project drawings or on previously developed 2D traditional survey elaborations, it is likely that the model will be mainly developed through a BIM object library. Similarly, in the case of recent or contemporary heritage it is often easier to parametrically adapt some library components to the regular geometries of the building, according to a forward modelling approach. On the contrary, in the case of an archaeological site, including ruins or highly irregular shapes, the reverse modelling approach is generally the most helpful. Finally, buildings representing exceptional values are often partly realisable according to forward modelling logic and partly require specific solutions more related to reverse modelling.

Therefore, it is possible to distinguish between drawing-to-BIM and cloud-to-BIM approach, according to the reference source for the model development, and both of them can be implemented with forward and reverse modelling solutions. Clearly a model including components developed according to different approaches will have different level of geometric accuracy and this information could be crucial for some model uses. The main challenges remain the unavailability of historical parametric object libraries, as well as the lack of proper tools for managing complex, irregular and uncertain shapes within most of BIM authoring environments (Lopez, 2018).

4.3.3 HBIM Modelling experiences

All these considerations on HBIM have been confirmed also from the analysis of three master thesis developed within the LAMARC in the last few years. These modelling experiences tested three different work-flows, referred as:

- drawing-to-BIM, that is mainly based on drawings and does not require on-site data acquisition;
- parametric library construction, that requires the presence of similar or recursive elements that can be parametrically adapted to the point cloud;
- mesh-to-BIM based on the segmentation of the point cloud and the creation of mesh surfaces for the development of ad hoc BIM objects.

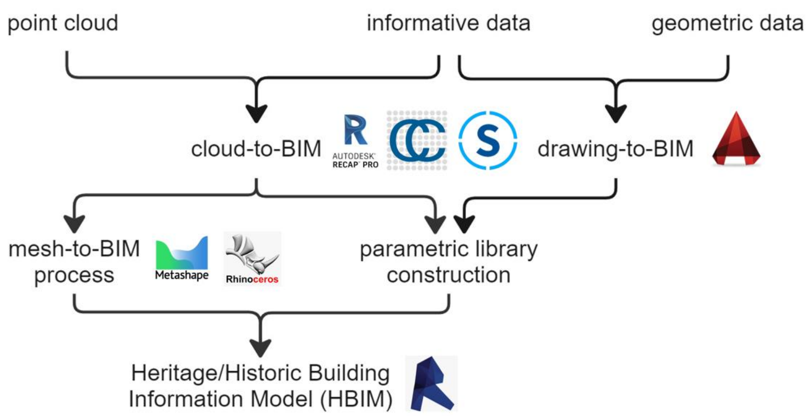


Figure 4.34 - Diagram presenting different approaches to Heritage/Historic Building Information Modelling.

BUM (Biblioteca Universitaria Mesiano) - drawing to BIM

The new library of the Department of Civil Environmental and Mechanical engineering in Mesiano is an example of contemporary heritage modelled starting from project drawings, mostly exploiting parametric objects already available within the BIM authoring software and a plug-in for heating floor systems design and representations.

The workflow included the following steps:

1. digitization of paper drawing;
2. analysis of recursive and/or similar elements;
3. parametric objects construction;
4. complementary data import in a BIM environment;
5. parametric object placement;
6. informative data integration.

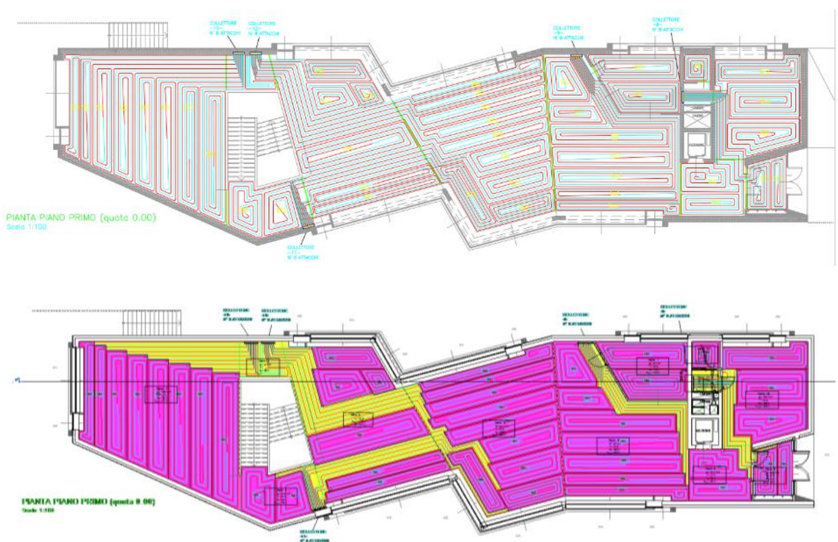


Figure 4.35 - View of the main floor of the BUM including the heating-floor panels in AutoCAD above and in Revit below (Murer, 2023).

Villa Penner - parametric library construction

Heritage building expression of historical and demo-ethno-anthropological values modelled starting from a point cloud and creating a library of parametric components, for the several recursive windows typologies.

The workflow included the following steps:

1. analysis of recursive and/or similar elements;
2. definition of the LOD and LOA of different components;
3. horizontal and vertical sections from the point cloud;
4. parametric objects construction;
5. complementary data import in a BIM environment;
6. object placement using the point cloud as reference;
7. parametric adjustment of the objects to the point cloud;
8. informative data integration.

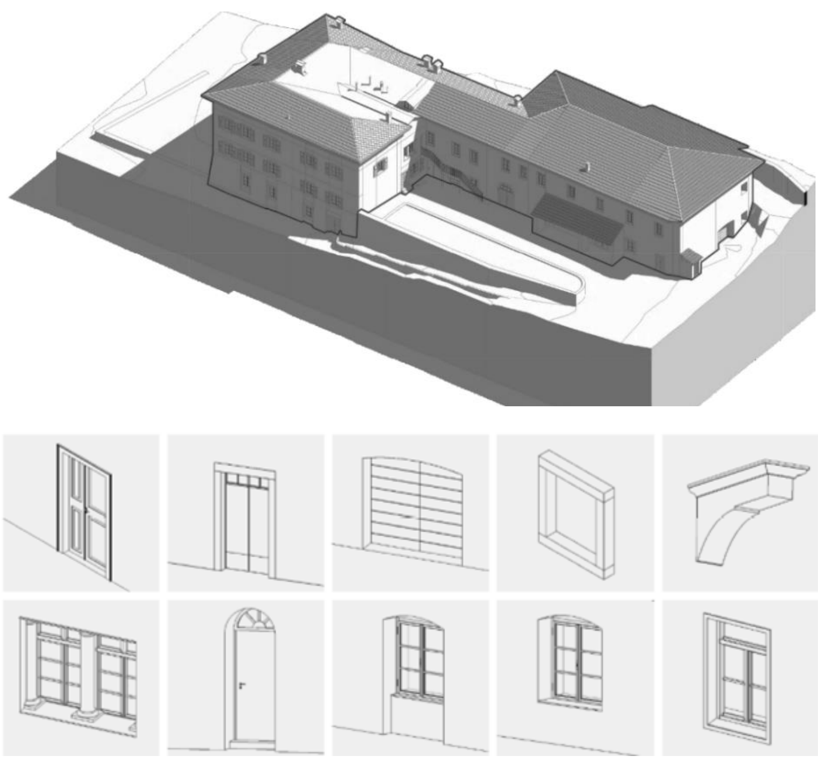


Figure 4.36 - HBIM model of Villa Penner above and some of the window and door developed as parametric object below (Gaspari, 2021).

Piazza Bellesini in Trento - mesh-to-BIM

Archaeological site modelled through a reverse modelling process exploiting the semantic segmentation of the point cloud transformed into a mesh, simplified and converted into a NURBS to obtain smooth geometries more compatible with the BIM authoring environment.
The workflow included the following steps:

1. point cloud to triangular mesh;
2. triangular to quadrangular mesh;
3. mesh to NURBS (Non-Uniform Rational Basis-Splines);
4. complementary data import in a BIM environment;
5. segmented NURBS import in a BIM environment;
6. in-place model element development from single NURBS;
7. informative data integration.

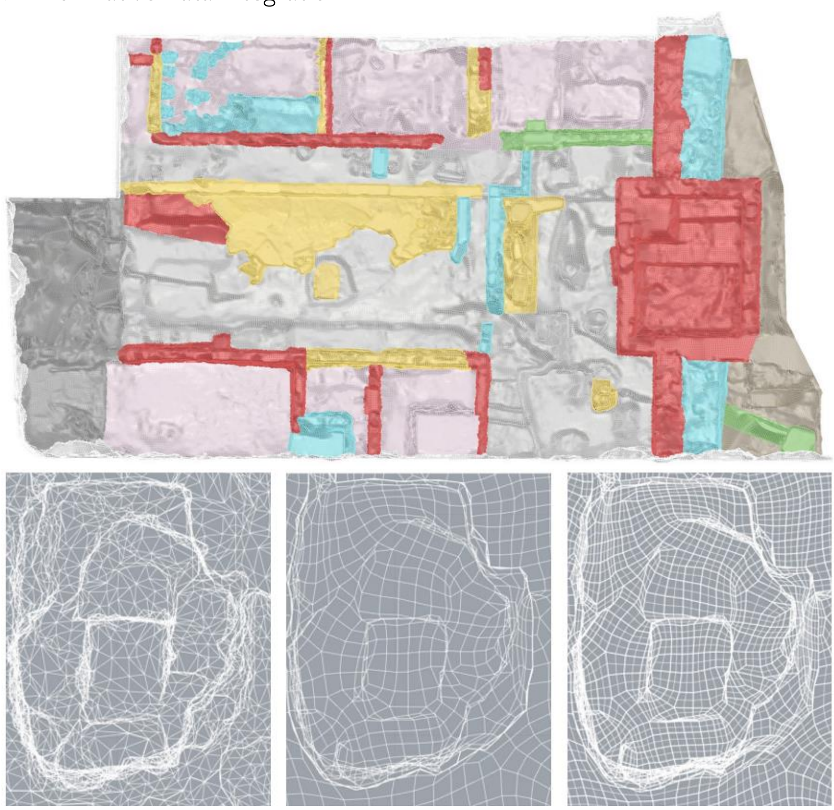


Figure 4.37 - Semantic segmentation of the point cloud of Piazza Bellesini above and mesh-to-NURBS evolution below (Scoz, 2021).

Casa Tinol and Palazzo Pretorio

The direct HBIM experiences, acquired in modelling the basement floor of Casa Tinol in Predazzo and the Castelletto of Palazzo Pretorio in Trento offered the opportunity to test and validate some possible strategies in the representation of irregular elements, the creation of a solution for recursive complex elements and the display of the level of accuracy of each component.

The creation of both models[82] involved the definition of a reference system, based on the distinction between the real and project north and the creation of reference level and grids based on the point cloud and the positioning and adaptation of floors and walls to the point cloud, adjusting eventual irregularity in the slope.

For the basement floor of Casa Tinol, it was not possible to develop a BIM object library because there were not recursive or similar elements, but most of the components (e.g. windows, doors, floors, niches, etc.) could be modelled as a an in-place object with the tools available in the BIM authoring environment, except from the vaulted ceilings, presenting irregular geometries.

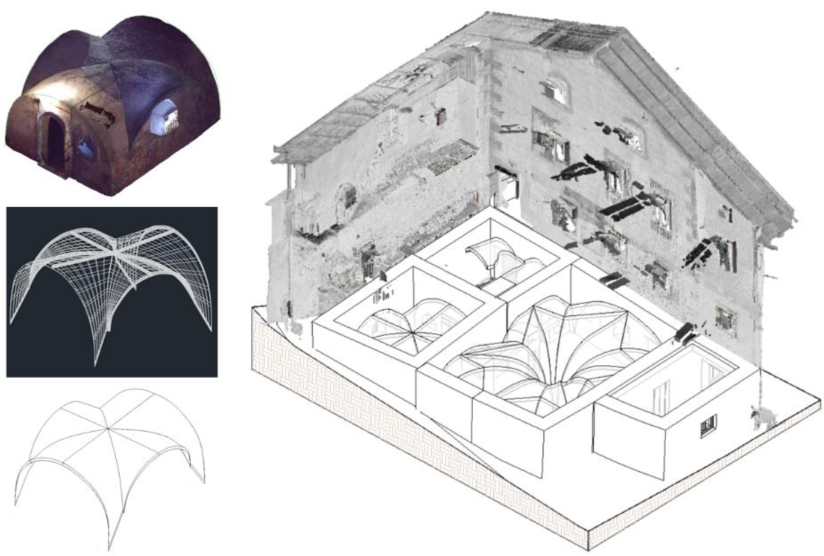


Figure 2.38 - Heritage Building Information Model of the basement floor of Casa Tinol.

[82] Using the educational version of Autodesk Revit 2023.

After testing different modelling strategies (Table 4.5), the solution to obtain the highest geometric accuracy and visual fidelity both in 2D and 3D view is developed in a 3D modelling environment[83] by creating loft surfaces between pairs of vault curves, such as arris and impost arches, retrieved from the point cloud.

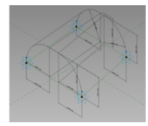
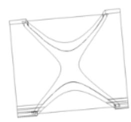
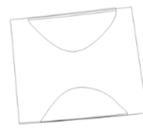
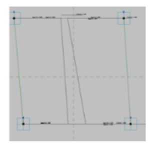
	A – Intersection of solids (BIM)	**B – Intersection of voids (BIM)**	**C- Adaptive models (BIM)**	**D - Loft surfaces (CAD 3D)**
3D axonometric view				
2D top view				
Modelling time	Short	Short	Medium	Medium
Accuracy	Medium	Low	Medium	High

Table 4.5 - Comparison of different modelling strategies for the irregular vaulted ceilings.

This solution tested for one of the vaulted spaces of the basement of Casa Tinol, was later extended to all the others, proving to be effective for different kinds of vaulted ceilings.
This approach resulted suitable also for the vaulted ceilings of Palazzo Pretorio (Fig. 4.39). In the case of the Castelletto it was also possible to develop some parametric components, dynamically adaptable to the point cloud, especially for some recursive windows. The main challenge of this building concerned the two apses of the Castelletto, which resulted particularly complex to model. Despite having different dimensions and proportions, both the apses are based on two elliptical arcs in the horizontal and vertical frontal section, while the transversal vertical section is an irregular arc. Since the BIM authoring environment does not include any modelling option for this kind of geometries, a VPL script has been developed to create one of the apses (Fig. 4.40).

83 Using the educational version of Autodesk AutoCAD 2023.

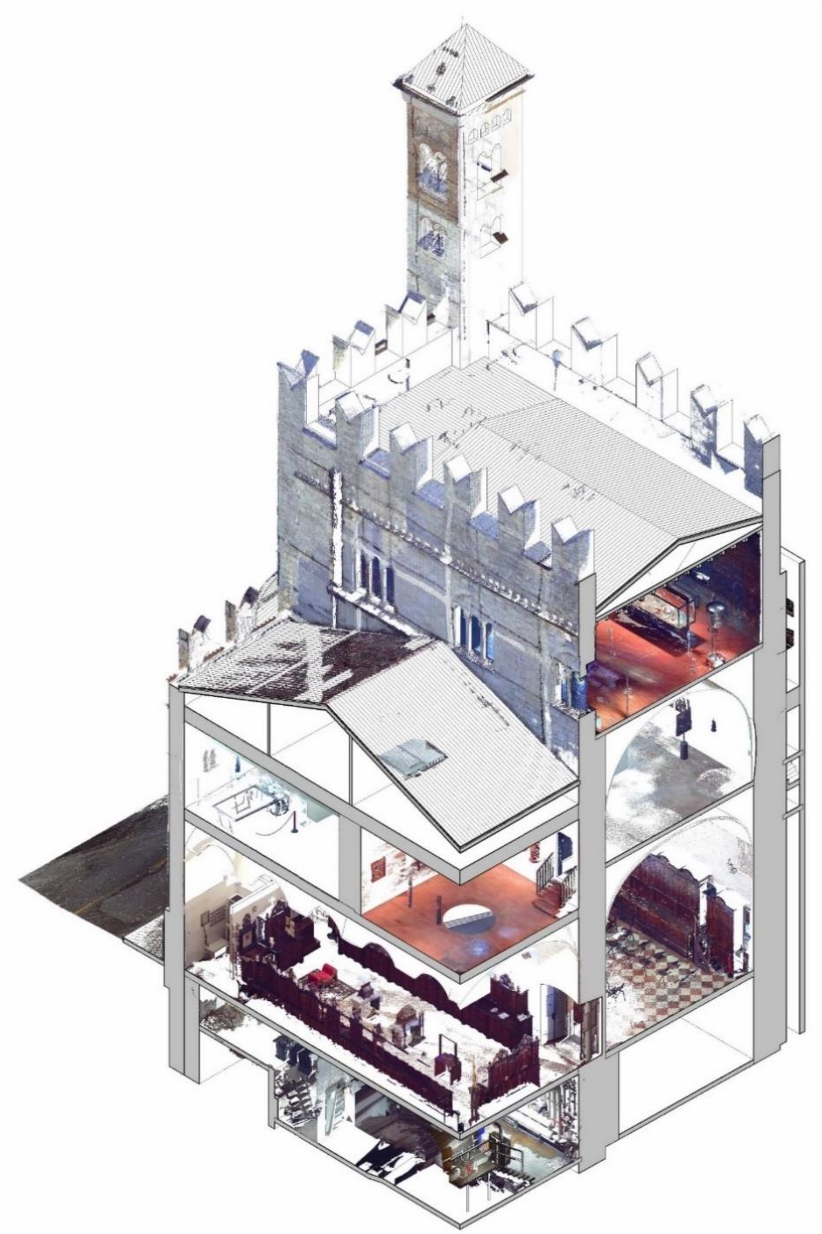


Figure 4.39 - Heritage Building Information Model of the Castelletto of Palazzo Pretorio.

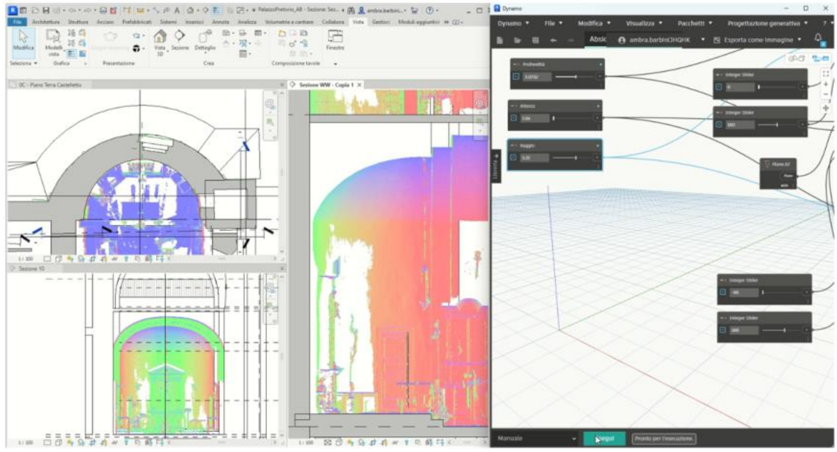


Figure 4.40 - Adjustment of the apses through the VPL script.

The arc of the transversal vertical section was described as an arc for four control points, whose extreme coordinates correspond to the centre of the two elliptical arcs and the others are dynamically adaptable to the point cloud profile. By setting the elliptical radii as variables, it was possible to exploit the same script to model both the apses, through the generation of a surface between two elliptical arcs along an arch for four control points.

Furthermore, to keep trace of the grade of reliability of different components, a parameter was associated to each element (Fig. 4.41), for a visual distinction among:

- elements entirely or partially based on the point cloud (green);
- elements based on photographic images (yellow);
- hypothesis, due to the lack of reliable survey data (orange and red).

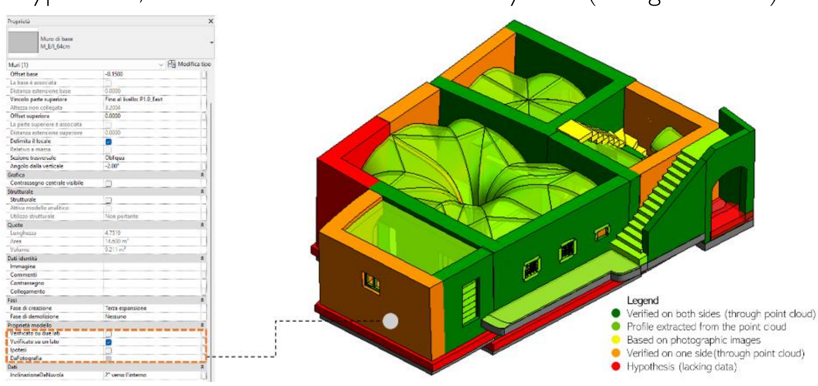


Figure 4.41 - Visual distinction of different grades of reliability in model components development.

4.4 Built heritage models

The process of creating built heritage models can follow various workflows, variable in terms of time investment, effort, and the quality of data required. These workflows are therefore not equivalent, and the choices and sensibilities of the operators play a crucial role at every stage, particularly in data acquisition and processing. The modelling experiences examined and presented in this study illustrate viable solutions, tailored to the unique features of each case study.

Decisions made during the acquisition and processing phases are often the result of a balance between the available resources - such as time, budget, equipment, and human resources - and the desired level of data quality.

Traditional direct survey is the least expensive solution, but it could be extremely time-consuming according to the extent and complexity of the object. Despite being viable with quite cheap instruments, it requires at least one expert surveyor to coordinate the operations. Anyhow it could be extremely helpful as validation or complementary method.

Topographic surveys require skilled professionals and expensive instruments. Given its high precision, topography often supports the integration of different survey data, but rarely works as a stand-alone method, unless the aim of the survey is to record a limited number of point coordinates.

Image-based survey can have very variable costs and requires experienced operators both in the acquisition and especially in the processing phase. Especially UAV aerial photogrammetry may have limitations due to restrictions on flight permits, while in some cases it is particularly suitable for surveying hard-to-access areas.

Range-based surveying is among the most expensive, except for low-cost instruments, which, however, achieve very low levels of accuracy. These instruments do not require any special skills, but the processing phase can be time-consuming as the size and complexity of the object increases.

As necessary intermediate step between the acquisition and the modelling phase, the processing phase prioritize accuracy, time, or cost. Digital 3D surveys require more time for data filtering and interpretation compared to traditional survey techniques, but generally include an extensive documentation of the analysed object. Indeed, the processing phase for image and range-based data involves different digital workflows using dedicated software. Laser scanning software supports scans registration, alignment, filtering, and cleaning. Photo-modelling software generate a 3D point cloud from high-resolution photos.

The acquisition and processing experiences analysed in the previous sections allow for the following considerations.

- The integration of various survey methods is often very helpful for comprehensive knowledge of the object.
- Image-based surveys often provide better visual quality, but lower accuracy compared to TLS, which has lower colour quality and is affected by lighting variations.
- Image-based models need accurate scaling using Ground Control Points or reference measures to achieve metric reliability.
- Processing workflows often require specialized operators to achieve accurate and efficient results.
- FOSS often offer an economically accessible solution, but their use requires awareness of the input data quality and quantity and time availability.

Multiple factors can impact the choice of geometric modelling strategies, including the architectural nature of the heritage item, the extent of geometric irregularities, the complexity of its forms, and the presence of repetitive or similar elements. Beyond these, the ultimate purpose of the model - whether for conservation, restoration, research, or digital archiving - and the priorities of the project - such as visual fidelity, geometric accuracy, detail richness and information richness - also play a significant role in guiding the selection of the most appropriate approach, as further analysed in section 5.3. This highlights the importance of a nuanced and flexible decision-making process that considers both technical and contextual considerations.

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5. BUILT HERITAGE INTERFACE MODELS

After studying and testing various possible procedures for built heritage data structure into digital models, the investigation focuses more specifically on Built Heritage Interface Models, exploring how these models can be helpful for professional and generic users, considering different points of view. The primary focus of this chapter is thus Built Heritage Interface Models, intended as devices for the interpretation and representation, aiming at the promotion of communication, codified according to objectives, contents and addressees, who can range from professional actors to generic audiences. In the case of professional actors, such communication takes the form of a dialogue, which can evolve into cooperation within an interoperable system. In the case of a generic audience, it takes the form of a cultural promotion or sensibilization and information on specific topics. In this phase, three aspects emerged as crucial for the definition of a Built Heritage Interface Models framework:

- the analysis of different possible fruition solutions, considering user needs and taking into account their level of familiarity with digital technologies - section 5.1;
- the systematic collection of the point of view of local AECO professionals to shed light on existing gaps between the academic state of the art and current professional practice - section 5.2;
- the usability of research outputs to AECO professionals - section 5.3.

The investigation of fruition solutions led to the further development of the case studies previously presented in the analysis of various solutions for the creation of built heritage digital models (section 4.3). The first section of this chapter aims at illustrating how it is possible to exploit digital models as interfaces with the built environment. Each interface example originates from real needs of information access and data exchange, expressed by local stakeholders, or from the interest in testing visual storytelling solutions for the promotion of knowledge transfer on technical or valuable features of the buildings object of analysis.

A questionnaire, disseminated in Trento Province, on the research's main topics investigates the point of view of the different professional categories of the construction supply chain, including questions on data exchange and collaboration forms, the adoption of digital technologies and the collection and processing of data on the built heritage.

Given the results of the questionnaire, some of the main outputs of the research have been organised into a set of tools, aimed at reducing the gaps between academic and professional communities. These include an orientation tool for the selection of the most suitable interface types, a dynamic guideline on HBIM modelling strategies and a checklist on interoperability frameworks. These tools aim to make this research more accessible to AECO operators, besides the detailed presentation of different case studies.

5.1 Fruition phase

The exploration of different digital model fruition solutions is based on the distinction between cognitive and instrumental interfaces, namely interface “to know”, enabling knowledge transfer and interface “to do”, empowering joint operations between different actors (Anceschi, 1993, pp. 20-21).
In both cases, the expected familiarity of the users with digital technologies also played a crucial role in distinguishing between traditional, experimental and advanced fruition solutions. Moreover, especially in the cases of real needs expressed by local stakeholders, the user's cultural background, context and reference system have been carefully analysed. Additionally, physical and virtual supports for visual storytelling have been considered, including traditional, interactive and immersive options, in developing fruition solutions for generic audiences.
Traditional fruition solutions, for all cases where it is better to avoid digital technologies, mainly rely on:

- static images, derived from an elaboration of the developed model or simply capturing data collected on the built heritage (e.g. a view of the point cloud, a montage of survey and archival images, infographics), that can be printed on physical support or displayed through a screen, in the case of generic audiences;
- technical drawings in orthogonal projection or axonometry, extracted from the model and delivered in digital or paper format for technical users.

Experimental fruition solutions, targeted to users with a minimum level of familiarity with digital technologies, can be based on:

- interactive physical elaborations, such as anaglyphs, site-specific perspective reconstructions, lenticular printing, tactile images or models, or virtual dynamic elaborations (e.g. animations, video, dynamic presentations) projected or available on a screen, in the case of generic audiences;
- accessible and low-cost digital technologies for the fruition of survey data (e.g. CloudCompare for point cloud) or digital models (e.g. BIMvision for an HBIM model), mainly based on demo versions of proprietary software or exploiting Free and Open Source Software (FOSS) for technical users.

Advanced fruition solutions, addressed to users with a good level of familiarity with digital technologies, can include:

- digital products supporting an interactive (e.g. hypertexts, maps, digital books, images with hotspots and augmented reality applications) or immersive (e.g. panoramic images and photos, virtual tours and virtual reality applications) fruition for generic users;
- interoperable workflow, based on the exploitation of the multidimensionality of BIM environments, to support data exchange and facilitate collaboration among technicians of the AECO sector.

Follows a list of examples, including traditional, experimental and advanced fruition solutions to promote information access and data exchange among specialised or generic users.

5.1.1 Tinol House - from traditional to experimental fruition

Users	Digital technology familiarity	Interface to do…	Interface to know…	Fruition solutions
Restorer and superintendence officer	low		the geometry of the building at the begin-ning of the restoration work	Traditional 2D drawings
		Discuss hypothesis on the building historical de-velopment		HBIM model in IFC format
ViC-CH Work-shop students	high	design a mul-timedia instal-lation in and on the building		3D model
Community of Predazzo and tourists	variable		the history of the building and its rela-tionship with its territory	Multimedia installation (e.g. posters, pro-jections, tan-gibe model, panorama pic-tures)

The enthusiasm of the actors involved in the restoration of Tinol House, starting from the restorer[84] to the involved officer[85] of the Superintendency of Cultural Heritage, the public administration[86] of Predazzo, the owners of the building and the local community, offer the opportunity to test different solutions for the fruition of the data collected through the 3D digital survey, as well as from the two models developed: a 3D through-sections model and a Heritage Building Information Model.

Directly from survey data were obtained static and dynamic images of the coloured point cloud, used to document the building conditions at the beginning of the restoration works and to display the point clouds to technicians and general audiences. It is also possible to explore this point

[84] Silvia Invernizzi

[85] Giovanni Dellantonio

[86] Giovanni Aderenti (culture councillor) and Maria Bosin (mayor)

cloud through virtual reality headsets to experience a past configuration of the building in immersive mode.
The 3D through-sections model consists of a horizontal section of the basement floor and two vertical sections, derived as intersecting point cloud profiles in a 3D CAD environment, completed with projections of visible parts and photo-plans of internal and external walls. These sections were made available to the restoration team in the form of traditional 2D drawings (Fig. 5.1) to provide a detailed description of the spaces and support the annotations of the restorers.

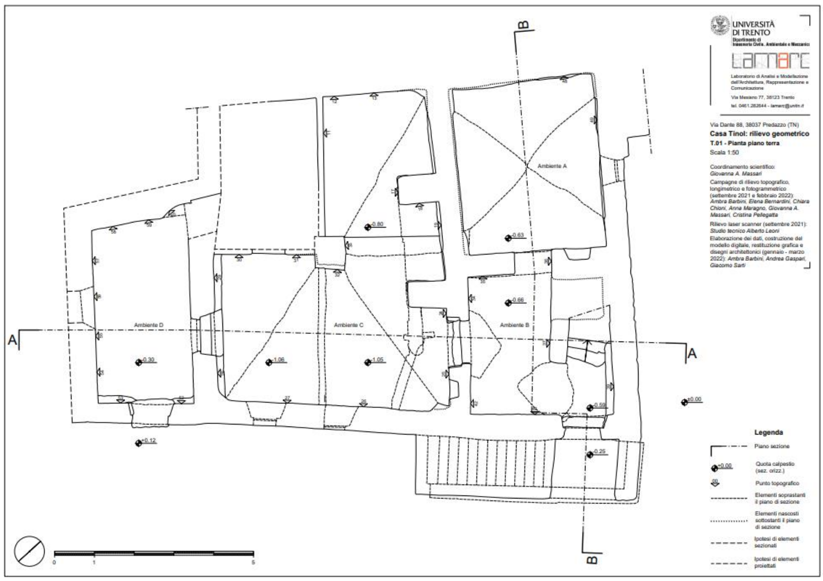


Figure 5.1 - Horizontal section drawings from the 3D model via sections. Elaboration by LAMARC.

The Heritage Building Information Model of the basement floor supported testing a collaborative workflow based on the combined use of a free IFC viewer[87] and the demo version of a plug-in[88] to support interaction also with users not familiar with the BIM environment (Fig. 5.2). This collaborative workflow aimed at discussing some hypotheses on the historical configurations and developments of the building (Fig. 5.3). The digital technologies tested together with the restorer and the officer of

[87] BIMvision, a free IFC viewer to visualise the geometries and information of BIM files in open format.
[88] IFC comments/BCF, plug-in of BIMvision aimed at supporting communication.

the Superintendence supported different interaction modes, including the highlight of spatially localised open issues, the reference to single model components, the annotation of comments and the request for feedback to a specific user.

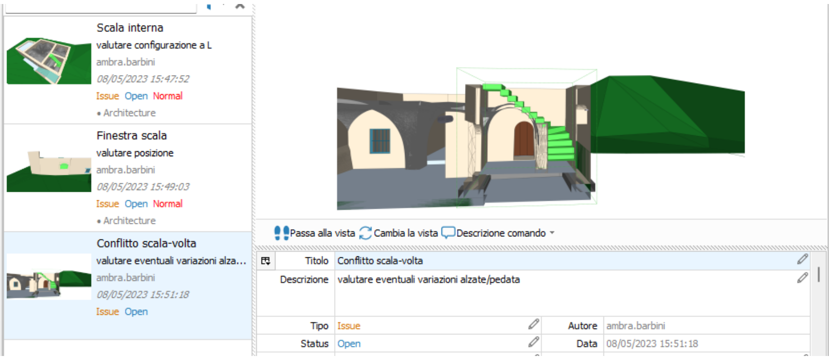


Figure 5.2 - Tool used for visualising and commenting the model of Casa Tinol.

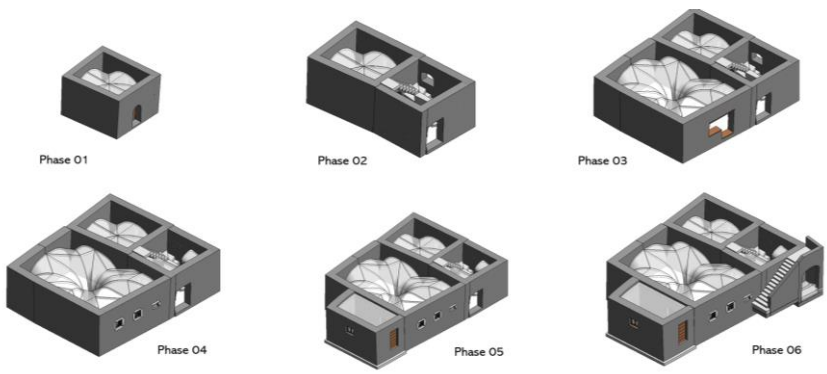


Figure 5.3 - Hypothesis of the historic development of Casa Tinol.

Moreover, the administration of Predazzo expressed the intention to transform the basement of Tinol House into a stop along a cultural itinerary, reconnecting the history of the building with the geological-mineral context of the Fiemme Valley. This intention inspired the third edition of the ViC-CH (Visual Culture and Cultural Heritage) project, which focused on the design of a multimedia installation for Tinol House. Thanks to a hospitable and vibrant local community, the staff[89] of the Laboratory of Analysis and Modelling of Architecture, Representation and Communication (LAMARC) organised a three-day residential work-

89 Ambra Barbini (organizative coordination), Elena Bernardini, Chiara Chioni, Anna Maragno, Giovanna A. Massari (scientific coordination), Starlight Vattano.

shop in Predazzo. The sponsorship of APT (Azienda Provinciale per il Turismo – Provincial Tourism Office) Fiemme and Fassa Valley hosted all the participants, offering them the opportunity to get in touch with the building but also with the local history and culture and to develop ideas for a possible configuration of the exhibition and its multimedia contents. The participants developed two integrated solutions, starting from the collected data and the developed models, integrated with bibliographic and iconographic references supplied by the Geological Museum of the Dolomites and the Cultural Heritage Superintendence. The first proposal focuses on the indoor spaces of the Tinol House basement and the other on the definition of a cultural itinerary oriented to the connection of the building with the history of Predazzo and its surroundings. The indoor installation includes informative totems with posters, floor projections and a 3D simplified model of the building's historical phases and some decorations, such as a trompe l'oeil and a printed glass, aimed at highlighting the peculiarity of the vaulted spaces of the basement and the transformations of the building (Fig. 5.4).

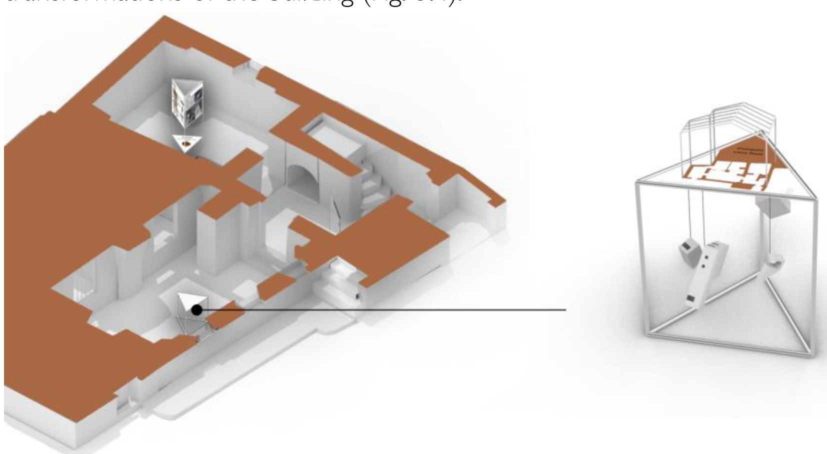


Figure 5.4 - Indoor installation designed using the Heritage Building Information Model of Casa Tinol. Elaborations by workshop participants.

The students also designed a map, which illustrates the cultural itinerary linking Tinol House with other historical buildings of Predazzo and indicating the fountains and other buildings meaningful for the local community, such as the museum and the library, hosting the workshop activities. The itinerary is completed with a press stamp near each stop to mark the back side of the map. Each stamp includes a QR code linking to a panoramic picture displaying the building with some informative hotspots.

This workshop experience with young students familiar with digital technologies shows how survey data and Heritage Building Information Models can support not only design processes but also visual storytelling, resulting in a valuable interface also for the local community and tourists. Moreover, the entire experience on this building from the initial exchange with the restoration team based on traditional drawings and the following interaction directly on the digital 3D model highlights the potential of built heritage models as both interface to know and to do.

5.1.2 Palazzo Pretorio - HBIM-based traditional fruition

Users	Digital technology familiarity	Interface to do…	Interface to know…	Fruition solutions
Research team	variable		the geometry of the building at the begin-ning of the restoration work	Traditional 2D drawings
		discuss hy-pothesis on the building historical de-velopment		HBIM model in IFC format
Museum visitors	variable		the history of the building	Multimedia installation

The multidisciplinary research project focused on the historical development of Palazzo Pretorio in Trento offered the chance to validate the use of Heritage Building Information Models as a structured synthesis of architectural survey data based on single building components reconstruction and assemblage. The actors involved in the project, with complementary expertise and specialisations, including historical archives[90], archaeology[91] and architectural restoration[92], expressed the need to use survey drawings first as a support for hypothesis annotations and drafting on historical uses and configurations of the single spaces of the building. Moreover, the research team needed visual support to present and communicate the research output. The LAMARC working group[93] developed a 3D through-sections model of the building, including one horizontal section for each floor and two vertical sections, made of highly detailed 2D drawings in orthogonal projections in paper and digital format, obtained as point cloud profiles.

[90] Franco Cagol and Roberta Iseppi
[91] Enrico Cavada and Elisa Possenti
[92] Joel Aldrighettoni, Michele Anderle, Giorgia Gentilini and Alessandra Quendolo
[93] Sara Di Valerio, Gregorio Gottardo, Anna Maragno, Giovanna A. Massari (scientific coordination), Cristina Pellegata (executive coordination)

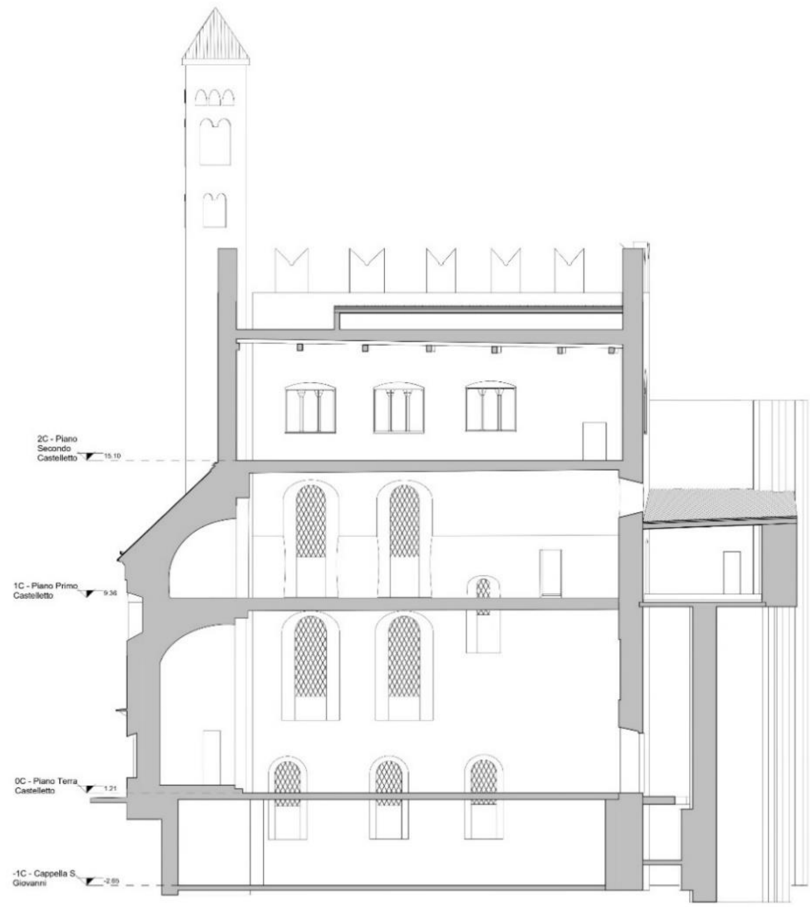


Figure 5.5 - Vertical section of the Castelletto extracted from the Heritage Building Information Model.

All the other sections and views, required for the investigation of the Castelletto of Palazzo Pretorio, have been obtained both in .pdf and .dwg formats from the Heritage Building Information Model, from which it is possible to derive multiple horizontal and vertical sections and 3D views in axonometric and perspective projection with a variable level of detail, information and accuracy, according to the strategies adopted during the modelling phase, as discussed in the previous chapter.
In this case, the research group needed seven integrative sections and four axonometric views to support technical considerations on the stratifications and transformations over time of the perimeter walls of the Castelletto, as well as for the visual communications of the most trusted hypothesis. This experience showed how HBIM can be easily integrated

with traditional workflows based on horizontal and vertical drawings, offering the possibility to extract all the necessary sections and views from the model. For this kind of use, it is crucial to consciously choose each component modelling strategy according to the required level of detail and accuracy to avoid the lack of important information or an overloaded model complex to store and manage with an average-performance workstation. This research is partly still ongoing, and the Heritage Building Information Model will host historical information on wall stratification and other constructive technologies, as well as a hypothesis of the historic development, associating to each component a construction phase and integrating demolished components. Moreover, the museum plans to develop a multimedia installation to illustrate to visitors the research results on the historical development of the building. This installation offers the chance to replicate the experience of Tinol House, exploiting a survey model for visual storytelling applications.

5.1.3 D'Arogno Square - experimental and advanced storytelling

Users	Digital technology familiarity	Interface to do…	Interface to know…	Fruition solutions
On site visitors	low		the history of the square	Printed collage of pictures
	advanced			Solid model (AR)
Off site visitors	intermediate			Virtual tour
	advanced			Point cloud model (VR)

From the overlap of different research interests of the PhD students[94] affiliated with the LAMARC, the study on Palazzo Pretorio has been extended to the surrounding urban spaces, including both the Duomo and the Adamo D'Arogno squares, North and South sides of the cathedral respectively. In particular, for the second one, the urban survey has been integrated with archival data from parallel research on the road surfaces in the historic centre of Trento to explore possible low-cost workflows for the fruition of historical information according to a contemporary aesthetic of images exploiting digital technologies. The study focuses on alternative design solutions for the staircase connecting Adamo D'Arogno Square and Garibaldi Street. Built at the end of the 19th century to connect the eastern base of the cathedral with the street level on the south, the actual configuration of the staircase was chosen among three possible alternatives, evidence of which remains in the municipal archives of Trento. A virtual reconstruction, combining archival data with 3D digital urban survey data, has been created for the discarded design solutions, testing an evocative and rational approach.

The evocative representation is based on the point cloud processing through cut-and-stitch operations and creates a suggestive environment that can also be enjoyed in immersive mode via virtual reality devices.

The rational approach exploits a volumetric model to represent one of the unrealized projects and can be compared with the current scale via an augmented reality application, easily accessible by framing a QR code via a smartphone. The historical iconography of the square, including

[94] Ambra Barbini, Elena Bernardini, Chiara Chioni and Anna Maragno (operative coordination).

postcards, drawings, engravings and lithography, has been integrated with survey data to show a comparison of the current outlook of this urban space with the past configurations, again according to a dual approach: evocative and rational. The evocative approach includes 2D collages of panoramic pictures and historical images on a printed or screen support. Based on the development of a virtual tour, the rational approach includes panoramic pictures enriched with hotspots, including historical information and images, available also for immersive fruition through virtual reality devices. This research experience provides a framework for alternative fruition solutions oriented to deliver historical information through visual storytelling, accessible to users with various levels of familiarity with digital technologies.

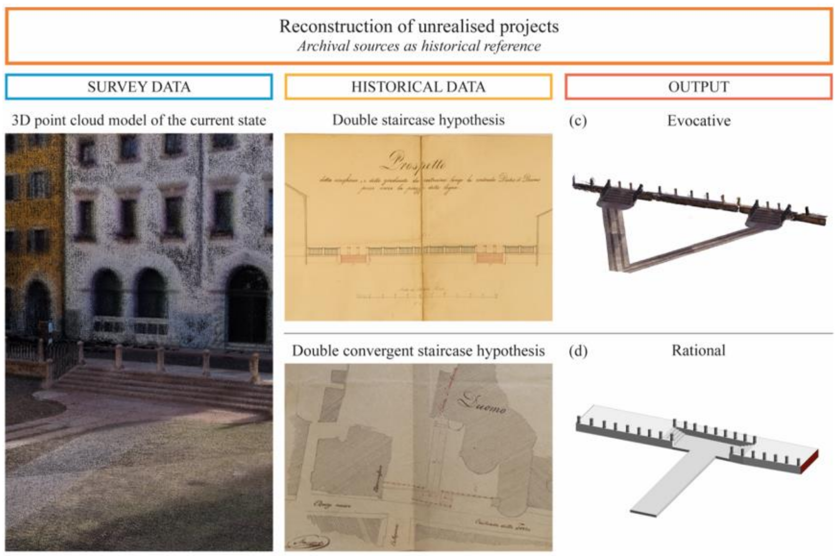


Figure 5.6 - Survey data and model based on historical data (Maragno et al., 2024).

5.1.4 BUM - advanced technical data visualisation

Users	Digital technology familiarity	Interface to do…	Interface to know…	Fruition solutions
Facility manager	intermediate	Improve indoor comfort conditions		Building Information Model linked with sensor data in proprietary format
Library staff and university community	variable		Real time indoor comfort conditions	Building Information Model linked with sensor data in IFC format

As part of a master's thesis[95] in Civil Engineering, the model developed to map the HVAC (Heating Ventilation and Air Conditioning) systems of the BUM (Biblioteca Universitaria Mesiano – Mesiano University Library), has been exploited also to spatially visualise data collected through humidity, temperature and CO_2 sensors. The combination of BIM and sensor data is intended to support the facility manager in the observation of possible relationships between sensor data, their positioning and the spatial and technological characteristics of the areas in which the data are collected, to improve indoor comfort over time, reducing energy consumption and environmentally harmful emissions. The analysed area of the library includes four sensors: one in the wardrobe area, one in the librarian's office and two in a large open space reading area: one closer to the stairs and the other closer to the librarian's desk. According to the location of the sensor, the building information model of the library is divided into four spaces corresponding to the sensor location, identified with the following names "wardrobe", "office", "reading-stairs" and "reading-desk". The sensor data is available in a spreadsheet where data is collected from 13.07.2022 to 11.01.2023 with intervals of 15-minutes timeframes. An algorithm developed using VPL (Visual Programming

[95] Murer J. (2023). *Analisi energetiche e rappresentazione delle informazioni: il caso studio della BUM.* Master thesis in Civil Engineering at DICAM - University of Trento. Supervisors: Paolo Baggio, Giovanna A. Massari and Alessandro Prada. Support for BIM and VPL: Ambra Barbini.

Language) relates the sensor data to the area where the sensors are installed and displays the humidity, temperature and CO_2 values by setting a specific time frame through a slider.

Figure 5.7 - Sensor data visualisation through Heritage Building Information Model (Murer, 2023).

The connection between the BIM environments and the spreadsheet data is performed by adapting to this case study a script previously developed for displaying building components' environmental impacts (Barbini et al., 2022a). After deriving summer and winter indoor comfort conditions from UNI EN ISO 16798-1:2019 - Annex B, the ranges of values to distinguish between high, low or ideal humidity, temperature values and CO_2 concentration were defined. Using a filter set within the BIM environment, it is also possible to colour the various rooms differently depending on the indoor comfort conditions. For example, according to the value recorded by the sensor in each timeframe, the related area is coloured green, yellow or red to warn in case of comfort, slightly or strongly discomfort values. This application has been developed to offer visual support to a facility manager with a high familiarity with the BIM environment. This could easily be extended to users with lower digital knowledge, adjusting the workflow developed for a previous study on environmental impacts visualisation through open BIM procedures (Barbini et al., 2022b). That study employs BIM vision as a free IFC viewer and the Python programming language for the BIM spreadsheet connection and overriding colours according to specific value ranges. Moreover, this application could be further developed to display sensor data in real-time through the informative totem of the library or on the University website to provide users with current information on indoor comfort in each area.

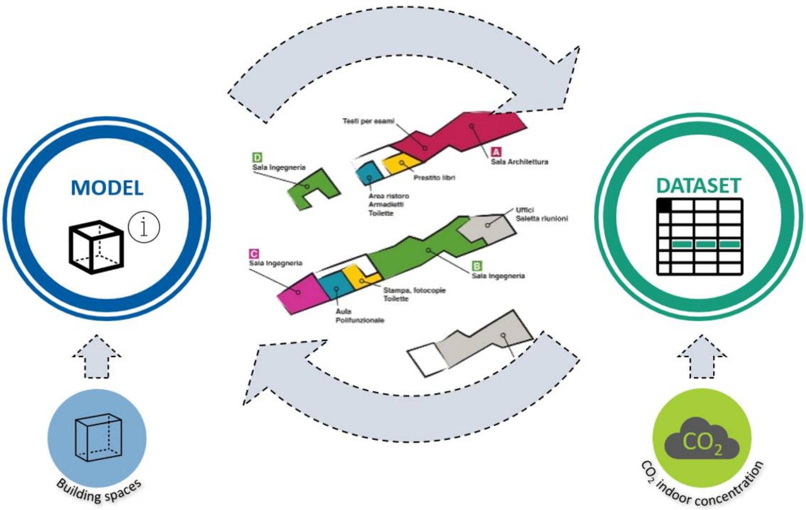


Figure 5.8 - Conceptual connection between the model and sensor data.

5.1.5 Renew-Wall - interoperability workflow

Users	Digital technology familiarity	Interface to do…	Interface to know…	Fruition solutions
Designers	Advanced	design the building covering with Renew-wall panels		BIM template with simplified library
Wood construction company	Advanced	cost estimation		BIM template with simplified library
		detail design definition		BIM template with detailed library
			manufacturing detail for CNC machines	Building Information Model in IFC format
Panel components suppliers	Variable		Necessary components quantity and characteristics	Schedules and bill of quantity
Client	Variable		design preview	Building Information Model in IFC format

Within the Renew-Wall research programme, aimed at defining a prefabricated panel system with a timber frame structure for energy retrofitting, a company active in the wood construction sector involved the LAMARC to define an integrated digital solution to support the entire workflow, from design to panel production and installation. The integrated digital solution had to be:

- easily usable by designers, replicable and adaptable to different configurations,
- implementable with detailed geometric as well as alphanumeric data,
- support information transfer both to CNC (Computer Numerical Control) machines to produce wood elements and to the suppliers of other components, such as windows and insulation panels.

For these reasons, the LAMARC team[96] developed a BIM template including a parametric library, representative of the different panel typologies. A library of parametric components is particularly effective for prefabricated building components with standardised geometric and technological features. After analysing and comparing different modelling strategies, as presented in detail in the contribution by Massari et al. (2022), parametric models of the four types of panels: full, window, door and corner, have been created. Each panel has been modelled starting from project drawings, according to the geometries and dimensions defined during the prototyping phase and including the necessary parametric flexibility to adapt each panel to different configurations in terms of size, technology and aesthetics.

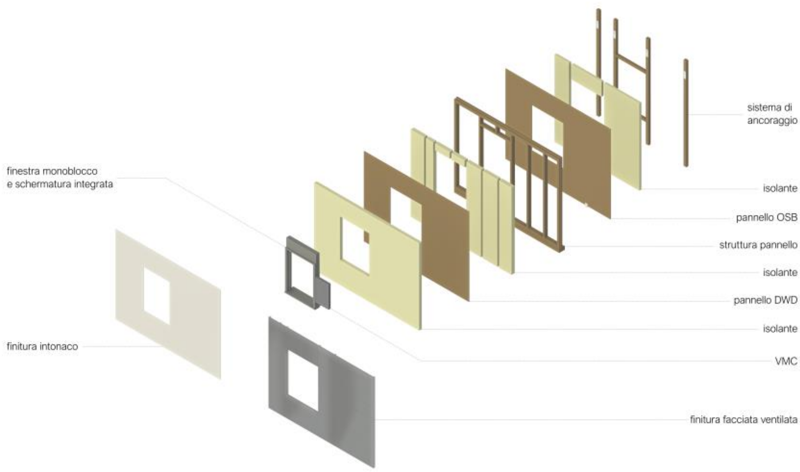


Figure 5.9 - Panel components and alternative finishings (Barbini et al. 2022c).

Based on collaboration and data exchange between different AECO professionals, this project offered the occasion for testing the multiple levels and dimensions of interoperability, i.e. technology, process, organisation and context, as described in Barbini et al. (2022c). The main technological challenge of the project concerned the data transfer from the BIM authoring to a CAM (Computer Aided Manufacturing) software, used to transfer project data to the CNC machines for the cut of wood components. For this reason, BIM-CAM interoperability, tested through

[96] Ambra Barbini (operative coordination), Elena Bernardini, Giovanna A. Massari (scientific coordination) and Oscar Roman

the visualisation of IFC file[97] through the CAM software[98] to verify the actual transmission of geometric and alphanumeric data previously modelled, has been a crucial parameter in defining the best modelling strategy. Conceived both as a synthesis of information on the different panel types and as a support tool for the exchange and management of information during the energy retrofitting, the BIM library is also at the heart of the workflow designed to ensure interoperability during the entire process, from project simulation to components production and assembly. Starting from a digital 3D survey of the building object of energy retrofitting, the workflow involves the design of the covering with the Renew-Wall panels in a BIM environment, from which the bill of panels necessary for the covering is then exported, as well as the bill of components necessary for the manufacture and assembly of each panel.

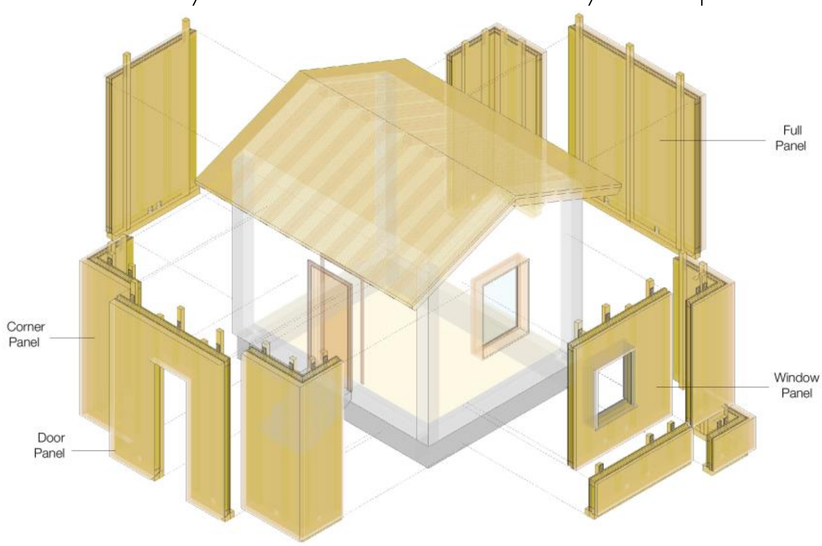


Figure 5.10 - Prototype building used to test the library of parametric panels for energy retrofitting (Barbini et al. 2022c).

The BIM template hosting the library answers the internal organisational issues of the company producing the Renew-Wall energy retrofitting system. Indeed, once the designer defines a covering design with a less detailed version of the library, the technical office can easily enrich the panel with information about the price to obtain quotations for custom-

[97] Developed in and exported from Autodesk Revit 2023.
[98] Dietrich's

ers. Moreover, the template permits each user to choose the best technological solution according to the building's peculiarity and to increase the level of detail of each panel to include all the necessary information to start the manufacturing process. Finally, the complementary tools, such as the presentation video (link) of the Renew-Wall system, and the manual, available in an extensive version in PDF format and in an abbreviated version directly in the BIM template, support the communication among different actors and facilitate the interoperability also at the context level.
The Renew-Wall project shows how efficient and entirely interoperable workflows can be developed when the partner network can fully exploit the opportunities offered by digital technologies, taking into account organisational, process and contextual aspects besides merely technological issues. We can look at the developed BIM template and library as a particularly flexible form of interface, supporting joint operation inside and outside the company that produces and instals the Renew-Wall system.

5.2 BHIM survey

The numerous meetings held with construction professionals working on the case studies outlined above raised the need to systematically gather the views of different categories related to the AECO sector on the research topics. While some professionals involved in research activities are beginning to benefit from the advantages of digital technologies, most still perceive them as distant and difficult to integrate into their daily workflows. However, the case studies offer only a partial opportunity to consider the point of view of AECO professionals, involving just a few actors. On the contrary, the creation, dissemination and analysis of a questionnaire makes it possible to simultaneously involve various categories of AECO professionals on different issues. The questionnaire, sharing its title "Built Heritage Interface Models – BHIM" with this research, has the dual ambition of stimulating interest in the research topics, reducing the gap between academia and professional practice, and taking a snapshot of current professional practice to investigate:

- how AECO professionals exchange data and whether they are taking advantage of the ongoing digital transition in their reciprocal collaborations, especially considering information access and data exchange;
- how they currently approach and use BIM in terms of application, software, formats, limits and potentials;
- how they perceive digital technologies considering interventions on the built heritage.

Although the research considers an international scientific context, the construction industry's digitization is not following a uniform path but is strongly affected by market evolution and national regulations (Figure 5.11). At the European level, but especially in Italy, the construction sector is mainly based on Small and Medium Enterprises (SMEs), most of which are micro-enterprises (European Commission, 2022). While larger enterprises can easily access the necessary resources for innovating internal processes and rapidly benefit from the digital transition, smaller enterprises could face a slower return on investment.

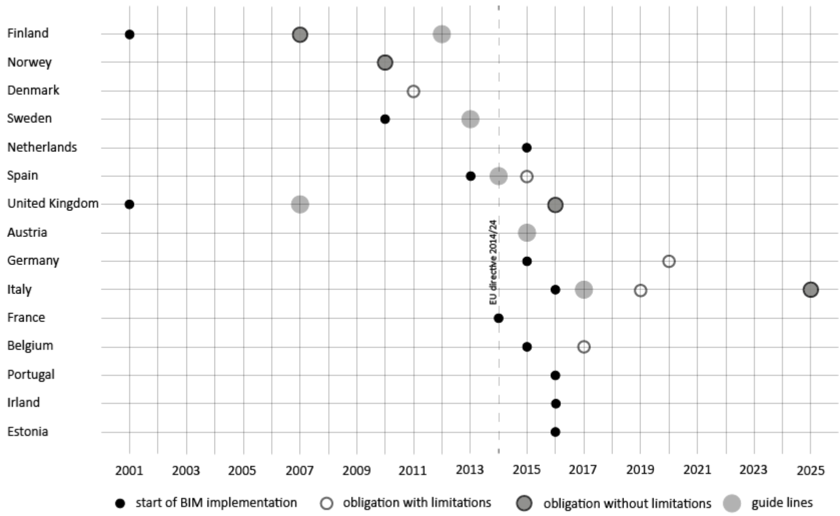


Figure 5.11 - BIM adoption in different European countries.

Even at the national level, the Italian economy is widely diversified and influenced by the geomorphologic features of the land, the presence of many family-owned businesses, the bond with the traditions and in some cases local autonomy.

Considering all these aspects, together with the fact that all the application experiences illustrated in the case studies took place at the local level, the predominant target audience of the survey was professionals active in Trentino.

Nevertheless, the questionnaire, developed in Italian, remained open to possible participants from other provinces, maintaining the possibility of filtering the results according to the respondent's origin. Thanks to the support and commitment of local stakeholders, the questionnaire offered valuable insight aimed at capturing not only average trends but also excellence in the digitisation of the construction sector. For this reason, the survey is structured in 6 parts, three dedicated to all the participants and others reserved only for professionals with at least a minimum familiarity with BIM methodologies and tools. The questionnaire also made it possible to assess how far the contents of the research are from the daily practice of local AECO professionals and the outcomes strongly oriented the solution selected for the collection and communication of the principal research outputs.

5.2.1 Creation and dissemination

The idea and the content of the survey evolved in parallel with the progress of the research activities. The survey development took advantage of discussions with some DICAM (Dipartimento di Ingegneria Civile Ambientale e Meccanica – Department of Civil Environmental and Mechanical Engineering) professors[99] and lecturers[100]. As anticipated the questionnaire is structured in sections and, besides a common introduction, there are two sections addressed to all the participants on data exchange (section 1) and built heritage digitization (section 4) and other reserved for respondents who:

- have basic knowledge of BIM (section 2A) or are already using BIM (section 2B);
- exploit open BIM applications (section 3);
- declare to need a geometric survey of built heritage at least sometimes (section 5).

Given this flexible structure, the survey can last between 5 and 15 minutes, respectively for participants responding only to the common sections and for respondents answering all the questions.

The introduction aims at collecting general information on the professional activities of the respondents. For example, each participant is asked to specify the range of employees of the company, to distinguish between micro (<10 employees), small (10-49 employees), medium (50-249 employees) and large (>250 employees) enterprises. However, all questions that may compromise the privacy of the participant (name, surname, company and e-mail address) are optional[101].

The section on data exchange focuses on data frequency and type of data exchange with other categories of AECO professionals, including some questions on digitization. Considering the literature review and based on the experiences gained through the case studies, the following categories of AECO professionals were identified: designers, construction companies, artisan companies, suppliers, counsellors and public bod-

[99] Albatici R., Dejaco M. C., Massari G. A. and Prada A.

[100] Cristofolini A. and Zuanni A.

[101] These as well as other personal data on the respondents are not considered relevant for the purpose of the questionnaire.

ies. Subgroups representative of the main professional activities were identified for some categories, as presented in Table 5.1, permitting the participants to add other unspecified groups or categories.

Designers	Construction companies	Artisan companies	Counsellor
architects	buildings	installations	design phase
engineers	infrastructures	finishings	construction phase
geometries	demolitions	restorations	validation phase

Table 5.1 - Subgroups identified for some of the professional categories.

The question on data exchange types (Q.1.4), is derived from a re-elaboration of the digital maturity level described in the UNI 11337-1 and illustrated in Figure 5.12. This question makes it possible to define an average “digital maturity level” of each category, distinguishing among the exchange of:

- documents, such as reports, sketches, pictures and tables;
- paper formats elaborations, such as archival documents;
- digital elaborations in proprietary format (e.g. .dwg);
- digital elaboration in open format (e.g. .dxf);
- building information models in proprietary format (e.g. .rvt);
- building information models in open formats (e.g. .ifc).

The question about BIM knowledge leads to the distinction among professionals who:

- use BIM in their working activities;
- have basic knowledge;
- are completely unfamiliar with the subject.

The first group is asked about reasons and satisfaction with BIM adoption, software and file formats. All the participants with at least basic BIM knowledge are asked about perceived advantages and potential applications of BIM, considering both new and existing buildings. All the other participants are redirected to the section on digitization of the built heritage. This section investigates the necessary information to work on the built heritage and leads the professionals who declare to need a geometric survey to the section on data acquisition and processing.

	0 - NON DIGITAL	1 - BASE	2 - ELEMENTARY	3 - ADVANCED	4 - OPTIMAL
Data transfer	**Non-digital,** mainly paper-based elaborations for all subject areas.	**Digital elaborations** for all subject areas.	Environmental and technical areas: **digital informative models**, integrated with digital graphic elaborations for details.Other areas: digital elaborations.	Product and process **information sheets** to relate data from digital models and other elaborations.	**Informative models**, for all subject areas.
Contractual agreement		**Paper support** of digital product content.	**Paper support** of digital elaboration and **digital support** of the informative models.	**Digital reproduction** of informative contents.	**Information content** of each model throughout the process.
Output	**Non-digital** project.	**Basic digital** project.	**Elementary digital** project.	**Advanced digital** project, partially relational.	**Informative model.**

Figure 5.12 - Synthesis of the digital maturity level of UNI 11337-1:2017.

The following tables report identification code and summarise the topic and type of each question, organised by sections.

Section 1 - Questions		
#	Topic	Type
Q.1.1	Professional categories	Multiple choice
Q.1.2	Data exchange frequency with other actors	Likert scale
Q.1.3	Interoperability levels frequency of use	Likert scale
Q.1.4	Data exchange types with other actors	Multiple choice matrix
Q.1.5	Digitized process	Multiple choice
Q.1.6	Need for education and training on BIM	Likert scale
Q.1.7	Interest for the investment in BIM education	Likert scale
Q.1.8	BIM knowledges	Likert scale

Table 5.2 - Questions on data exchange.

Section 2A - Questions		
#	Topic	Type
Q.2.1.A	BIM advantages for new and existing buildings	Likert scale matrix
Q.2.2.A	BIM uses for new and existing buildings	Multiple choice matrix
Q.2.3.A	BIM advantages in data sharing with other actors	Likert scale matrix

Table 5.3 - Questions for respondents with basic BIM knowledges.

Section 2B - Questions		
#	Topic	Type
Q.2.1.B	Reasons for BIM adoption	Multiple choice
Q.2.2.B	Satisfaction with BIM adoption	Likert scale
Q.2.3.B	BIM advantages for new and existing buildings	Likert scale matrix
Q.2.4.B	BIM uses for new and existing buildings	Multiple choice matrix
Q.2.5.B	BIM advantages in data sharing with other actors	Likert scale matrix

Q.2.6.B	BIM content development	Multiple choice matrix
Q.2.7.B	BIM software in use	Multiple choice
Q.2.8.B	Common Data Environment in use	Multiple choice
Q.2.9.B	BIM content exchange formats	Multiple choice

Table 5.4 - Questions for respondents who use BIM.

Section 3 - Questions		
#	Topic	Type
Q.3.1	BIM software in use for open formats files	Multiple choice
Q.3.2	Main difficulties in the use of open formats files	Multiple choice

Table 5.5 - Questions on open BIM procedures

Section 4 - Questions		
#	Topic	Type
Q.4.1	BIM advantages for new and existing buildings	Likert scale matrix
Q.4.2	BIM uses for new and existing buildings	Multiple choice matrix
Q.4.3	BIM advantages in data sharing with other actors	Likert scale matrix

Table 5.6 - Questions on built heritage digitization.

Section 5 - Questions		
#	Topic	Type
Q.5.1	Frequency of a	Likert scale matrix
Q.5.2	BIM uses for new and existing buildings	Multiple choice matrix
Q.5.3	BIM advantages in data sharing with other actors	Likert scale matrix

Table 5.7 - Questions on metric data acquisition and processing.

The survey is completed with a brief introduction to clarify the context and the purposes of the investigation and provide essential data on the questionnaire structure and duration. Moreover, all the respondents are requested to read a complementary sheet offering more information on the research project and the questionnaire. This sheet also reports that:

- information on individual participants will remain confidential and any identification data will be deleted at the end of the work;
- all material collected will be stored securely and only researchers involved in the project will have access to it;
- once processed and aggregated, the data of the questionnaire could be presented or published to share the outcomes of the project.

Since the questionnaire does not imply any direct risk to the psycho-physical well-being of the subjects involved or limits their right to confidentiality, information and autonomy of decision-making, it was not necessary to submit the study to the research ethics committee.

Developed as a Google Forms, the survey is mostly based on a Likert scale but also includes some multiple-choice questions and some matrices based on a series of multiple choice or Likert scale (table B-G). Moreover, often it is possible to add a new field and integrate comments or further explanations. Polo Edilizia 4.0, a cluster of all the main AECO institutions[102] in Trentino, supporting innovation in the construction market, provided a key contribution to validate the questionnaire and its subsequent dissemination. Most AECO institutions associated with the Polo Edilizia 4.0 actively contributed to the dissemination among their members between November 2023 and January 2024, by sending an email, including the link to the Google Forms of the BHIM survey. During the dissemination phase, the number of participants in each category

[102] Founding members: ANCE Trento, Associazione Artigiani Trento, Confindustria Trento, Collegio Geometri Provincia di Trento, Consiglio Nazionale delle Ricerche, Cooperazione Trentina, Green Building Council Italia, habitech, Ordine degli Architetti Pianificatori, Paesaggisti e Conservatori della Provincia di Trento, Ordine degli Ingegneri della Provincia di Trento, Ordine dei Periti Industriali e dei Periti Industriali Laureati della Provincia di Trento. More information is available on the website: https://www.poloedilizia.tn.it/. Last access: 15.10.2024

was monitored to promote the acquisition of representative data for the entire AECO sector, however, some categories were particularly complex to reach, both as individuals and through representative associations.

5.2.2 Data processing

The dissemination produced 205 answers from all the abovementioned professional categories, including researchers. An Excel spreadsheet with all the answers facilitated the development of graphs and statistics, according to a previous experience documented in Codemo et al. (2023). For the Likert scale questions and multiple choice admitting a single answer, the percentage of each option has been calculated and displayed through pie or bar diagrams. In some cases, to draw a comparison between different categories of respondents, for Likert scale questions the weighted average has been calculated. For the multiple-choice questions admitting several answers, the total number of responses for each option is calculated and visualised through bar diagrams. For Likert scale matrices and closed multiple choice matrices the percentage of each option is calculated, and data are visualised through stacked or grouped bar diagrams. In the case of open multiple-choice matrixes, the total responses for each option have been calculated and displayed through grouped bar diagrams.

The following pages include brief comments on the collected data[103], selecting the most meaningful insights from each section. Almost all the respondents are from the Trentino-Alto Adige region (98%) and a large part of them are micro enterprises (73%), only some of them are small enterprises (21%), while medium (3%) and large (2%) enterprises are almost absent. Most respondents are designers (71%), followed by construction companies (16%), while only a few public bodies, counsellors, suppliers and artisan companies answered the questionnaire. Among designers, most survey participants are geometers (80%) and only a few are architects (10%) or engineers (10%). Considering construction companies, most respondents are involved in the realisation of buildings (56%), fewer infrastructures (38%) and only a few works in demolition companies (6%). Most counsellors declared to be mainly active in the design phase (61%), some in the construction phase (31%) and only few in the validation phase (8%).

[103] Please note that in some cases the sum of the percentage could be less than 100 due to some non-represented decimals.

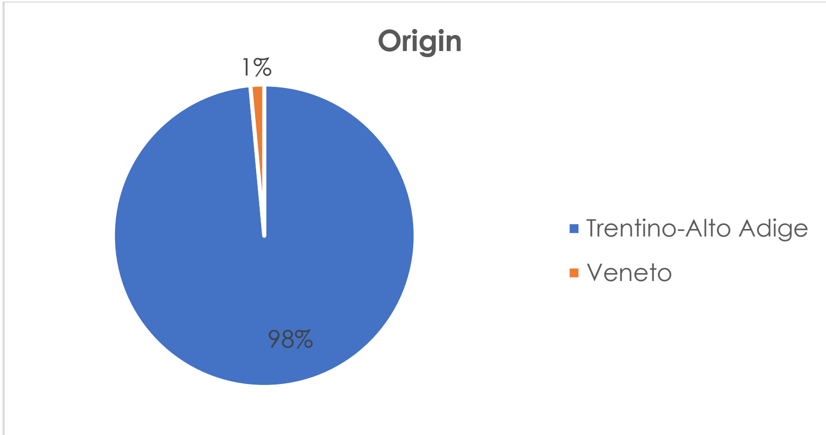


Figure 5.13 - Origin of respondents.

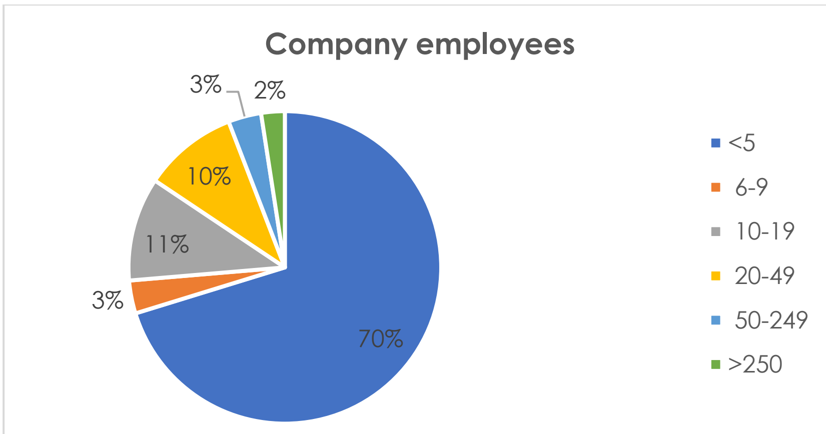


Figure 5.14 - Number of employees.

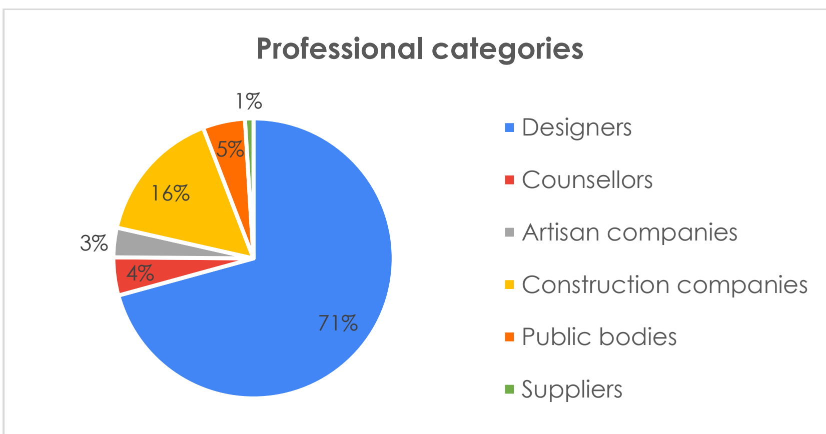


Figure 5.15 - Professional categories.

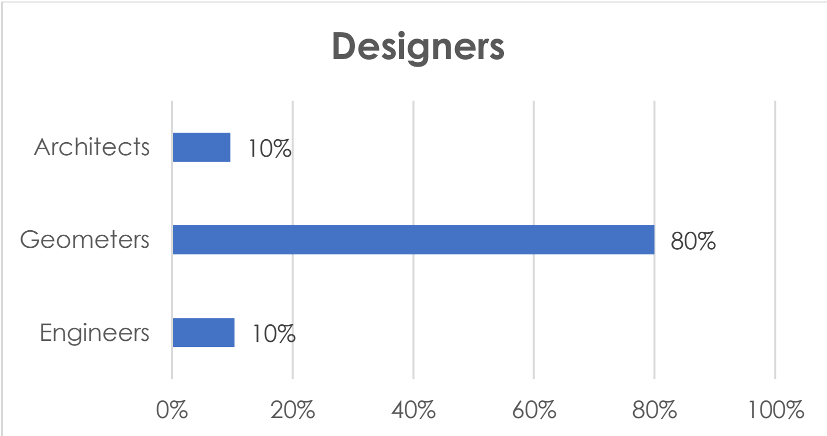


Figure 5.16 - Designers' sub-categories.

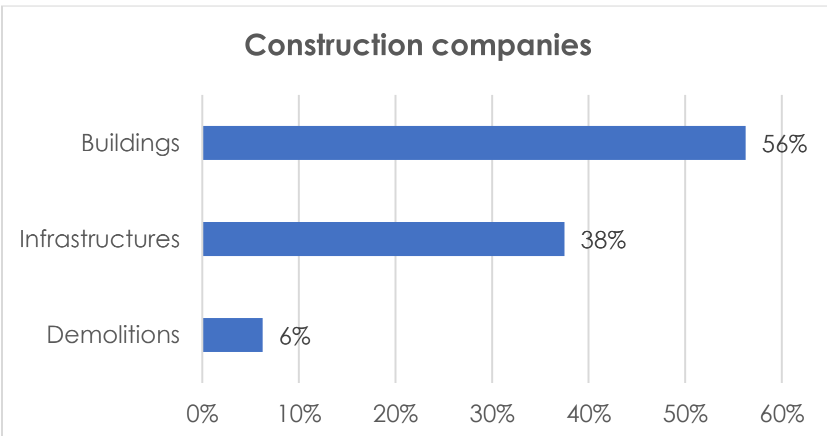


Figure 5.17 - Construction companies' sub-categories.

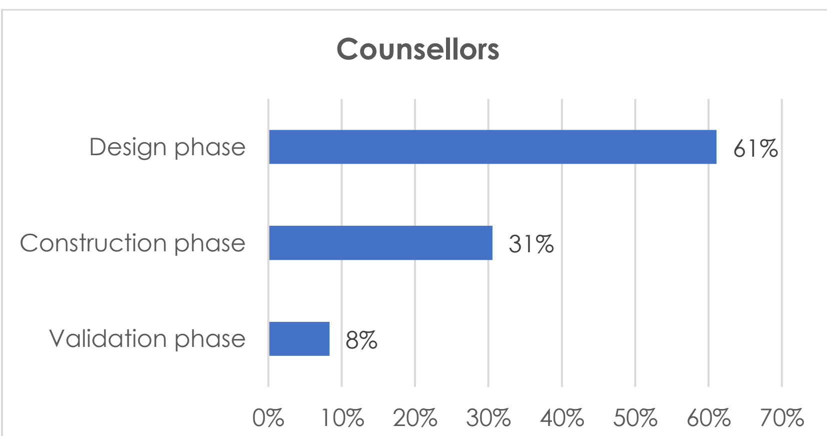


Figure 5.18 - Counsellors' sub-categories.

Observing the frequency of data exchanges, it is possible to notice that participants have frequent or extremely frequent data exchanges with clients and designers, followed by public bodies, construction companies and artisans. While with suppliers and counsellors, the exchanges are mostly occasional or rare.

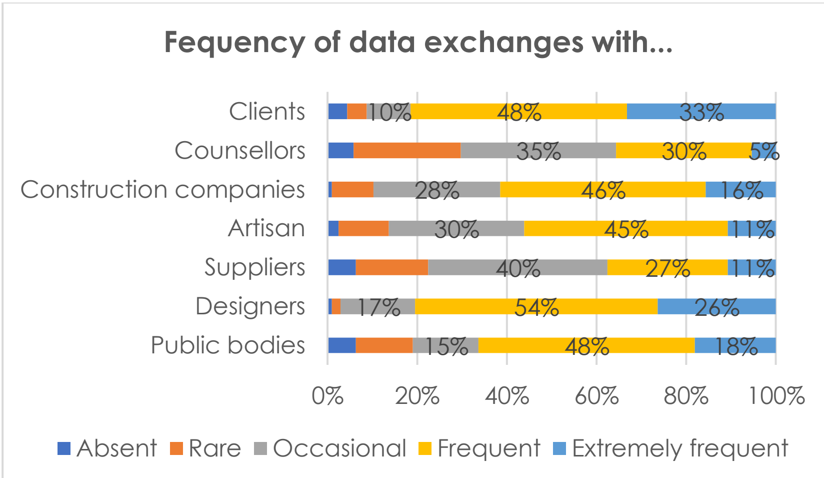


Figure 5.19 - Frequency of data exchange among different categories.

Considering the European interoperability framework, previously presented (Chapter 2.2), most respondents declared that technical aspects are often considered, organisation and semantic aspects are considered only sometimes, while legal aspects are rarely considered. These data also show how interoperability is mainly associated only with technical issues, without considering all the other aspects.

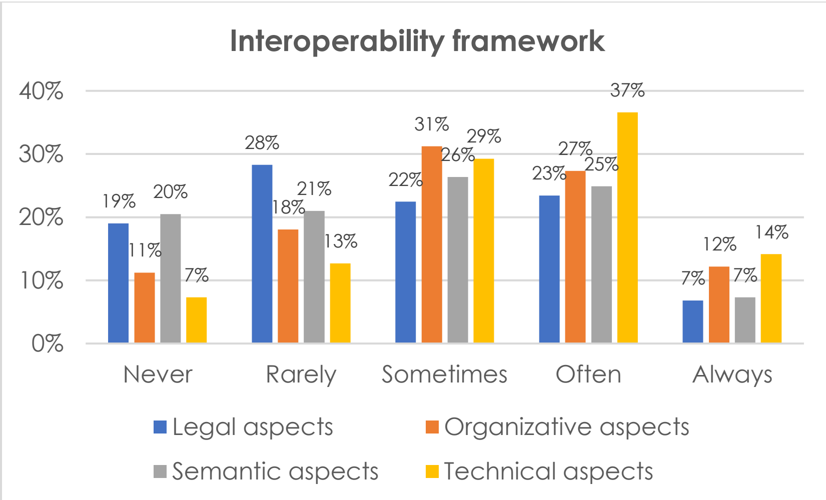


Figure 5.20 - Frequency of consideration of different interoperability aspects.

From the analysis of data types exchanged among the various actors emerged that:

- most respondents exchange digital elaborations in proprietary formats and this can be approximately associated with a general base level (1) of digital maturity according to UNI 11337-1;
- also the exchange of paper elaborations and miscellaneous documentation is quite common;
- only a few professionals use digital models for data exchange, slightly preferring open over proprietary formats;
- multimedia contents are mainly exchanged with clients.

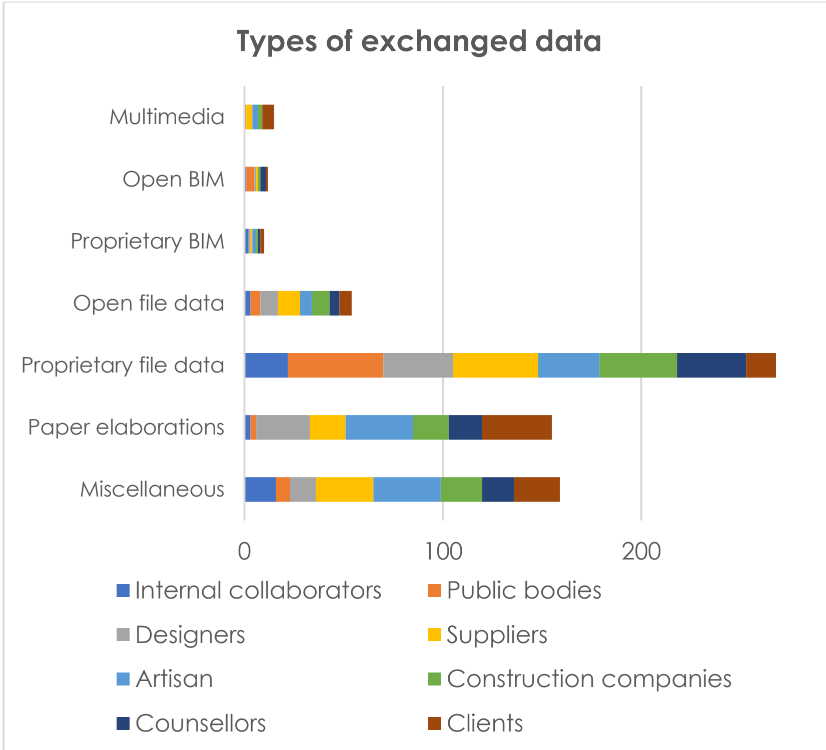


Figure 5.21 - Mainly exchanged data types from different categories.

Among the most digitised processes, emerged computation and quotations, executive projects and administrative practices, while the less digitized are orders of supplies. Most respondents declared to perceive the need for information and updates more than enough (83%), as well as to be interested in BIM educational investments (72%). The high interest in BIM information and education is justified also by the fact that most participants have basic or absent knowledge of BIM (78%).

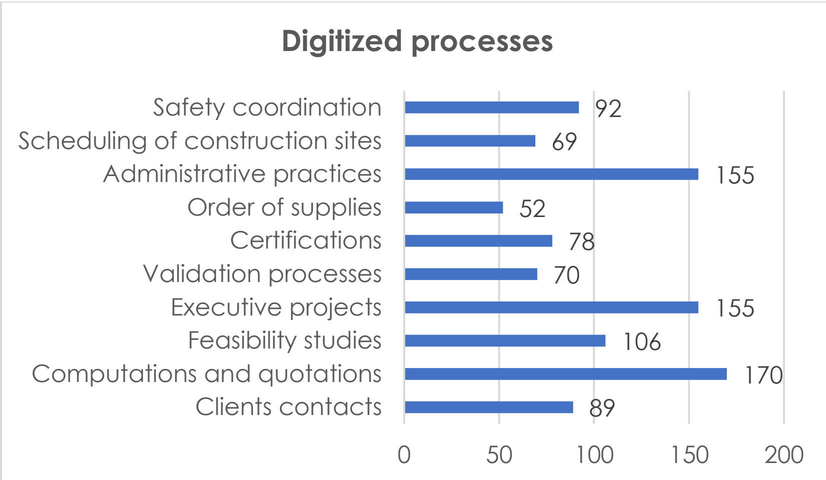


Figure 5.22 - Most digitized processes.

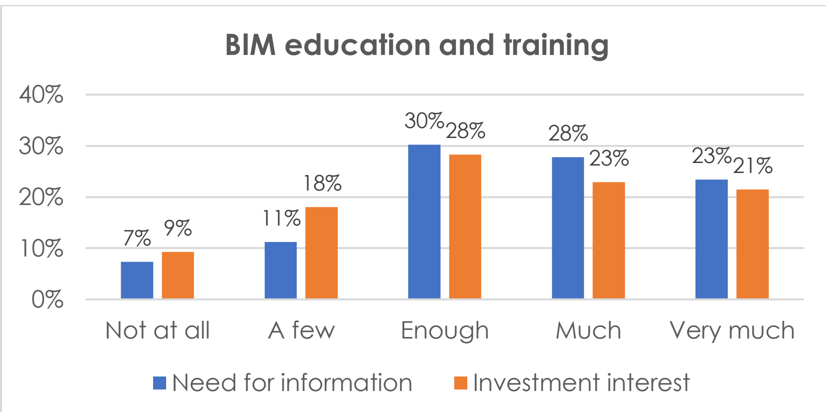


Figure 5.23 - Interest in BIM education and training.

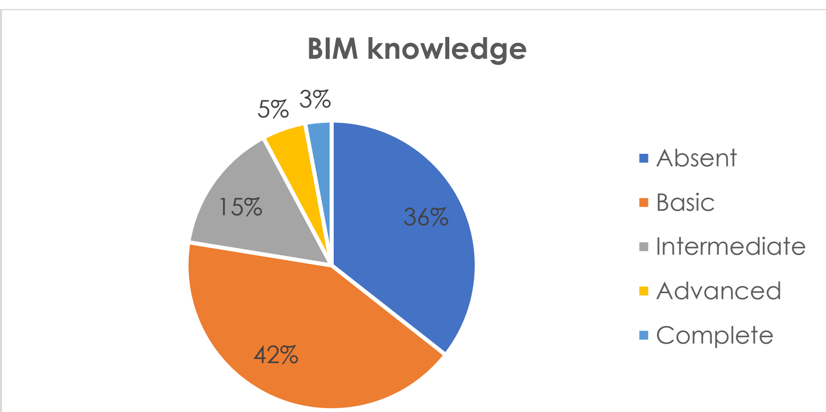


Figure 5.24 - Self-assessed BIM level of knowledge.

Comparing the point of view of respondents who only have basic knowledge of BIM and actual users, it is possible to notice that:

- the perceived advantages of BIM are higher among BIM users both for new and existing buildings;
- the most common BIM expected applications (non-BIM users):
    - for new constructions are project development, quantity take off, simulations and documentation production,
    - for existing buildings are analysis and documentation, project development and simulations;
- the most common BIM actual applications (BIM users):
    - for new constructions are project development, documentation production and quantity take off,
    - for existing buildings are project development, documentation production and analysis and documentation;
- communication advantages are mostly expected and confirmed with designers and internal collaborators, even if in general experienced communication advantages are higher than expected from non-BIM users.

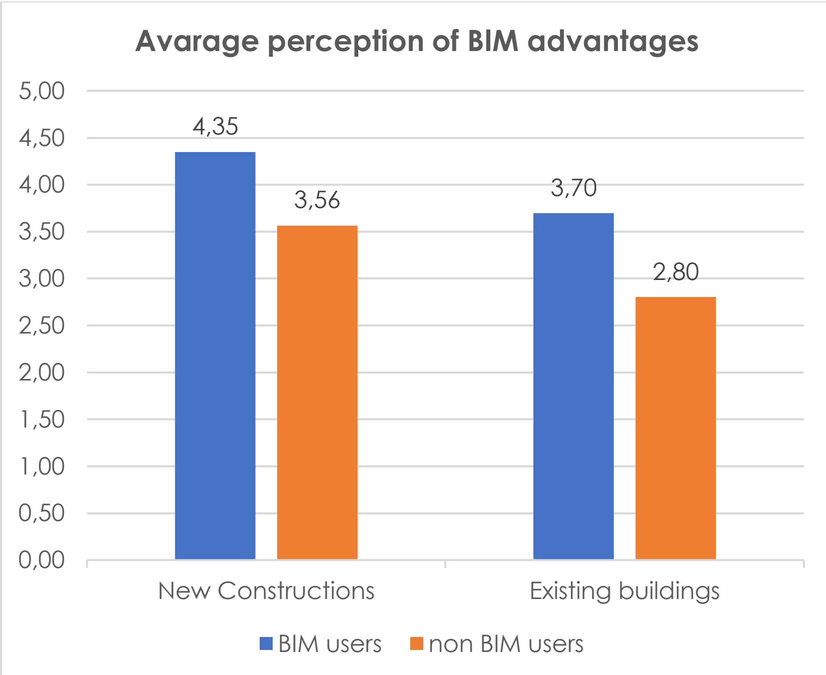


Figure 5.25 - BIM advantages perception among BIM users and non-users.

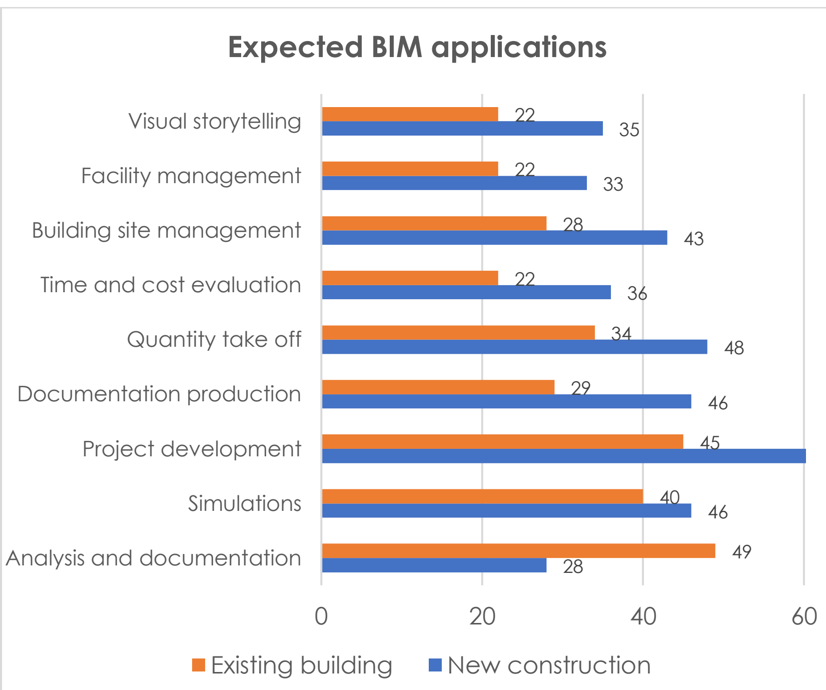


Figure 5.26 - Expected BIM applications for existing and new buildings.

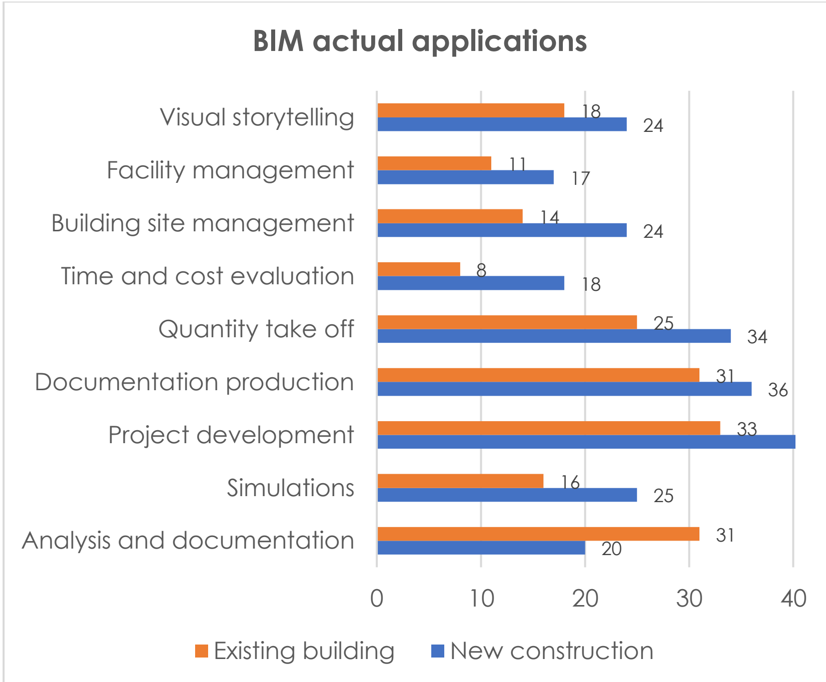


Figure 5.27 - Actual BIM applications for existing and new buildings.

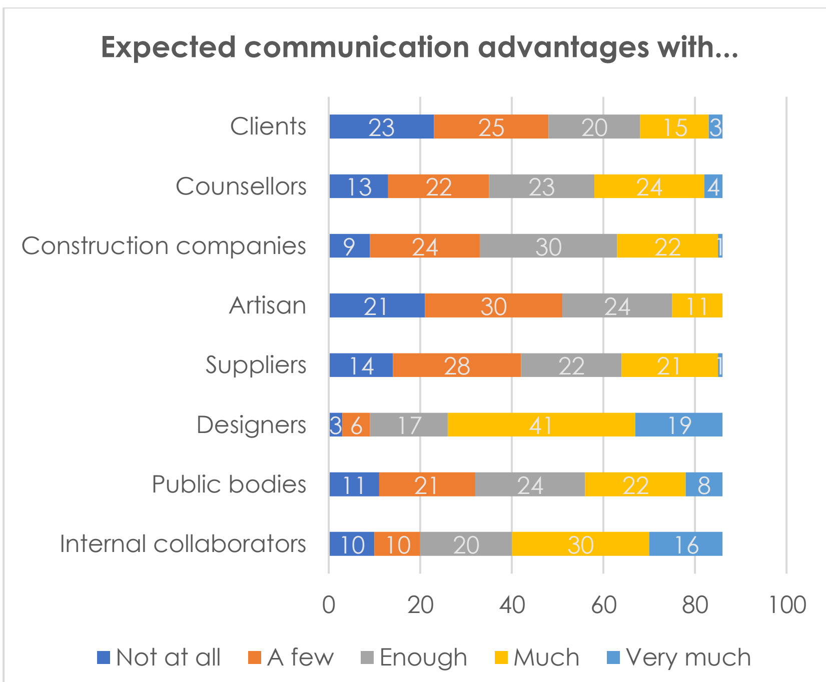


Figure 5.28 - Expected BIM communication advantages with different categories.

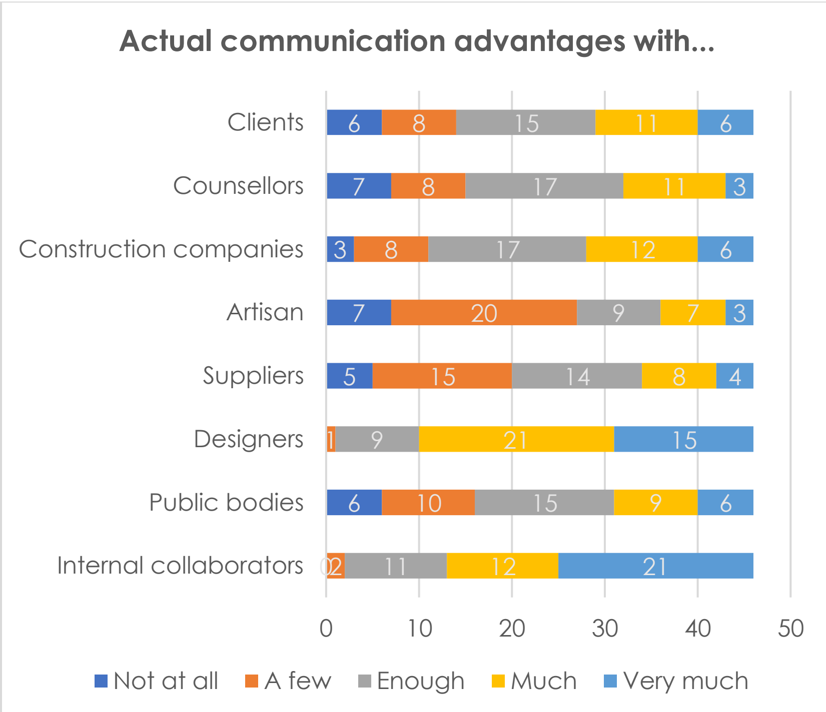


Figure 5.29 - Actual BIM communication advantages with different categories.

Considering respondents who declare to use BIM:

- the main reasons for BIM adoption are the greater control over the project, as well as costs and resource optimization;
- most of them are satisfied with the investment;
- among the contents and processes internally managed, the most common are executive projects, feasibility studies and quotations;
- among the contents and processes externalised, the most common are specific BIM object libraries, generic BIM object libraries and executive projects;
- the most common BIM software is Autodesk Revit (25 respondents), followed by Acca Edificius (11 respondents);
- the most common CDE (Common Data Environment) is Autodesk BIM 360, even though many respondents declare to have never used a CDE;

- Autodesk Revit (11 respondents) and BIMvision are the most commonly used software for opening a BIM file in an open format;
- Information visualisation (47%) is the most common challenge in the use of open format files, only a few experience difficulties in data processing (19%) or geometry visualisation (17%) and some respondents declare to face no issues at all (17%).

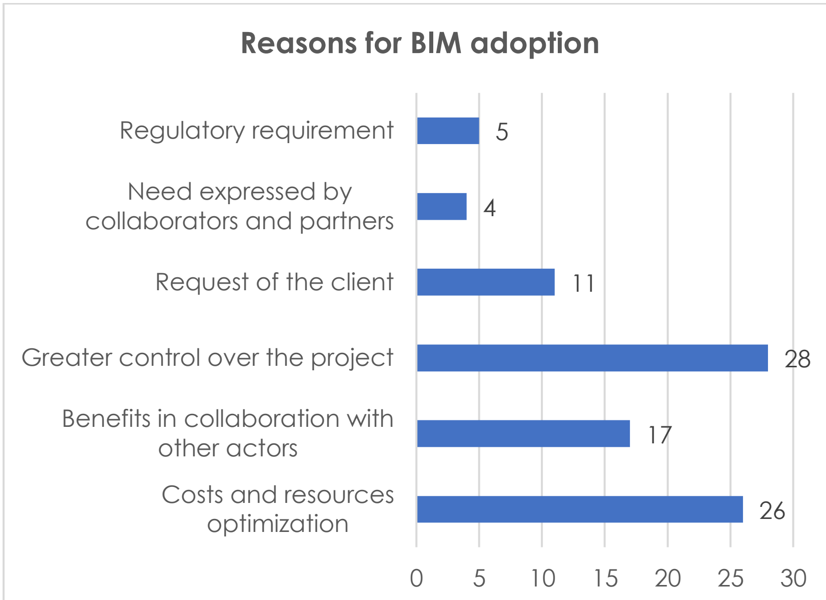


Figure 5.30 - Most common reason for BIM adoption.

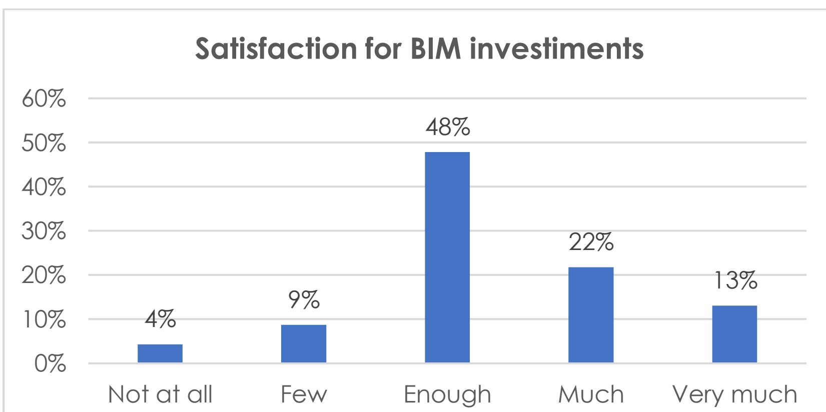


Figure 5.31 - Level of satisfaction for BIM adoption.

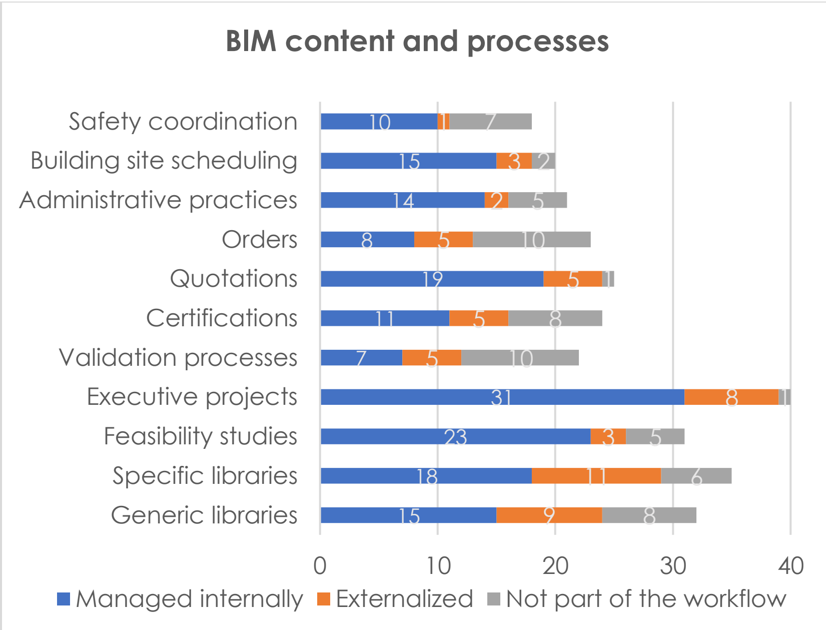


Figure 5.32 - Most common BIM applications.

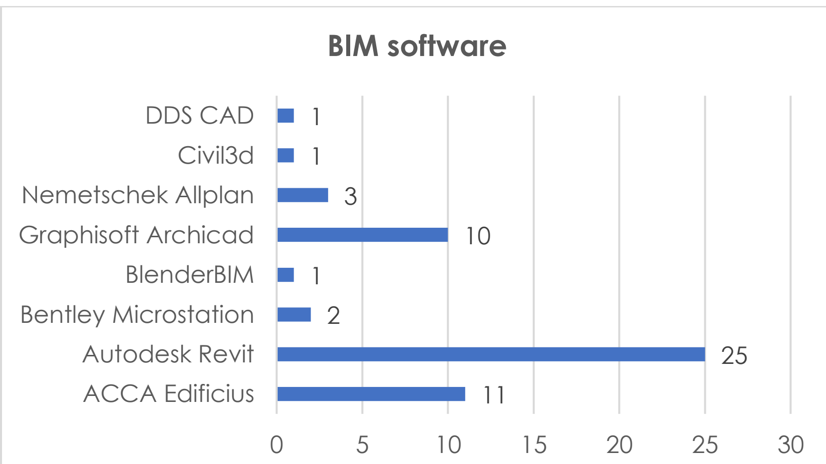


Figure 5.33 - Most common BIM software.

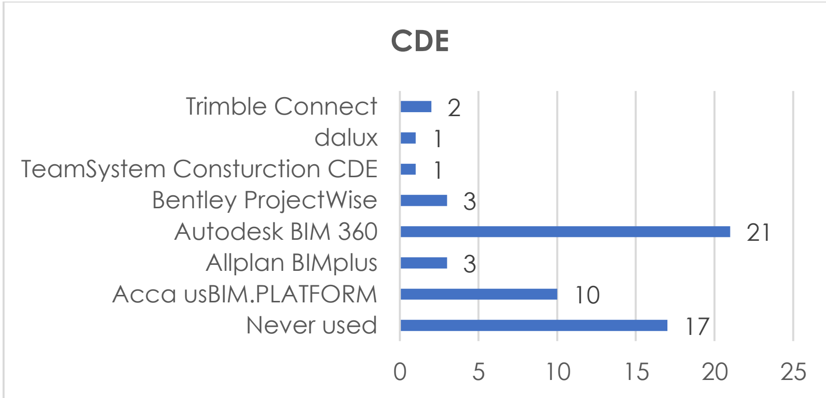


Figure 5.34 - Most common CDE platforms.

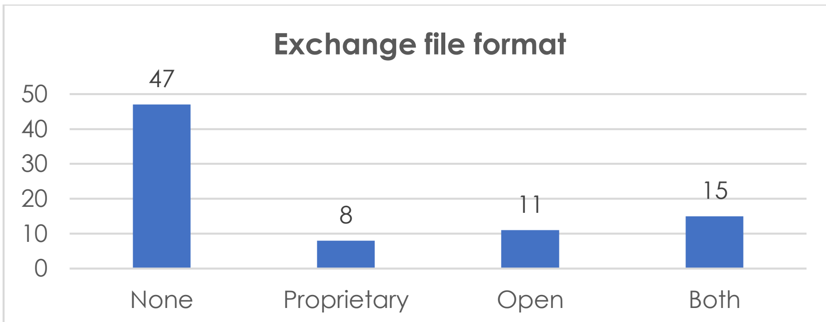


Figure 5.35 - Most common exchange formats.

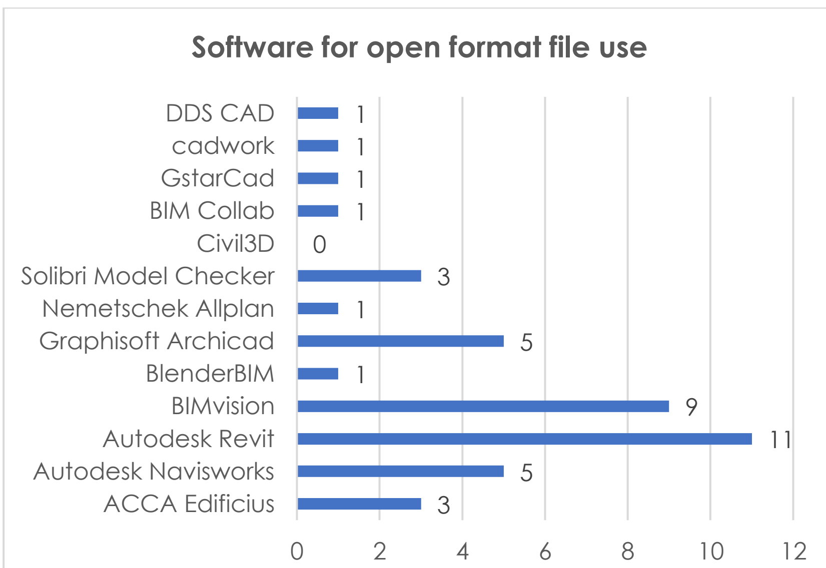


Figure 5.36 - Software in use to access open format files.

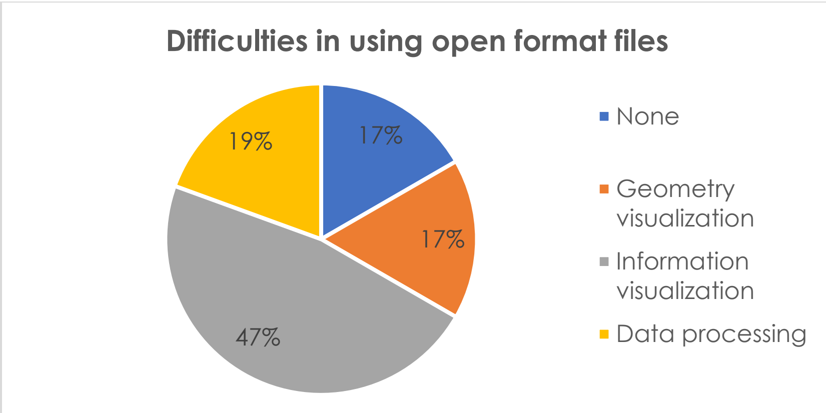


Figure 5.37 - Most common difficulties with open format files.

Considering the questions on heritage buildings:

- most respondents declare to often work on existing buildings (67%);
- project drawings, cadastral documents and metric surveys are the most required data;
- architectural surveys are often (41%) or always (42%) requested and most of the time are managed internally (80%);
- the most common acquisition tools are laser distance metres, total stations, tradition handmade survey tools and low-cost photo cameras;
- acquired data are mostly processed using 2D CAD applications.

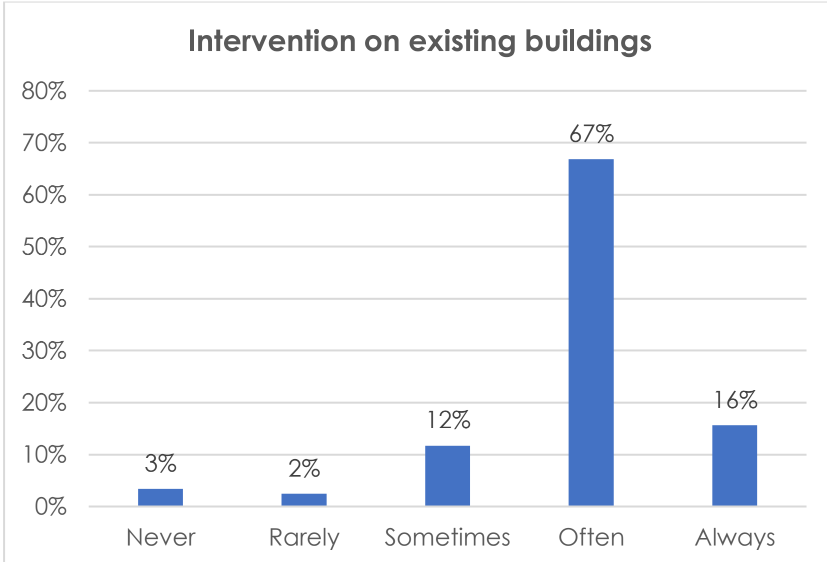


Figure 5.38 - Frequency of intervention on existing building.

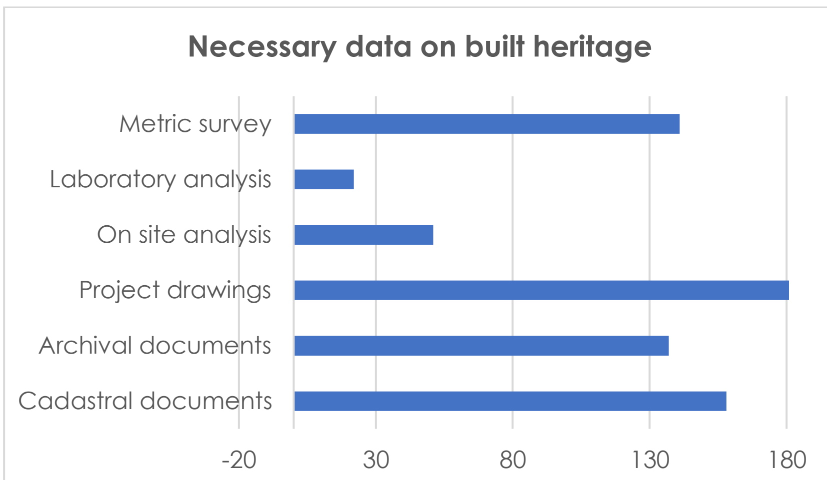


Figure 5.39 - Necessary data for intervention on existing buildings.

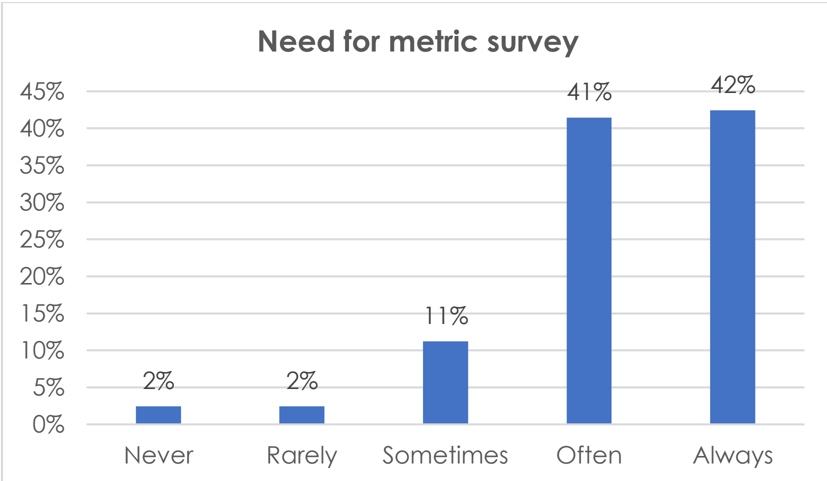


Figure 5.40 - Frequency of need for metric survey.

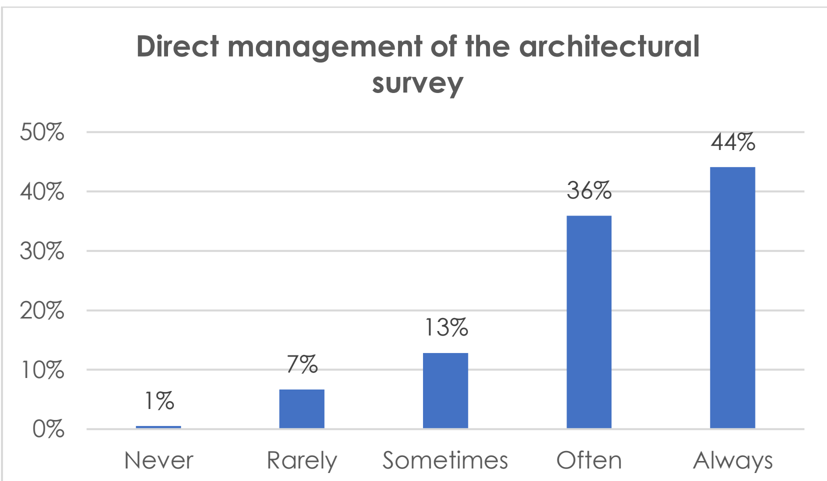


Figure 5.41 - Frequency of direct survey management.

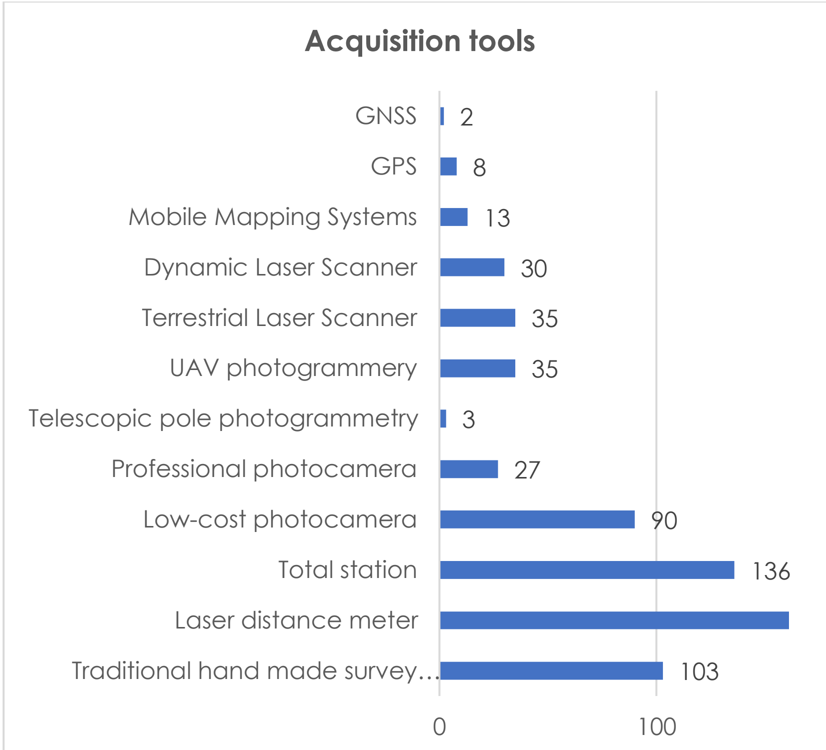


Figure 5.42 - Most common survey acquisition tools.

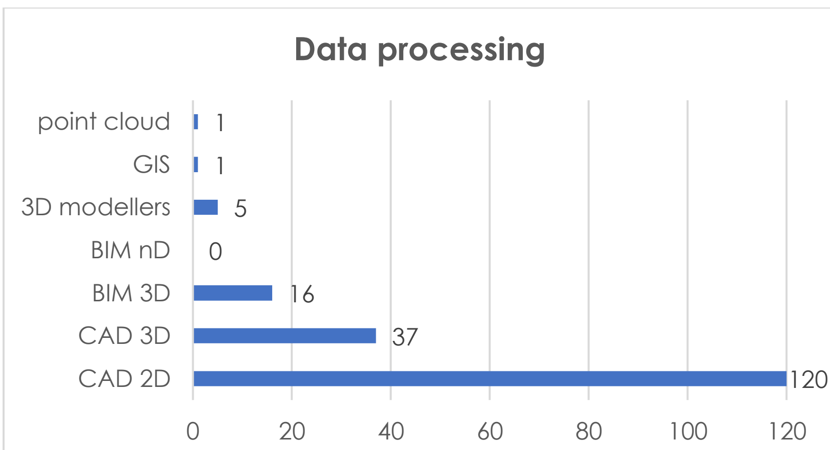


Figure 5.43 - Most common data processing tools.

5.2.3 Considerations

The questionnaire results reveal a local context mainly characterised by micro-enterprises strongly interconnected where the digital transition is still in its early stages, but most participants are willing to commit to making progress in this direction.

Despite most participants declaring to have frequent data exchange with others, collaborations are still mainly based on traditional tools, such as digital elaborations in proprietary format (e.g. .dwg), paper elaborations and miscellaneous documentation. Similarly, despite exceptional cases of professionals using advanced technologies for architectural surveys, most still use low-cost and traditional tools.

The same happens during the processing phase, mainly based on 2D CAD environments. In terms of digital transition, it is possible to notice how, more than half of the respondents have at least basic knowledge of BIM, but less than one-third use it, and more than one-third declare not knowing BIM at all, so there is a strong need for education and training.

Most BIM users state that the reasons for adoption are mainly due to perceived opportunities rather than regulatory requirements or requests from principals or partners. The question comparing the use of BIM for existing and new buildings, confirms the literature review data, highlighting how BIM methodologies and tools are more suitable for new constructions.

Many BIM users report finding significant benefits and applications in the built heritage area as well. It is also interesting to notice that some of the participants consider the different aspects of the European interoperability framework at least sometimes. However, the entire sector could benefit from an increased awareness of interoperability on multiple issues, especially on legal aspects.

Considering the professional groups of respondents, it is possible to notice how the local community of geometers appears quite enthusiastic about the new technologies, as well as designers in general. On the other hand, the actors who were more difficult to engage, such as artisans and suppliers, also appear to be the most distant from adopting digital tools. Despite requiring more complex elaboration processes, matrix questions offer the advantage of a broader overview of some specific aspects and, in this case, of an insight into the less represented AECO professional categories.

As well as for other research outputs, the collected data are open to possible integrations in terms of both further dissemination and data analysis. In general, the survey proved to be a useful tool to better understand the dynamics among professionals on the research topics.

5.3 BHIM tools

The direct experiences with local built heritage stakeholders and the indirect knowledge gained through the questionnaire consolidated the idea that bridges between researchers and final users can bring meaningful benefits to both parties. On the one hand, the actual needs of the final user can help in orienting, enriching and validating research activities. On the other hand, small and medium enterprises in the AECO sector often have very tight work rhythms and lack the resources for development and innovation. Moreover, some stakeholders may have the economic resources to manage the built heritage innovatively but not the expertise to identify the most suitable solution.

Considering the impact of both local stakeholders and AECO professionals on the research activities presented in this study, the promotion of further exchanges and collaborations represents a precious opportunity for both sides. For all these reasons, a set of three tools has been developed with the main aim of offering insight into the main research outputs to all the interested stakeholders.

These tools cover progressively more specific topics, from interface options to modelling strategies, up to collaboration enhancement, without any ambition to offer definitive or integral solutions. On the contrary, the goal is to guide, orient and support those moving the first steps in the field of built heritage interface models or to provide a second opinion, confirmation or an opportunity for discussion to those who have already matured a vision or defined a strategy. The first tool on interface types addresses a broader audience of all stakeholders working on or with the built heritage. The other tools are mainly aimed at AECO professionals, and particularly those who already have some basics knowledge of 3D modelling, in the case of the second tool, and anyone involved in the built heritage life cycle, in the case of the interoperability checklist tool.

In developing these tools, an online platform[104] facilitating the creation of online forms and surveys in engaging and dynamic formats has been

[104] Demo version of Typeform (link)

tested. In addition to a wide range of question types (e.g. multiple-choice, matrix, rating, ranking) that can be customised in shape and content, this platform offers the possibility of defining logical connections to give tailored feedback based on the answers provided by each respondent (Fig. 5.44). Therefore, interested users can receive immediate and synthetic feedback, as well as references and contacts for further investigations and discussions.

Moreover, this platform supports the collection and analysis of responses provided, supporting the further development of the study and eventually an improvement of these tools. However, these possibilities still need to be tested, since the developed tools have been validated only within the LAMARC working group. This stage of development is compatible with the demo version of the online platform used, which permits a maximum of 10 answers for each tool. Developed during the final phase of the research, this set of tools only has a medium-low readiness level and can be considered more an interactive synthesis of some of the research outputs, as well as an anticipation of possible future developments, rather than an arrival point.

The three tools presented in the following pages reflect some of the questions recurring during the research, coming from the analysis of the literature review, the study and observation of different workflows and approaches. These tools also benefit from direct experiences in communicating built heritage content, in developing Heritage Building Information Models and in accomplishing effective and interoperable collaborations.

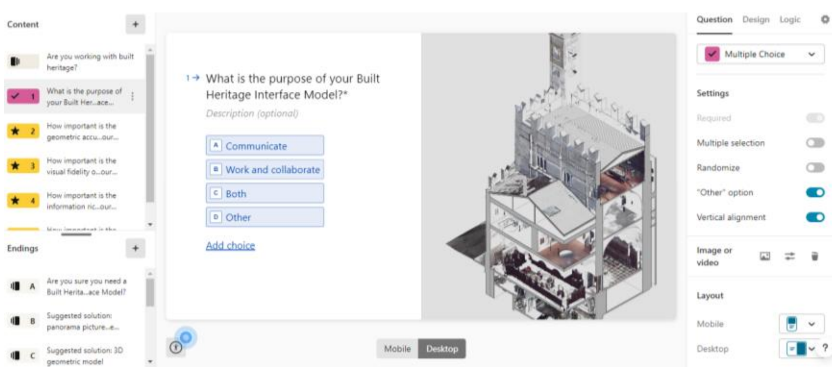


Figure 5.44 - Interface of the online platform used.

5.3.1 Built Heritage Interface Model types

The first tool developed focuses on the selection of the best solution as *Built Heritage Interface* among different *Model* solutions. The first crucial step included the analysis of the different built heritage representation forms, considering various possible approaches, from exclusively geometric contents to information inclusion, up to visually and spatially organised solutions. Combining the experiences collected through the case studies presented in the modelling phase section (Chapter 3.3) and the fruition phase section (Chapter 4.1), three main categories have been identified:

- 3D geometric Models (3DM), which include discrete and continuous models, respectively point or line-based and surface or solid models;
- 3D geometric and informative models, which correspond to the adoption of the BIM methodology for the description and documentation of heritage buildings, namely HBIM;
- Extended reality models (XR), which include virtual, mixed and augmented reality models, enabling dynamic and interactive fruition experiences.

According to the literature review and considering the experiences collected through the case studies, each category has been further decomposed up to single model types, with different peculiarities in terms of costs, opportunities, advantages and shortcomings. The first two categories of models are developed from metric data, such as an architectural survey or project drawings, and can therefore have different levels of reliability. The third category differs from the others in the possibility of communicating visual content (e.g. images, text, audio, links, models, ...) organised in a 3D space, independently of a metric reference. This category is analysed according to possible applications in virtual, mixed or augmented reality, and considering the type of content with which they can be enriched, such as images, information and models.

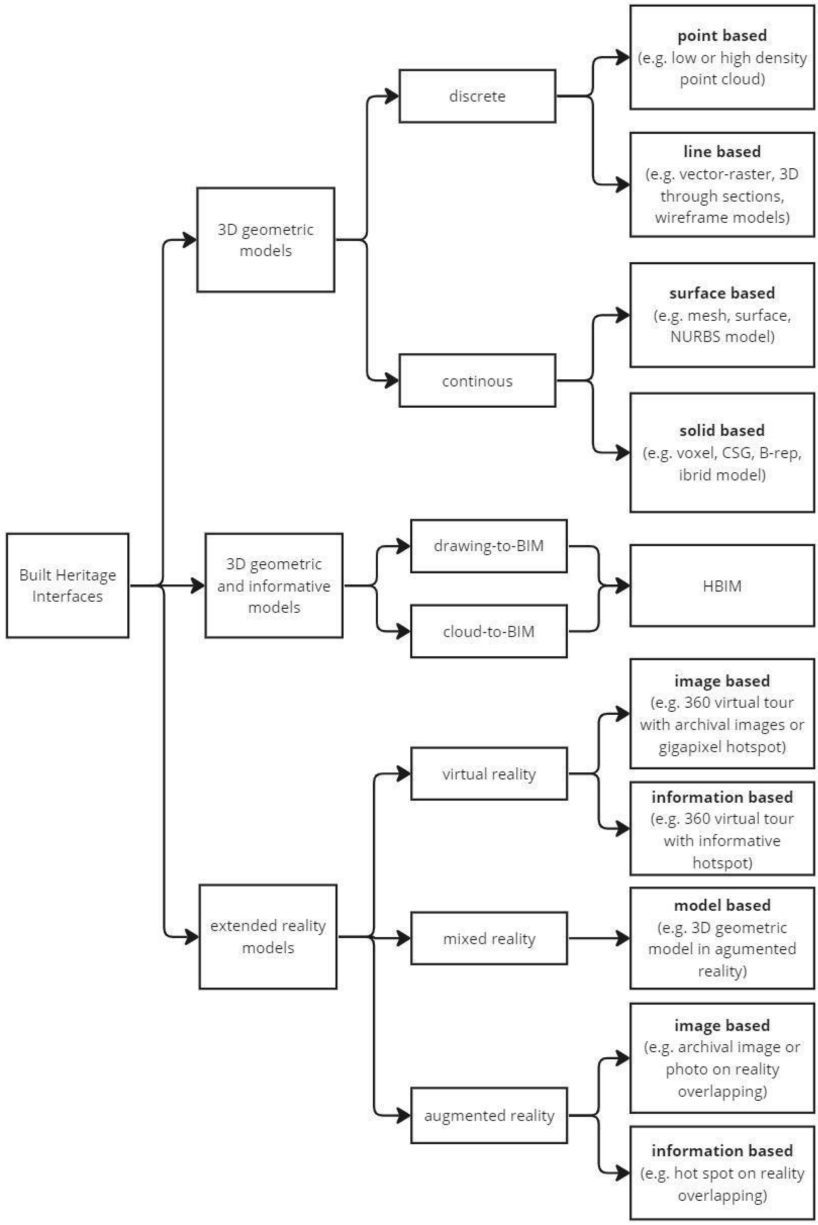


Figure 5.45 - Diagram representing different Built Heritage Interface Models.

Despite not having explicit sub-categories, HBIM can derive from different data sources (e.g. geometric survey or project drawing) and lead to various levels of development (UNI 11337-4) and grade of accuracy (Brumana et al., 2020). Moreover, in developing a Heritage Building Information Model, it could be necessary to balance visual fidelity and parametric flexibility, as well as geometric accuracy and information richness (Radanovic, 2020). Moving from these considerations on HBIM variables, four parameters have been identified to evaluate and compare each model type: visual fidelity, geometric accuracy, detail richness and information richness. These parameters, borrowed from the literature review on HBIM and shortly described in the following lines, resulted particularly suitable for defining different possible priorities in the analysis and evaluation of the previously identified model types.

Visual fidelity refers to the representation of the visual aspects of a building, such as architectural features, materials, and textures. It encompasses the faithful recreation of the appearance of the building, ensuring that it closely mirrors the original design and condition.

Geometric accuracy denotes the precision and correctness of the digital representation in terms of spatial dimensions, proportions, and relationships. It involves measurements and data capture techniques to correctly represent the geometry of single elements and spatial layout.

Detail richness consists of the careful representation of details, such as architectural ornamentation, degradation features, and craftsmanship nuances. It involves meticulous data capture or comprehensive documentation, but above all the analysis and interpretation of the visible traces and details of the buildings.

Information richness refers to the repository of information embedded in the model, integrating diverse datasets and metadata. It can be measured according to the depth and breadth of data encapsulating various aspects of the model, which can include historical context, construction materials, structural elements, and conservation details.

Each model type has been rated according to these parameters, considering the maximum achievable performance that could be reached given the peculiarity of each alternative and leading to the definition of logical operators for the selection of a specific model option according to the final user's purposes and priorities (Table 5.8).

Model type	Visual fidelity	Geometric accuracy	Detail richness	Information richness
Point-based	***	***	*	*
Line-based	*	***	***	*
Surface-based	***	***	**	*
Solid-based	***	***	*	*
HBIM	***	***	***	***
Image-based VR	***	-	***	*
Information-based VR	***	-	*	***
Model-based MR	according to model type			
Image-based AR	-	-	***	-
Information-based AR	-	-	-	***

Table 5.8 - Rating of the different model types according to the selected parameters.

While geometric models and heritage building information models have been extensively discussed, it is worth noting how XR can be analysed through the lenses of these four parameters. In the case of virtual reality models, considering, for example, a set of interconnected panoramic images, creating a virtual tour, we can say that this model has a high level of visual fidelity. Moreover, it is possible to enrich the virtual tour with different types of content adding some hotspots spatially anchored in each panoramic image. If the hotspots give access to detail or gigapixel pictures, the model will also have a high detail richness, while if the hotspots display information, the model can reach a higher information richness. Augmented reality models overlap contents directly in the real environment and therefore remove the need for visual fidelity, but according to the type of content it is possible to reach a higher detail or information richness. Mixed reality models overlay virtual products, such as 3D geometric models or Heritage Building Information Models, on a real environment. In these cases, visual fidelity, detail and information richness depend on the type of model, as well as geometric accuracy, which does not apply to VR and AR models.

The actual construction of the tool is based on the definition of a list of 4 questions asking to rate the importance of each parameter on a scale from one to three thumbs-up (Fig. 5.47-50). To have the chance to evaluate the priorities associated with various purposes, a fifth multiple choice question has been added to this list, asking what the general purpose of the model is and offering four options: *communicate*, *work and collaborate*, *both* and *other* (Fig. 5.46). Moreover, the questions are anticipated by some definitions of the selected parameters, to increase the respondents' awareness and avoid misunderstandings. According to each respondent answers the tool[105] is programmed to give different feedback as illustrated in the images below.

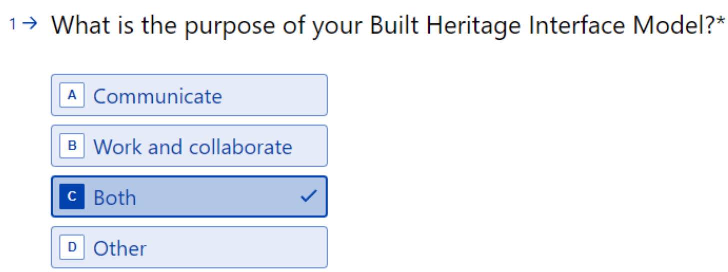
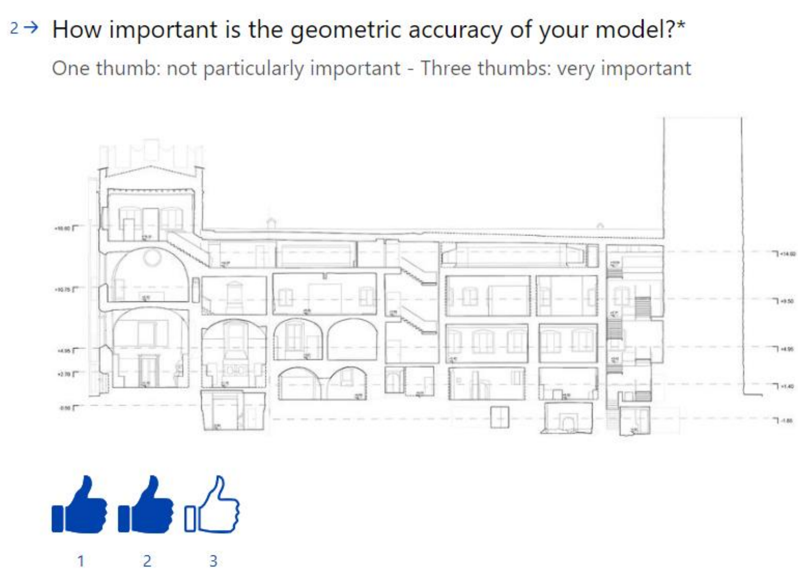


Figure 5.46 - Question on the model purpose.



105 Available at the following link.

Figure 5.47 - Question on the importance of geometric accuracy.

3 → How important is the visual fidelity of your model?*

One thumb: not particularly important - Three thumbs: very important

Figure 5.48 - Question on the importance of visual fidelity.

4 → How important is the information richness of your model?*

One thumb: not particularly important - Three thumbs: very important

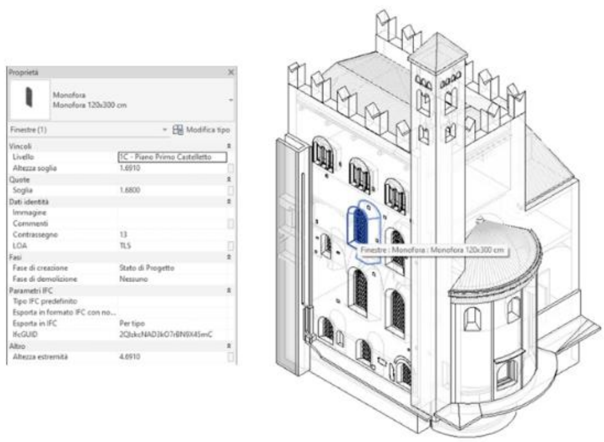
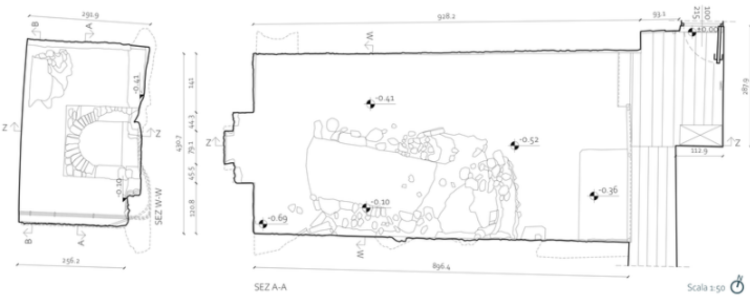


Figure 5.49 - Question on the importance of information richness.

5 → How important is the detail richness of your model?*

One thumb: not particularly important - Three thumbs: very important



1 2 3

OK

Figure 5.50 - Question on the importance of detail richness.

Suggested solution: HBIM

If you want to keep together geometric accuracy, visual fidelity, information and detail richness this could be a good option for you!

Let's find out which modeling strategy fits the best your case!

Figure 5.51 - Output resulting from the answers illustrated above.

5.3.2 Heritage Building Information Modelling strategies

This second tool, focusing on the selection of the most appropriate modelling strategies according to the peculiarity of the object to model, is very similar to the first one in terms of structure and logic. The solutions tested in the discussion of the modelling phase (chapter 3.3) have been collected and classified according to the following five features of the object of analysis:

- site accessibility;
- irregularity of the geometry of the building;
- similarity among irregular elements;
- recognisable edges of irregular elements;
- level of complexity of the eventual recursive elements.

These features have been transformed into five questions (Fig. 5.54-5.57), completed with example and clarifications, and connected through logical operators to suggest as output a specific modelling strategy or, more often the combination of some complementary solutions (Fig. 5.58). The single strategies, analysed or directly tested, include two main approaches, namely drawing-to-BIM and cloud-to-BIM, depending on the input data respectively retrieved from previously elaborated drawings or a digital 3D survey. Generally, except for all those cases where high geometric accuracy is not required, for built heritage it is preferred to use data acquired on the field. For this reason, the drawing-to-BIM approach is only recommended in cases where the building is not accessible for safety reasons or because it has been destroyed or never built. Indeed, the first question asks the user whether the building is accessible or not, to distinguish between a cloud-to-BIM or a drawing-to-BIM approach. These two main approaches can be further tailored according to the following strategies:

- solid models are suitable for most elements with no particularly irregular shapes;
- parametric objects considerably reduce modelling time in the case of recursive or similar elements;
- NURBS (Non-Uniform Rational B-Splines Modeling) are suitable for irregular elements for which edges can be identified;
- meshes are suitable for irregular elements for which is not possible to identify edges;
- scripting can be very useful in modelling complex and recursive elements.

It is crucial to notice that the association of these modelling strategies with the peculiarities of the object is not intended to exclude other possible solutions, but only to provide indications based on what has been analysed and tested within the framework of this research.

The logic established behind the too[106], according to the associations described above, leads the user to different endings according to the answers given to a combination of 3 or 4 questions (Fig. 5.52). This means that each combination of answers has been assigned to a specific ending, proposing the user a modelling strategy, based on the object peculiarities.

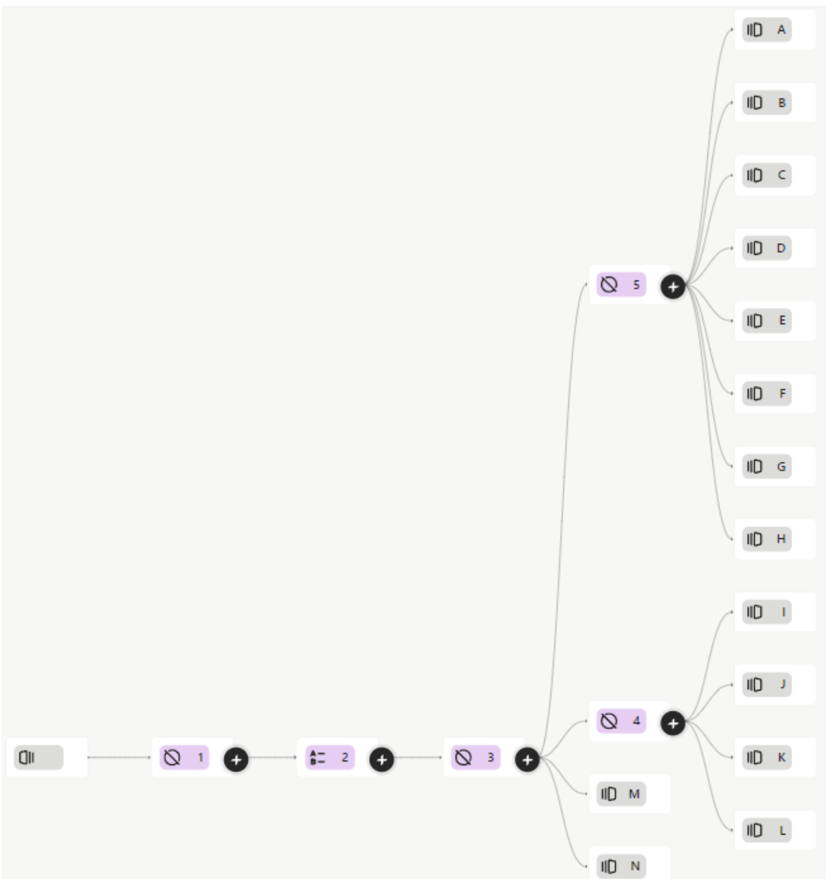


Figure 5.52 - Logic connecting the combinations of answers to different possible endings, where the nodes in violet with numbers are questions and the nodes in grey with letters are endings.

[106] Available at the following link.

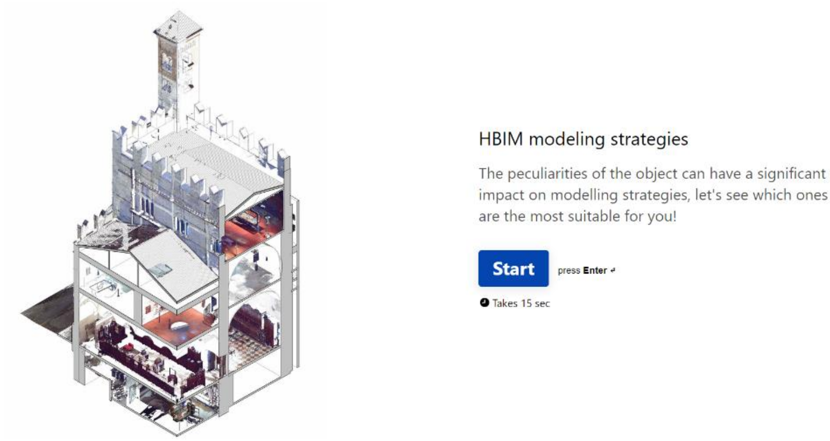


Figure 5.53 - Starting page of the "HBIM modelling strategies" tool.

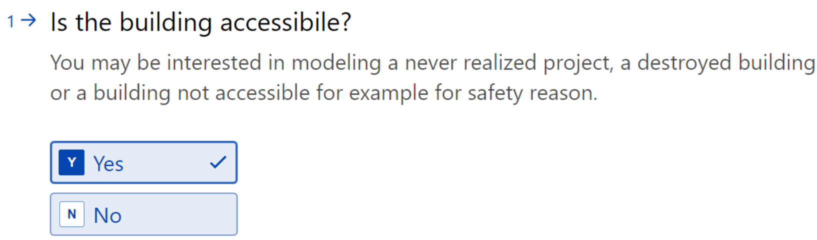


Figure 5.54 - Question on the building accessibility.

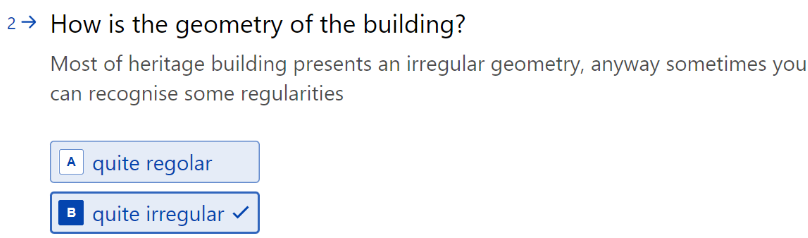


Figure 5.55 - Question on the irregularity of the building geometry.

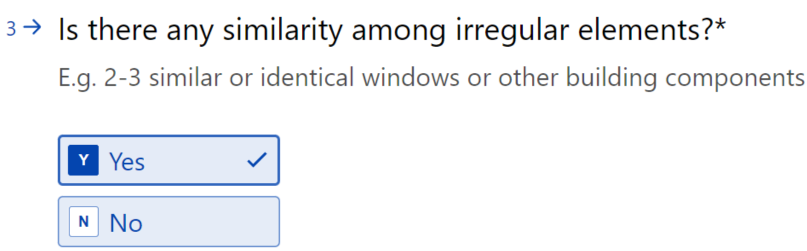


Figure 5.56 - Question on the similarity among irregular elements.

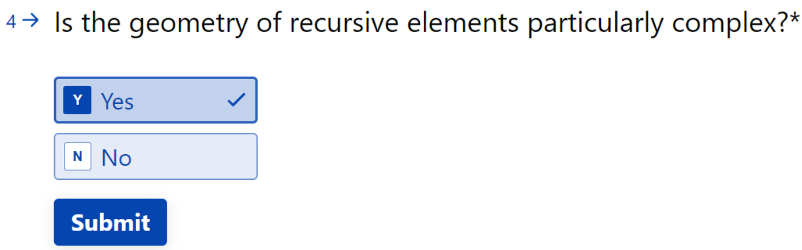


Figure 5.57 - Question on the complexity of recursive elements.

Solid cloud-to-BIM (+scripting)

After processing geometric survey data, some of the building components can be obtained through solid modeling. Recursive irregular elements can be modelled through scripting (e.g. via VPL - Visual Programming Language)

Figure 5.58 - Output resulting from the answers illustrated above.

BIM is expected to be progressively implemented in public works both at the European and at the Italian level, where the new procurement code (D. Lgs. 32/2023) prescribes to use methods and tools for the digital information management of buildings in the design and realisation also of interventions on existing buildings. In Europe most of the buildings belong to the common heritage and in both cities and rural areas there is plenty of buildings with secular history.

Beyond the legal requirements, BIM makes it possible to associate heterogeneous data, locating them spatially in rooms or components of a building, producing an integrated digital archive that is extremely valuable for the digital management of the built heritage.

This tool is expected to support AECO professionals, who will start facing the challenge of representing the irregular shapes of built heritage within BIM environments, which are currently more suitable and optimised for reproducing standard and regular building components.
As anticipated, this tool has no ambition to solve modelling problems or to give comprehensive and detailed guidance on modelling solutions. Instead, the goal is to gather in a simplified and easy-to-access tool some guidance for modelling the built heritage in a BIM environment, based on the experiences collected through this research. To further support potential users, each ending of the tool also reports the lab's website and the author email contact for direct insights on this topic.

5.3.3 Interoperability checklist

Working on the built heritage often involves the collaboration among several stakeholders and different professionals, supporting each project with their knowledge and expertise. This could lead to collaboration issues, especially when it comes to work on data previously processed by other teams and that should be accessible and usable for other users. For this reason, this third tool focuses on the enhancement of collaboration processes, with the aim to facilitate interfaces among AECO professionals working on the built heritage.

This tool is based on the analysis and comparison of different interoperability frameworks presented in chapter 2.2, combined with the direct experiences collected through the case studies illustrated in chapters 3.3 and 4.1, as well as the feedback of local AECO professionals on the European Interoperability Framework.

From the combination of the different interoperability frameworks retrieved from the literature review emerged a list of six possible aspects of interoperability:

- technical interoperability is intended as the compatibility of different technologies and the possibility of seamlessly transferring and exchanging data, without losing quality or content;
- semantic interoperability is associated with the need for a common agreement or a shared base on the meaning of the different languages in use among all the involved actors;
- organisation interoperability is meant the importance of defining some rules and strategies among internal collaborators;
- process interoperability is linked to the definition of a common workflow for data exchange throughout the entire process shared and agreed with all the project partners;
- context interoperability is understood as the definition of some guidelines and other communication tools, presenting and describing the whole process to outsiders;
- legal interoperability refers to contractual agreements and internal regulations defining responsibility and duty among all the involved parties in the joint operations based on information access and data exchange.

The developed tool[107] has the format of a checklist, expressed through eight yes/no questions on different interoperability aspects (Table 5.9).

Interoperability aspects	Question
Process	Is the contribution you can offer to the project clear to all your partners in terms of level of development, grade of accuracy and visual fidelity?
Organisation and process	Do you know how your internal collaborators and/or external partners will use the contents you are developing, in terms of applications, software and formats?
Organisation	Have you defined an internal strategy and workflow for the project development with your internal collaborators?
Process	Have you agreed with your external partners how the involved actors will manage information during the entire project life cycle?
Technical	Have you tested data exchange procedures and solved any potential incompatibility issues?
Semantic	Have you adopted a common language in terms of graphical codes and abbreviations?
Context	Have you agreed and shared a set of guidelines or rules on all these aspects?
Legal	Have you established a contractual agreement with your partner on all these aspects?

Table 5.9 - List of questions associated with different interoperability aspects.

Considering processes based on reciprocal information access and data exchange among AECO professionals, the proposed questions are designed to help them in:

- structuring effective solutions at the beginning of a collaboration;
- verifying if some crucial aspects are missing and identifying potential improvements in ongoing collaborations;
- assessing previous experiences and gaining awareness on strengths and weaknesses.

These questions are anticipated by a couple of questions on ongoing, past or future experiences in collaboration, to support the collection on

[107] Available at the following link.

data that could support further study on interoperability workflows (Fig. 5.560-5.61).

As declared in the starting page (Fig. 5.59), this series of questions is designed both as a survey to gather more data on this topic and as a tool to increase user awareness on the various aspects that contribute to achieving good interoperability. The data collected through this tool may help in identifying whether some aspects are more significant than others in ensuring good interoperability. The tool also provides the user with an output that helps identifying whether there is a specific aspect to be improved for better interoperability or whether it is necessary to work on more than one aspect, but in any case, proposes to further discuss the user interoperability experiences contacting the author (Fig. 5.62).

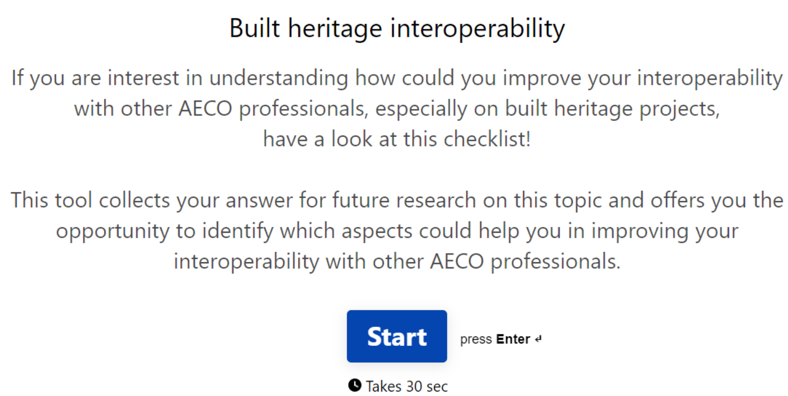


Figure 5.59 - Starting page of the interoperability tool.

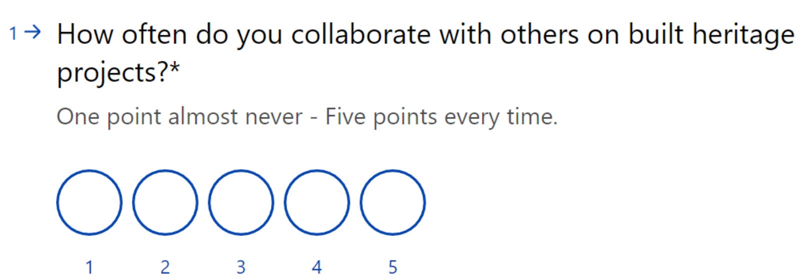


Figure 5.60 - Question on the frequency of collaboration on built heritage projects.

Figure 5.61 - Question on the quality of collaboration on built heritage projects.

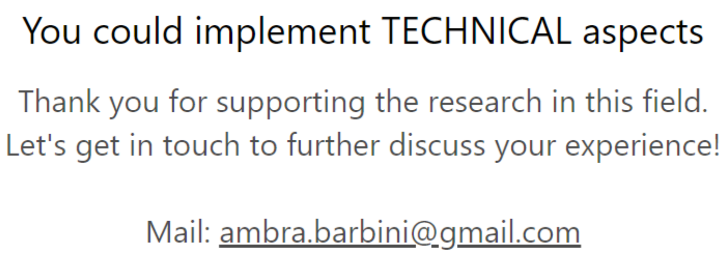


Figure 5.62 - Example of output if the user is already fulfilling all aspects for good interoperability except the technical ones.

References Chapter 5

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UNI 11337-4 - *Edilizia e opere di ingegneria civile - Gestione digitale dei processi informativi delle costruzioni - Parte 4: Evoluzione e sviluppo informativo di modelli, elaborati e oggetti.* Ente nazionale italiano di unificazione.

6. CONCLUSIONS

This research has investigated the potential of geometric and informative models of built heritage as multipurpose interfaces for information access and data exchange. The study illustrates how built heritage graphic-visual models have the potential to be effective intermediaries, facilitating communication, collaboration, and coordination not only among AECO sector practitioners but also for other stakeholders.

A theoretical framework, based on the research keywords, clarified the research objects, purposes and tools. This framework explains how "built heritage" can include not only the expression of exceptional values but also the entirety of the built assets inherited from the past and available to current and future generations. The term "interface" is understood as a connection that facilitates knowledge transfer or joint operations, supporting content communication and enhancing professional collaboration. Finally, the term "model" is intended as a discretization and simplification of the complexity of reality, resulting from an interpretative process aimed at imitation.

Whether public or private, the buildings assumed as references in this study are examples of tangible heritage that witness past cultures, embed cultural values or express current or past aesthetics and standards. The analysis of these buildings, regardless of whether driven by management, prevention, maintenance, restoration or rehabilitation purposes, involves a wide amount of heterogeneous data and requires the integration of diverse knowledge and skills, involving several specialists and experts.

The study outlines some strategies to simplify the complexity of existing buildings into geometric-informative models using current digital technologies, with the aim to encourage and facilitate preservation, management and interaction with the built heritage. In the belief that digital models can bridge gaps between disciplines and improve the overall accessibility and usability of acquired, processed and structured data. Analysing the scientific literature and some case studies it is evident that current digital technologies provide various alternative solutions not only for data acquisition, processing and modelling, but also for the visualisation, communication and management of built heritage.

Given the wide range of model types that could be helpful in representing heterogeneous data on the built heritage, the research proposes an orientation tool to identify the best built heritage model option according to the interface scope and priorities. Each model type, indeed, is associated with variable intensity of four parameters retrieved from literature review, namely visual fidelity, geometric accuracy, detail richness and information richness.

The creation of built heritage models can follow different workflows not equivalent in terms of time, effort and data quality required. Moreover, the operators' choices and sensibility heavily influence each stage of the process, including data acquisition and processing. The modelling experiences analysed and presented in this study support the definition of some operative evaluations considered helpful in the selection of the most appropriate strategy according to the peculiarity of each case study. While the choices during acquisition and processing phase are often the result of a trade-off between available resources (e.g. time, budget, equipment, operators) and data accuracy. Various factors can influence the selection of a geometric modelling strategy, including the nature of the heritage building, the level of geometric irregularities, the complexities of shapes, the presence of recursive or similar elements.

The ongoing advancements in science and technology, particularly in artificial intelligence, are expected to streamline various aspects of data acquisition, processing and analysis, leading to time and resource-effective workflows. This should facilitate more widespread adoption of digital models as a coherent storage of built heritage information.

In the analysis of possible fruition solutions, the research acknowledges the centrality of users' needs and expertise. According to initial distinction between interface "to know" and interface "to do", two main user goals are analysed, namely the access to information and the collaboration based on data exchange. Moreover, since users could not be used to interact with digital tools, fruition options are classified according to three possible level of familiarity with digital technologies: traditional, experimental and advanced fruition solutions.

An increased familiarity with digital technologies is expected for future generations and this could increase the level of interaction between common users and built heritage interface models. Information associated to single buildings or components could be expanded exploiting the outputs of collaborative process, including not only experts and specialists but also local communities and other stakeholders, according to the principles of citizen science.

The potential applications of the developed models are explored through various case studies, where different options are tested to enable both specialized and general users to access technical and cultural data. The perspectives from various professional groups within the construction supply chain are further examined through a questionnaire distributed in the Province of Trento. The survey focuses on data exchange, collaboration practices, the adoption of digital tools, and the collection and processing of built heritage data. In conclusion, three tools have been created to enhance the accessibility of the research outcomes for AECO professionals and other stakeholders in built heritage:

- an orientation tool that helps determine the most appropriate model interface based on the project's objectives and priorities;
- a dynamic guide designed to assist in choosing the most suitable modeling strategy, considering the specific characteristics of the object (e.g. accessibility, irregularity of shapes);
- a checklist outlining various layers of interoperability to improve collaboration and communication among AECO professionals.

In conclusion, the research demonstrates that while there are significant challenges in using geometric and informative models of built heritage as multipurpose interfaces, the benefits and potentials are substantial. Most of the results have been published during the research activities, including journal publication and conference presentations ranging from the theoretical framework to the most applicative experiences. The collaboration with local operators and the BHIM survey confirm the interest for digital technologies applied to the built heritage not only for professional purposes but also for cultural or technical data communication with wider audiences. With the right strategies and technologies, it is possible to create accessible, reliable, and versatile models that facilitate information access, data exchange, and professional collaboration. Future development of this research should continue to explore innovative solutions and refine existing methods to further enhance the effectiveness and applicability of these models in the preservation and management of built heritage, also through the validation and exploitation of the developed tools.

List of abbreviations

AAA - Associazione Archivi di Architettura

ADSI - Associazione Dimore Storiche Italiane

AECO - Architecture, Engineering, Construction and Operation

AIPAI - Associazione Italiana per il Patrimonio Archeologico Industriale

ANCBS - Association of National Committees of the Blue Shield

ANCE - Associazione Nazionale Costruttori Edili

AR - Augmented Reality

ARCo - Associazione per il Recupero del Costruito

BIM - Building Information Modeling

BUM - Biblioteca Universitaria Mesiano

CAD - Computer Aided Design

CICOP - Centro Internazionale per la Conservazione del Patrimonio Architettonico

CIPA - Comité International de la Photogrammétrie Architecturale

CLI - Command Line Interface

CNC - Computer Numerical Control

DICAM - Dipartimento di Ingegneria Civile Ambientale e Meccanica

DOCOMOMO - Documentation and Conservation of the Modern Movement

EIF - European Interoperability Framework

ICA - International Council of Archives

ICAR - Istituto Centrale per gli Archivi

ICBAS - Istituto Centrale per i Beni Sonori e Audiovisivi

ICCD - Istituto Centrale per il Catalogo e la Documentazione

ICCU - Istituto Centrale per il Catalogo Unico delle Biblioteche

ICBAS - Istituto Centrale per i Beni Sonori e Audiovisivi

ICBS - International Committee of the Blue Shield

ICCROM - International Centre for Conservation of Rome

ICOM - International Council on Museum

ICOMOS - International Council on Monuments and Sites

IEEE - Institute of Electrical and Electronics Engineering

IIC - Istituto Italiano dei Castelli

IIC - International Institute for Conservation

IFC - Industry Foundation Classes

IFLA - International Federation of Library Associations and Institutions

E-FAITH - European Federation of Associations of Industrial and Technical Heritage

EFFORTS - European Federation of Fortified Sites

EHHA - European Historic Houses Association

FAI - Fondo per l'Ambiente Italiano

FRH - Future for Religious Heritage

GUI - Graphical User Interface

HBIM - Heritage/Historic Building Information Models

HCI - Human-Computer Interface

LAMARC - Laboratory of Architectural Modelling and Analysis Representation and Communication

MiBACT - Ministero per i Beni e le Attività Culturali e per il Turismo

MR - Mixed Reality

NURBS - Non-Uniform Rational B-Splines Modeling

TICCIH - The International Committee for the Conservation of Industrial Heritage

UI - User Interface

UNESCO - United Nations Educational, Scientific and Cultural Organization

ViC-CH - Visual Culture for Cultural Heritage

VPL - Visual Programming Language

VR - Virtual Reality

WMF - World Monuments Fund

XR - Extended Reality

List of pictures

Chapter 2

Chapter 3

Chapter 4

Chapter 5

List of tables

Chapter 4

Chapter 5

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