Università Politecnica delle Marche
Scuola di Dottorato di Ricerca in Scienze dell'Ingegneria
Curriculum in Ingegneria Civile, Ambientale, Edile e Architettura
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The development of data management systems by BIM for the built heritage

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XXXIV cycle

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Acknowledgements

Firstly, I would like to acknowledge and give my warmest thanks to my supervisor Prof. Eva Savina Malinverni who gave me the opportunity to conduct the Doctorate in the most interesting and compelling way possible.

I would also expresse my sincere gratitude to my co-advisor Prof. Ramona Quattini for her support in my research activity.

I especially thank the committee members in making my defense an enjoyable time and for your helpful and fair comments and suggestions.

I would also like to give special thanks to my parents, my colleagues and my friends as a whole for their continuous support and understanding when undertaking my research and writing my project.

Finally, a thank you to myself for satisfactorily achieving this aspiring goal despite some difficulties related to my being deaf, particularly during the covid-19 pandemic situation.

15.05.2022

Francesco Di Stefano

To Prof. Gabriele Fangi,
in memory of him

Declaration of originality

I hereby declare that the content of this thesis entitled "The development of data management system by BIM for the built heritage" is my work and was entirely carried out for the Degree of Doctor of Philosophy in Geomatics under the guidance and supervision of Professor Eva Savina Malinverni, Professor Ramona Quattrini at the Università Politecnica delle Marche, Italy.
The thesis has not been submitted for any degree or other purposes. I also certify that all the assistance received in preparing this thesis and sources have been acknowledged.
Finally, I declare that the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

Francesco Di Stefano
Ancona, May 2022

Abstract

Fragmentation of construction information has been challenging in the Architecture, Engineering, Construction (AEC) sector, including the field of built heritage, for a long time, and caused significant difficulties of information management. This fragmentation is also reported to be a major contributing factor to loss of knowledge. Several methods and tools have been developed to solve the problems of fragmentation and mitigate loss of knowledge. Building Information Modeling (BIM) has emerged as one of the tools, and is mainly intended to build a repository of shared digital building information models. In the meanwhile, to increase the productivity and efficiency, knowledge management plays an important role in construction processes. However, current BIM systems are information-centric with little focus on knowledge modeling. Similarly, BIM and the process of managing and transforming information into knowledge are limited, causing a great drawback in defining a knowledge model. Therefore, there is a fundamental need to embed knowledge modeling within BIM system. Currently, little known research has been conducted in this area during the last decade. This research would illustrate tentative approaches to define a Building Knowledge Modeling and Management (BKMM or BKM^{2}) and to explore and outline the possibilities to knowledge modeling and management within and beyond BIM.

With particular regard to the built heritage or existing buildings, this thesis addresses the development of data management that will be structured and interpreted to achieve a certain level of information through the use of the BIM system. Then through the semantic interpretation of the collected information, an attempt was made to define the basis of a knowledge model.

This trinomial of data, information and knowledge are closely related, and it is commonly known that knowledge has a higher level than information, and information has a higher level than data.

data > information > knowledge

The first step of data management concerns the contribution of geomatics that with its techniques and technologies, from those at more remote distances to those close-range, allows you to acquire and process metric data to obtain geometric models of the objects detected. The collection of data also includes what are defined as non-geometric data that relate to architectural aspects, historical, temporal, technical, structural that are used to identify the state of conservation and maintenance of built heritage or existing buildings.

Once a reality-based geometric model is obtained, it will serve as the basis for the next phase of information management. In this framework, BIM constitute a reference tool creating an informative data collector. Therefore, in short, a BIM system is characterized by the presence of a three-dimensional model and by a sort of archive, in the form of relational databases, which collects the information linked to it both in its totality and in the single parts that compose it.

In the field of information management by BIM, international research is particularly interested in this topic as is confirmed by the growing trend of publications in the last decade. This technological and digital innovation has created a dual current of research: on the one hand researchers are dedicated more to achieve the highest level of detail for the three-dimensional (3D) representation of the artefact through the accurate processing of survey data and the definition of particular geometric shapes. On the other hand having a basic 3D model the focus deal with how to better manage the information associated with it in order to obtain a 3D object that can communicate beyond its geometric shape. These two currents of research just described do not intend to remain separate, but will be useful to lay the foundations for a new current of unified research to achieve a complete and efficient system of management and modeling information increasingly innovative and through pre-set and automated processes. While the first current of research is now fairly well established, the second is still little addressed. This is due to the fact that while for the 3D modeling of the built environment you have a lot of starting data to process, as regards the management of information related to a 3D model there is no basic structure due to the fact that there are many more issues to deal with, from the use of software, the type and purpose of the project, the management of different file formats, the storage system of such data, the accessibility of these databases, and more.

This brief excursus to explain that the research presented in this thesis has focused on this second trend going to know the functionality of a BIM system for the management of information related to built heritage.

Information management through relational databases is developed through the definition of an ontological schema that identifies domains to syntactically group and semantically link information related to the built heritage. BIM as parametric software features hierarchical and structured information management so it is difficult to import and implement an ontology schema. The term HBIM does not refer to a BIM system for built heritage or existing buildings, but to an information system that is customized, not so much for the concept of reverse engineering, but on the basis of the parameters to be included in order to better support the heritage conservation processes. An integrated approach to architectural knowledge modeling has been developed combining an empirical (ontology) and visual and descriptive (3D model) representation of a historical or existing building.

The knowledge-led strategy of information system will become compulsory thanks to the dissemination of BIM data with other figures involved in built heritage projects, for example with open BIM platform. An additional degree of knowledge is achieved when data from different information techniques, such as GIS, are managed. Data interoperability between BIM and GIS is ensured through the definition of a semantic ontology as a unified domain that allows for standardization of information and overcomes the barriers to heterogeneous data management and sharing. This lack of direct interoperability across BIM and GIS domains can be solved using the semantic web. The semantic web environment is composed by a set of technologies used for combination, representation, publication of data on online platforms. This methodology, which tends to overcome the limitations of BIM and aims at managing, integrating and enriching information coming from information techniques, can be indicated with the new term of Building Knowledge Management and Modeling (BKMM or BKM^2).

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Chapter 1.

Introduction

1.1 Research topics

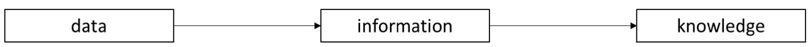
In recent years, in the AEC sector, there has been considerable technological progress that has brought about a radical change in the methods and systems of cataloguing and managing information: from common relational databases we have come to use more extensive information systems such as BIM.

This digital revolution has made it possible to create new types of information and forms of communication through technologies such as semantic data structuring, computational intelligence and the data web world, which therefore favour the sharing of knowledge, cooperation and collaboration between people through the definition of integrated information systems.

In short, it starts from the data, of various types and origin, available to build information, the content of which combined with other types of information through integrated management systems has the ultimate goal of representing a form of knowledge.

The concepts of data, information and knowledge are closely related, and it is commonly known that knowledge has a higher level than information, and information has a higher level than data.

Data is a set of raw facts.
Information is structured and interpreted data.
Knowledge is refined information.



This thesis therefore aims to address the issue of technological innovation concerning information management, which is at the basis of any project aimed at the built environment, with particular attention to the built heritage (BH).

This technological innovation has also involved surveying techniques, which, with the contribution of information technology, are becoming more widespread and used, as is the subsequent phase of data processing and management through specific information systems. We are therefore witnessing a new revolution, or rather, a new implementation between surveying, information management and technology: a trinomial enclosed in the term *geomatics***.**

Therefore, starting from the data obtained through the geomatic survey, integrated with any other technical-descriptive data, it is possible to construct the 3D model of the existing structure which, enriched with geometric and non-geometric information, becomes the basic object of the information system.

In the field of geomatics, international research is particularly interested in this topic of information management for BH as confirmed by the trend of publications in the last 10 years (2010-2021). This technological and digital innovation has created a twofold current of research: on the one hand, there is a focus on achieving the highest level of detail for the 3D representation of the artefact through the accurate processing of survey data and the definition of particular geometric shapes; on the other hand, having a simplified basic 3D model, we are studying how to better manage the information associated with it in order to obtain a 3D object that can communicate beyond its geometric shape. These two currents of research just described should not be considered as separate but become useful to lay the foundations of a new stream of unified research to achieve a system of information management increasingly innovative and with increasingly automated processes.

While the first research trend can be defined as fairly well established, the second is still little addressed. While for 3D modelling of the built environment one has a lot of source data to process, there is no basic structure for managing the information linked to a 3D model. For the latter, there are many more issues to deal with, from the use of the software, the type of project, the management of different file formats, to the accessibility of this information.

The research presented in this thesis focuses on this second trend going to know the functionality of a BIM system for the management of information related to BH (Figure 1).

Information management through relational databases is developed through the definition of an ontology that identifies domains to syntactically group and semantically link information related to the built heritage. BIM as parametric software features hierarchical and structured information management, so it is difficult to import and implement an ontological schema. The term HBIM does not refer only to define a BIM system applied to built heritage or existing buildings, but to an information system that is customized, not so much for the concept of reverse engineering, but on the basis of the parameters to be included in order to better support the heritage documentation objectives. An integrated approach to architectural knowledge modeling has been developed combining an empirical (ontology) and visual and descriptive (3D model) representation of a historical or existing building.

The knowledge-led strategy of information system will become compulsory thanks to the dissemination of BIM data with other stakeholders involved in built heritage projects, for example with open BIM platform. An additional degree of knowledge is achieved when data from different information techniques, such as GIS, are managed. Information interoperability between BIM and other information systems is ensured through the definition of a semantic ontology as a unified domain that allows for standardization of information and overcomes the barriers to heterogeneous data management and sharing. This lack of direct interoperability across domains of information systems used for built heritage documentation can be solved using the semantic web. The semantic web environment is composed by a set of technologies used for combination, representation, publication of data on online platforms. This methodology, which tends to overcome the limitations and weaknesses of BIM and aims at managing, integrating and enriching information coming from information techniques, can be indicated with the new term of Building Knowledge Management and Modeling (BKMM or BKM^2).

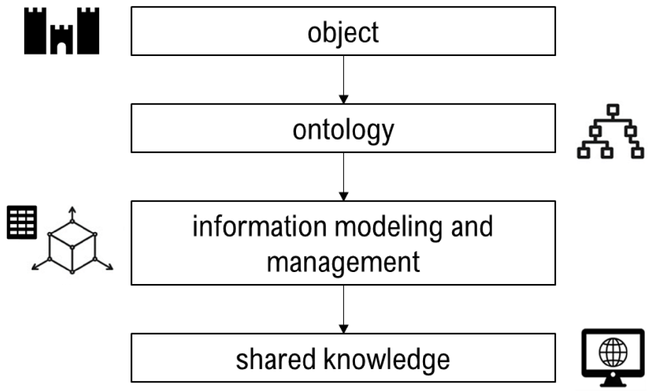


Figure 1. Graphical abstract

1.2 Specific research questions

As explained in the previous paragraph the objective of this research is based on the management of data through an information system that promotes knowledge of the BH.

Below, a list of questions that highlights the main steps of the methodology of developing an information system applied to a BH, following the trinomial *data-information-knowledge*:

Data

Which kind of data of a BH can be managed through an information system?

What are the factors to be taken into account when capturing data for BH?

At the end of the preliminary acquisition and research phase, how can be structured these data?

Information

Referring to the BH, how should an information model be built for the collection and integration of various type of data? Is there a basic structure that can lead to the implementation of an information management system?

For the 3D modelling of a BH object we often rely on the level of detail or development that we can/should achieve, but as far as the level of information contained in a 3D model is concerned, how is this measured?

What are the strengths and weaknesses of using a BIM system for BH (or HBIM)?

Knowlegde

Through which tools is the exchange and sharing of information between different information systems applied to BH ensured?

What does semantic ontology provide for knowledge management for BH?

Which benefits would be the implementation of an adopted BKMM (Building Knowledge Management and Modeling) for BH?

1.3 Objectives and main research contributions

It was therefore explained that the field of application of this thesis is the geomatics contribution, both in the form of surveying techniques and information management, is applied for the BH. First a brief excursus on what is meant by knowledge of the BH is outlined, then the importance of the topic of cultural heritage in the international panorama is focused on.

According to Historical England and the Department for Communities and Local Government of United Kingdom the definition of BH assets is: "*A building, monument, site, place, area or landscape identified as having a degree of significance meriting consideration in planning decisions, because of its heritage interest*." (Department for Communities and Local Government of United Kingdom, 2012). Historic buildings and sites should be preserved as cultural legacy and common heritage (Gazzola et al. 1964). The Charter of Krakow is the most recent document defining the principles for conservation and restoration of BH (De Naeyer et al. 2000; Petzet, 2004). There are categories among the existing buildings and sites depending on its cultural values, antiquity or artistic importance. They are categorised depending on the country or state; generally, they include common recent existing buildings, catalogued buildings with protected areas and heritage buildings that are clearly protected (Eppich, 2007). Considering the definition of the Outstanding Universal Value (ICOMOS, 2008), all the information available about a historical building is useful to allow a widespread reconstruction, interpretation, conservation and dissemination for future generations. Tangible cultural heritage, particularly immovable assets (monuments, archaeological sites, and so on), is the main subject of application in the new approaches. A structured digital 3D model as part of the architectural heritage improvement process is an urgent need, nowadays. Moreover, the digital 3D model must be converted into a crucial reference frame for the understanding and monitoring of documentation, thus creating a data source (graphics and semantics) that is suitable for assisting in conservation, restoration, and reconstruction projects (Penttilä et al., 2007).

Over the last decades, innovative 3D digitisations and geomatics technologies has entered the field of cultural heritage, mainly in order to meet the needs of documentation, management and protection. The aim is to ensure that the information regarding the significant historical characteristics (shape, appearance) of a cultural heritage entity will be reserved in case of natural or other damages (Gomes et al., 2014).

The term heritage often appears in the UNESCO lexicon, in its various forms, promoting its knowledge on the educational, cultural and scientific profile. This theme is included among the Sustainable Development Goals (SDGs) of the UN 2030 Agenda (Hosagrahar et al., 2016), where it is addressed both directly and transversally, as a promoter of other goals, as reported in the targets of some of these goals (Figure 2).

Figure 2. Sustainable Development Goals of the UN 2030 Agenda and specific targets associated with the theme of BH

Briefly summarising the contents of the targets identified, it can be seen that the theme of heritage is associated with issues of education, economic and social productivity, broad participation with particular involvement of young people, creation of sustainable and inclusive communities, promotion of heritage and technological innovation to ensure the sharing and accessibility of knowledge.

Cultural heritage is also addressed in the Faro Convention (2011) (Zagato, 2015), which emphasises the important aspects of cultural heritage in relation to human rights and democracy. It promotes a broader understanding of cultural heritage and its relationship with communities and society. The Faro Convention is a "framework convention" which defines the issues at stake, the general objectives and the possible fields of action for Member States to move forward. Each Member State can decide on the most appropriate means of implementing the Convention according to its legal or institutional framework, its practices and its specific experience. Compared with other conventions, the "framework convention" does not create specific obligations to act, but is intended to suggest shared best practices.

Based on these objectives and issues related to BH, the contributions of this research are as follows:

- know the main geomatic surveying techniques of recent development and technological innovation (applied to the architectural and urban scale) and the data they obtain;
- understand what the documentation of a BH should be based on: factors, principles and actors involved;
- understand the concept of semantic ontology for the management of BH information;
- define information management guidelines for an inter-/multi-disciplinary approach between geomatics and other disciplines concerning the built heritage;

- know the strengths and weaknesses of an information system (e.g. BIM) for a BH with regard to information management related to the 3D model;
- how to make an information system interoperable with others through the exchange and sharing of information;
- how to promote the knowledge of the built heritage through the management of open source information systems such that they guarantee usability and accessibility to stakeholders.

1.4 Structure of the thesis

After the Introduction (Chapter 1), the thesis is developed according to this structure:

- *Chapter 2. The development of BIM as information management system*: an overview of the general framework of the BIM legislation with special regard to its implementation for the BH and an analysis of the scientific research on this topic through literature search.
- *Chapter 3. Data management for built heritage*: illustration of factors, processes, requirements, stakeholders involved, techniques and technologies for managing the data collected for the documentation of a BH.
- *Chapter 4. Information management by (H)BIM implementation*: data storage and integration methodologies through the definition of database and ontology for the BH. Implementation of an ontology-based (H)BIM system and promotion of an open BIM system to ensure information sharing and accessibility.
- *Chapter 5. Knowledge management: integration of (H)BIM with other information techniques*: introduction to other information systems that manage data for the built heritage, analysis of interoperability between BIM and other information systems through the definition of a unified ontology in a semantic web environment, promotion of a new method of knowledge of a built heritage through BKMM.

Finally, critical discussions, conclusion and suggested further research directions are oulined.

Chapter 2.

The development of BIM as information management system

During the decades, the AEC sector has been affected by profound changes due mainly to technological evolution, which has introduced new information technology tools, processes and procedures. In correlation with technological progress, building design has become more complex and sophisticated due to the ever-increasing demands for high levels costruction performance. The BIM approach stands at the heart of this revolution as a key element that encompasses all the paradigms of Industry 4.0 to lead the construction sector towards progressive digitization.

BIM is neither a tool nor a software, it is a new approach to the design and realization of a work, a methodology that involves all stages of the process and with them all the workers who are part of it. In the 2018 National Building Specification (UK) report (National NBS, 2018[1]), BIM is as follows. defined, "*BIM is not just one thing. It is a gradual progression toward greater collaboration and greater sharing of increasingly standardized project information*". Another definition comes to us from the BIM Dictionary (Model, 2016): "*BIM is a set of technologies, processes and policies that enable multiple parties to collaboratively design, build and manage a building or infrastructure, within of a virtual space*". There are two main aspects that are highlighted in the definitions presented and that constitute the innovative character of BIM: the introduction in the project of the concept of information, intended not only as geometric and constructive information but all those functional to the complete management of the building, and the collaboration between the various actors involved in the project and that interact through a single digital environment of data sharing for the realization of the work.

It's enough to do a little research to discover that the concept of BIM presents numerous definitions that are often similar to each other, but there is not unique classification probably due to the continuous and constant evolution to which it is subjected.

From the vast panorama of definitions on BIM information modeling, the three main meanings of the BIM acronym explain the basic principles upon which the methodology is based (Department of VA, 2010[2]):

1. Building Information Model - Object: a digital object-based representation of the physical and functional characteristics of a building or infrastructure. It serves as a shared knowledge resource for obtaining information about a work, providing a reliable basis for decisions throughout the life cycle of the work from the initial moment of conception.

[1] National NBS: National BIM report 2018. Royal Institute of British Architects (2018).
[2] Department of VA. (2010). The VA BIM Guide. http://www.cfm.va.gov/til/bim/BIMGuide/downloads/VA-BIM-Guide.pdf

2. Building Information Modeling - Process: a collection of uses, workflows, and methods for modeling the defined model, employed to obtain as outputs specific, repeatable, and reliable information from the model. Modeling methods affect the quality of information generated from the model. The when and why a model is used and shared impacts the effective and efficient use of the BIM method to achieve the desired project outcomes and as an aid to decision making.

3. Building Information Management - Data Definition: Building Information Management underlies the standards and requirements applied to data for BIM use. Data continuity allows for the secure exchange of information in a context where both sender and receiver understand the information.

2.1. Recent regulatory framework

2.1.1. First BIM regulatory in Europe and Italy

The regulatory level reference of BIM in Europe is undoubtedly the Public Procurement Directive 2014/24/EU, approved in February 2014 by the European Parliament and the Council. The Directive called on EU member states to promote through legislative measures the adoption of BIM methodology for all publicly funded projects and works (Directive 2014/24/EU[3]). The first countries to do so were: United Kingdom, Netherlands, Denmark, Finland and Norway. The planned adaptation was to occur by 2016.

In its strategic vision, the Community legislator affirms the centrality of technology and, with it, of research and innovation so as to pursue intelligent and sustainable growth in the public sector, thus encouraging member states to reformulate the way in which invitations to tender are drafted so as to use public procurement to improve the efficiency and quality of public services.

Following these objectives, in paragraph 4 of Art. 22 (Directive 2014/24/EU[3]), the legislator wants to in some way somehow encourage EU countries to require the use of specific electronic tools, such as electronic simulation tools for building information or similar tools among which we can easily include BIM. In fact, it should be noted that in the English version of the standard, unlike the Italian translation, explicit reference is made to Building Information Modeling or similar tools, while maintaining the non-compulsory nature of their use.

[3] Directive 2014/24/EU of the European Parliament and of the Council of 26 February 2014 on public procurement and repealing Directive 2004/18/EC Text with EEA relevance. OJ L 94, 28.3.2014, p. 65–242 (BG, ES, CS, DA, DE, ET, EL, EN, FR, HR, IT, LV, LT, HU, MT, NL, PL, PT, RO, SK, SL, FI, SV). http://data.europa.eu/eli/dir/2014/24/oj

The transposition of the aforementioned Directive arrives in Italy with the entry into force of "Nuovo Codice degli Appalti" (D. Lgs. 50/2016[4]), with which the foundations are laid at a regulatory level for the introduction of digitization in public contracts. The Decree represents a fundamental step in the regulatory evolution of BIM in Italy. Article 23, paragraph 13 (D. Lgs. 50/2016[4]), introduces for the first time the concept of BIM for public procurement as electronic methods and tools that use interoperable platforms by means of non-proprietary open formats, in order not to limit competition among technology providers and the involvement of specific designs among designers.

The Ministry of Infrastructure and Transport (of Italy) established the introduction of the principle of compulsoriness on the use of tools electronic modeling in the design construction and management of public works (D.M. 560/2017[5]). It is often referred to as the "BIM Decree" precisely because it represents a fundamental step for the affirmation of BIM and the consolidation of the digital revolution in the Italian panorama construction sector.

2.1.2. ISO 19650:2018

With the approval of the new ISO 19650[6] standard starting in 2018, new regulatory scenarios are slowly emerging at the international, European and individual national level to define a unified standardization system on the use of BIM for information management.

Regarding the regulations in the world, according to the subject that has elaborated them we have:

- international standards that are developed and published by ISO (International Organization for Standardization), can be adopted at the national level by each member state on a voluntary basis.
- European standards which are drawn up by CEN (European Committee for Standardization) in the three recognized languages, English, French and German. Each member state is obliged to transpose them and withdraw any conflicting national standards in force.
- national standards that are drawn up by the recognized national body. They have value on the national territory and are written in the mother tongue of each country. In Italy are deputies to write standards UNI.

[4] D. Lgs. 50/2016. Decreto Legislativo 18 aprile 2016, n. 50. Attuazione delle direttive 2014/23/UE, 2014/24/UE e 2014/25/UE sull'aggiudicazione dei contratti di concessione, sugli appalti pubblici e sulle procedure d'appalto degli enti erogatori nei settori dell'acqua, dell'energia, dei trasporti e dei servizi postali, nonche' per il riordino della disciplina vigente in materia di contratti pubblici relativi a lavori, servizi e forniture.

[5] D.M. 560/2017. Decreto Ministeriale 1 dicembre 2017, n. 560. Direzione generale per la regolazione dei contratti pubblici e la vigilanza sulle grandi opere. Ministero delle Infrastrutture e dei Trasporti, Governo Italiano.

[6] ISO 19650:2018. Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) -- Information management using building information modelling.

Thanks to recognition agreements between ISO and CEN, it is possible to activate the Vienna Agreement that allows a joint publication of a standard both at European and international level. In this case the acronym for Italy would be UNI EN ISO (Figure 3).

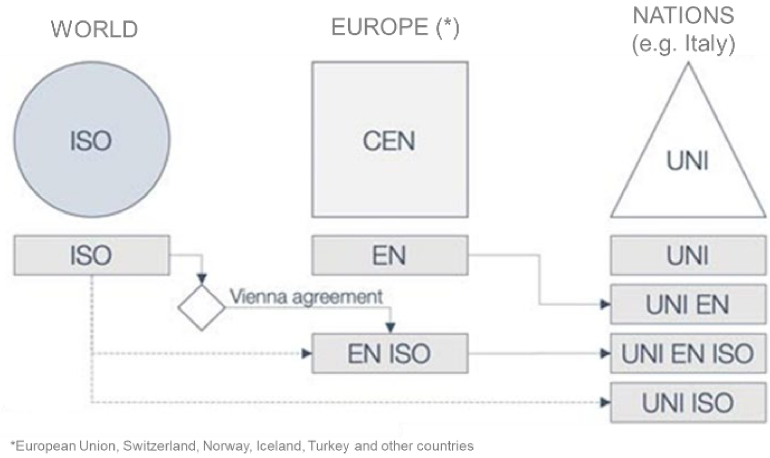


Figure 3 - Application scheme of the standards in the world

Standards are written by practitioners, experts, researchers and stakeholders in general, both public and private, whose represent who will use the standards and/or benefit from their effects.

Through the national standards body, all stakeholders can participate in standards work, which is carried out by Technical Committees, which are usually structured into Sub Committees and/or Working Groups. The latter have purely operational tasks and are responsible for drafting the texts of the standards to be submitted to the higher hierarchical level.

Therefore, in the case of a national standard, the texts, once approved by the technical body that elaborated them, are subjected to two public inquiries, so that all those who are not part of the technical body of elaboration can give their contribution for the improvement of the standard and increase its consensuality.

All over the world, technical standards are voluntary; they have application if mentioned in a contract, if referred to in a law and, in general, in case of litigation, if assumed by the judging body, as a clear demonstration of the rules of art in a specific sector (standard as an expression of the rules commonly accepted by all stakeholders of a specific service, process or product). The standard, therefore, is not a doctrinaire text or a manual, but represents the state of the art, practice and science shared, at a given time, by all stakeholders, public and private, with respect to a specific product, process or service. ISO 19650 is a standard that satisfies the characteristics of consensus, democracy, transparency and voluntariness.

In December 2018, ISO 19650 is adopted, which through the direct adoption mechanism of the Vienna Agreement becomes a European (EN) and national standard for each member state during 2019.

The first two parts of the approved standard:

- ISO 19650 - Organization of information about construction works - Information management using building information modelling - Part 1: Concepts and Principles
- ISO 19650 - Organization of information about construction works - Information management using building information modelling - Part 2: Delivery phase of the assets addresses respectively the general aspects of the BIM process and the information flow of the development phase of a real estate project.

Figure 4 - Overview of the international voluntary regulatory system BIM and construction digitization

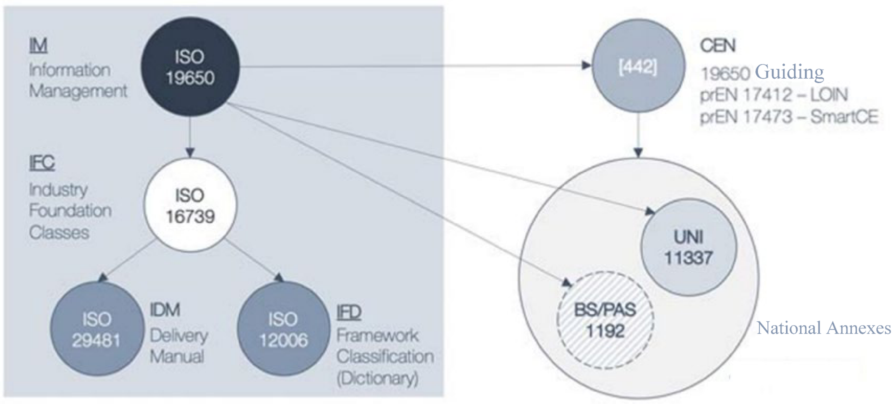


Figure 5 - Map of the international voluntary standards system with the release of ISO 19650

This main framework is applied (or should be applied) worldwide. In particular, in the CEN countries, it is accompanied by further EU standards and, in United Kingdom (UK) and Italy, by the respective national annexes. ISO 19650, in fact, foresees the principle of national annexes of reference for the local market. At the moment this principle has been adopted only by UK and Italy (2020).

For UK through an annex of the local guidelines - part 0 - and the withdrawal of BS 1192 (British Standards) and PAS 1192-2 (Publically Available Specification) whose principles are deemed to have been absorbed into the body of ISO 19650 1 and 2 (Figure 6).

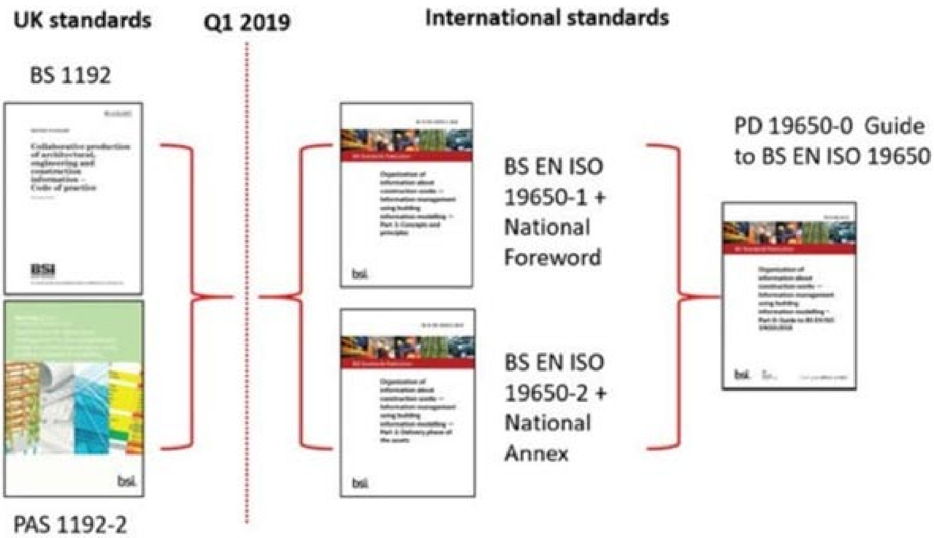
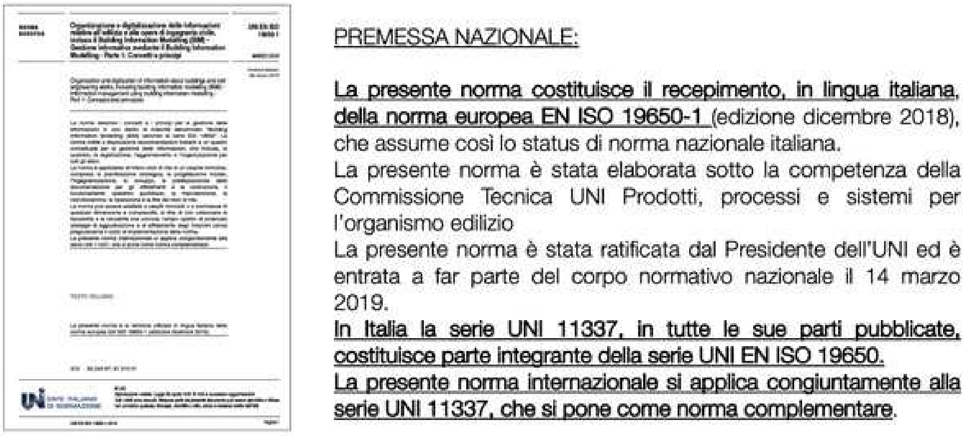


Figure 6 – British Standards, illustrative diagram of ISO 19650 adoption in UK

For Italy, however, instead of an annex to Part 2 of ISO 19650, in view of the large number of detailed standards already in place, it has been decided that the whole of UNI 11337, in its various parts, constitutes a national annex to ISO itself. With the principle of the primacy of the superior standard (ISO 19650) over any possible interference or inconsistencies in the dependent standard as well (UNI 11337[7]) (Figure 7).

[7] UNI 11337:2017-2021. Edilizia e opere di ingegneria civile - Gestione digitale dei processi informativi delle costruzioni


PREMESSA NAZIONALE:

La presente norma costituisce il recepimento, in lingua italiana, della norma europea EN ISO 19650-1 (edizione dicembre 2018), che assume così lo status di norma nazionale italiana.
La presente norma è stata elaborata sotto la competenza della Commissione Tecnica UNI Prodotti, processi e sistemi per l'organismo edilizio
La presente norma è stata ratificata dal Presidente dell'UNI ed è entrata a far parte del corpo normativo nazionale il 14 marzo 2019.
In Italia la serie UNI 11337, in tutte le sue parti pubblicate, costituisce parte integrante della serie UNI EN ISO 19650.
La presente norma internazionale si applica congiuntamente alla serie UNI 11337, che si pone come norma complementare.

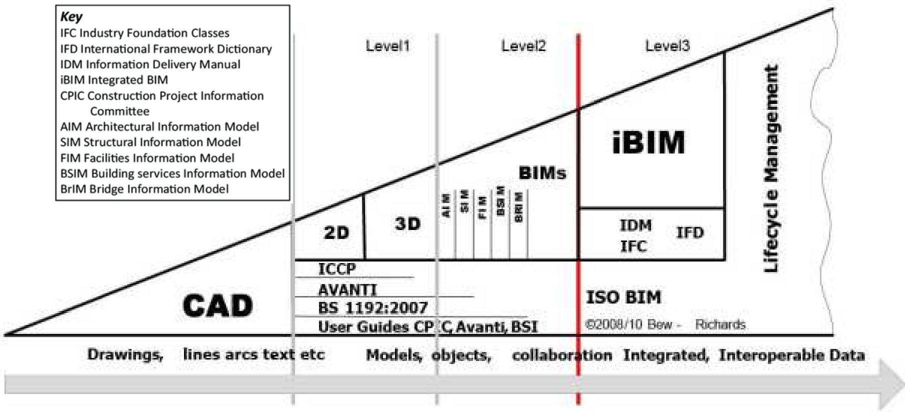
Figure 7 - National preface to the Italian version of UNI EN ISO 19650

In particular, the Part 1 of ISO 19650 frames the information flow of the building process in the wider Project Management horizon, outlining the reference framework standards. Chapter 4 re-proposes the concept of BIM Maturity, with a schematization similar to the well-known Bew-Richards triangle (Figure 8).

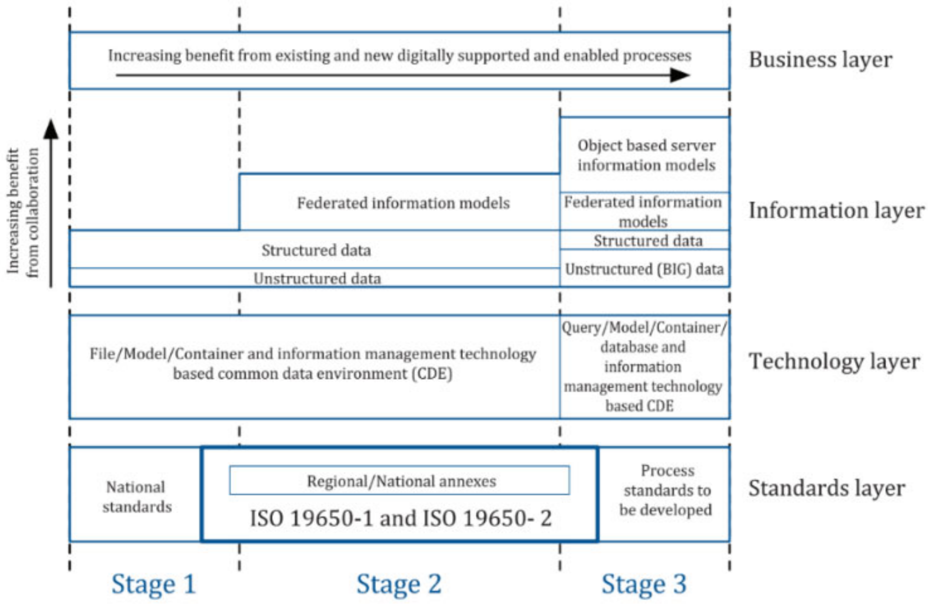
Figure 8b introduces the 'layers' from ISO 19650:

- Standards layer: this establishes the processes and polices in which information contained in the information layer (be it models, federated models, programmes, certificates, schedules, databases, drawings, documentation, etc.) are collated, managed and exchanged in a secure environment across the whole life cycle of an asset, reaping the full benefits of collaboration.
- Technology layer: this includes digital innovations; for example, a CDE (Common Data Environment), which should ensure that information is stored and is easily accessible as and when required for all stakeholders across the life cycle of an asset. The ISO part 1 guide emphasises that a CDE is not necessarily a single solution: it may be a range of technologies that store and manage information in a number of 'information containers' that are able to interface with each other, even if interoperability issues are envisaged. Therefore, CDE is an information management technology, whether singular or multiple systems.
- Information layer: this also includes data that, by adopting digital technologies can be captured, interrogated and analysed to inform decisions that feed into the business layer.
- Business layer: this represents the benefits derived from the integration of the previous layers (standards, technology and information) across the life cycle of an asset. These benefits include capitalising on innovative ways of working to reduce waste and/or reworking across the design, construction, operations and maintenance of an asset. Another benefit is improved performance of a physical asset through the use of databased

intelligent models, which enables simulations and 'optionneering' of an asset system, informed by real-time information garnered from sensors and/or devices connected to the IoT.



a.



b.

Figure 8 – a. Bew-Richards BIM Wedge Maturity Model;
b. ISO 19650:2018 information management maturity diagram

ISO 19650 - Part 1 outlines, in Chapter 5, the different types of information requirements (Figure 9) and specifies that the client should have the function of understanding what information to request about their asset or job, in order to support their organizational or job objectives. These requirements could arise within your own organization. The client should communicate them to the stakeholders and the relying party. In this way, the contracting party can produce and deliver the information products defined by the client in the contracting phase and complete the work with the right knowledge and information quality.

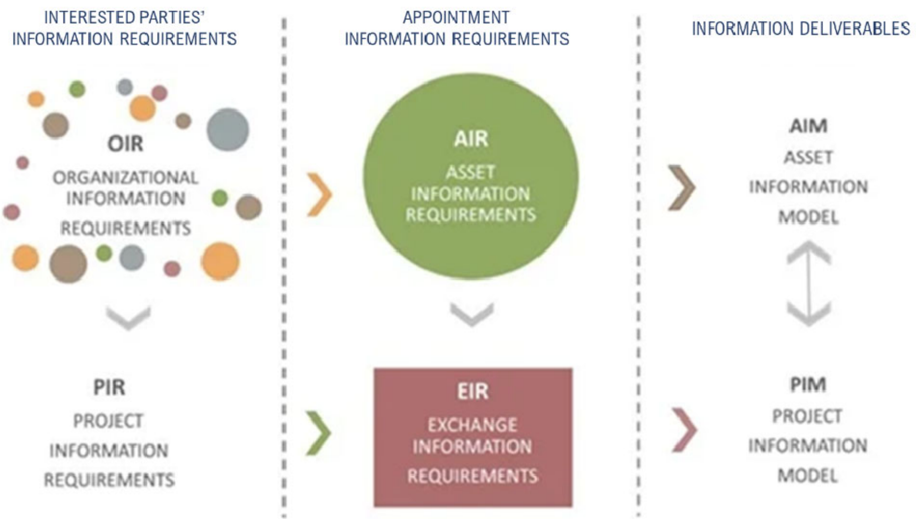


Figure 9 - Hierarchy of information requirements (ISO 19650-1)

- Organizational Information Requirements (OIR): these requirements relate to the information needed to meet or illustrate the internal strategic objectives of the client's business structure.
- Project Information Requirements (PIR): these requirements illustrate the information needed to respond to the strategic objectives of the OIR in relation to a particular order.
- Asset Information Requirements (AIR): these requirements define the managerial, commercial and technical aspects of the information production of the asset.
- Exchange Information Requirements (EIR): these requirements are inherent to the exchange of information and define the information management criteria, methods and production procedures that the contractor must implement.
- Asset Information Model (AIM): this is the information model of the asset and has the function of supporting the strategic and daily management processes of the asset established by the proposing party.

• Project Information Model (PIM): the following information model of the order supports the delivery of the same and contributes to the AIM integrating it for the subsequent management activities of the asset.

Regarding the management phase, from the AIM model we transfer a first level of initial information to the PIM model (it is not necessary that in the AIM model there are geometries, we mean it in the sense of "reference model"). This is the step represented on the right of Figure 9. The PIM model comes developed along the various phases until arriving to the phase of construction and delivery (in the centre of Figure 10), when the information transfer from the PIM to the AIM in sight of the managerial phase is verified again (on the right of Figure 9, Figure 10). The information cycle is triggered by each "trigger event". A trigger event is a "planned or unplanned event that changes an asset or its status during its life cycle, resulting in an exchange of information. To every triggering event corresponds a different use of the model: structural analysis, energetic analysis, but also approval documents, etc.

Key

AIM Asset Information Model

PIM Project Information Model

A Start of delivery phase (see 3.2.11) – transfer of relevant information from AIM to PIM

B Progressive development of the design intent model into the virtual construction model (see 3.3.10 Note 1)

C End of delivery phase – transfer of relevant information from PIM to AIM

Figure 10 – Generic project and asset information management life cycle (ISO 19650-1)

From the point of view of the lifecycle of the real estate asset, then, is proposed in a synthetic and illustrative schema (Figure 11), the entire information flow with the highlighting of the various intermediate moments of evaluation, verification and approval, in which the client is also called to express his opinion about the satisfaction of the project requirements initially expressed.

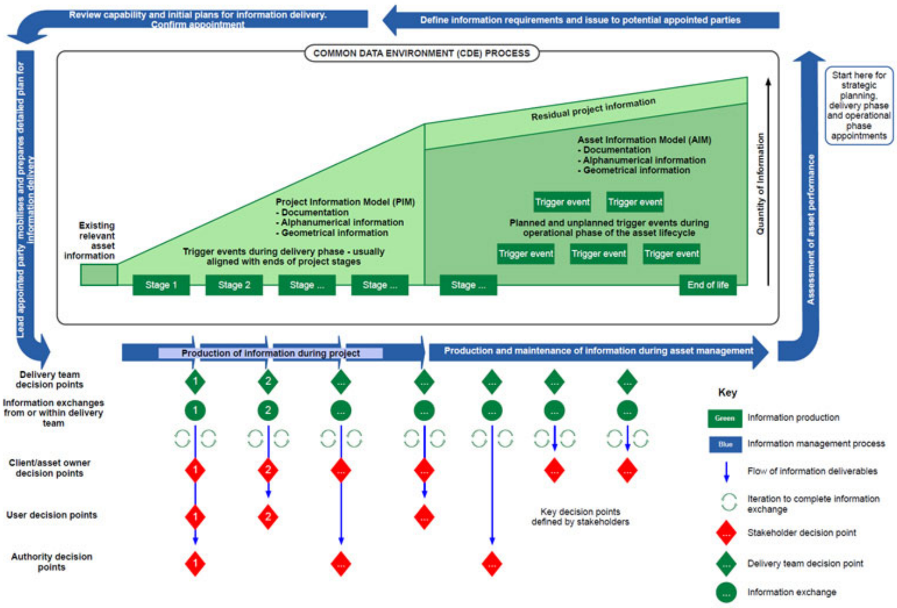


Figure 11 – Overview and illustration of the information management process

The Part 2 of the ISO 19650 standard, then, enters more specifically into the information process, dealing first of all with the players, specifying their position within the process chain and their relative roles and functions (Figure 12).

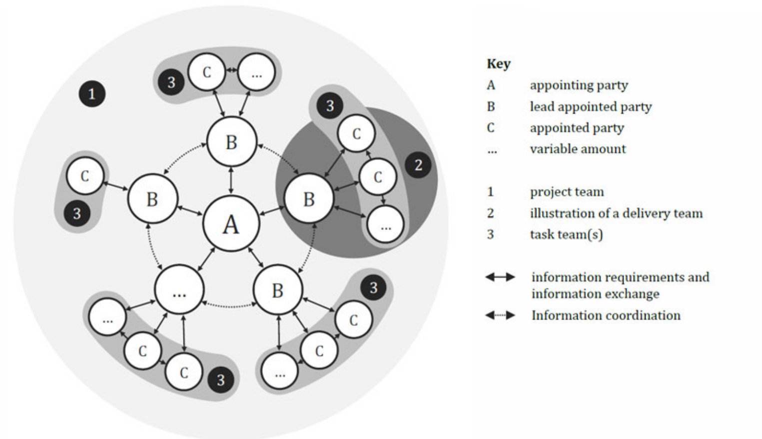


Figure 12 – Interfaces between parties and teams for the purpose of information management

One of the most challenging aspects has been the containment (elimination) of terminology and references to contractual aspects. In fact, for countries with a more organized state and legislative structure, the presence of a technical reference standard with well-defined references could have introduced an element of conflict and/or a constraint on future regulatory developments within them. For this reason, expressions such as "apponted party" or "apponting party" have been introduced to indicate, in a generic way, those figures that in a contract (in Italy) are defined as the contractor and the client.

An other important aspect highlighted in the ISO 19650 is the Common Data Environment (CDE) as an efficient and effective transfers of information between project team members (Figure 13). ISO 19650 3.3.15 CDE is defined as: "*agreed source of information (3.3.1) for any given project or asset (3.2.8), for collecting, managing and disseminating each information container (3.3.12) through a managed process.*". ISO 19650 defines the requirements, and the National Annexes define the actual standards associated with those requirements. A CDE is not a technology solution alone – it requires the project team to follow a standard process that can be enabled and enhanced by the technology.

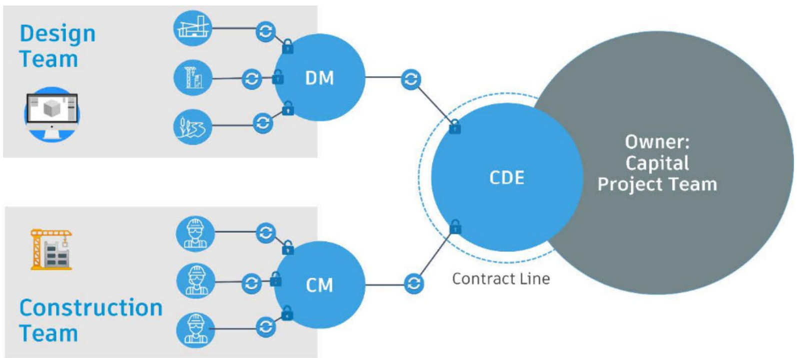


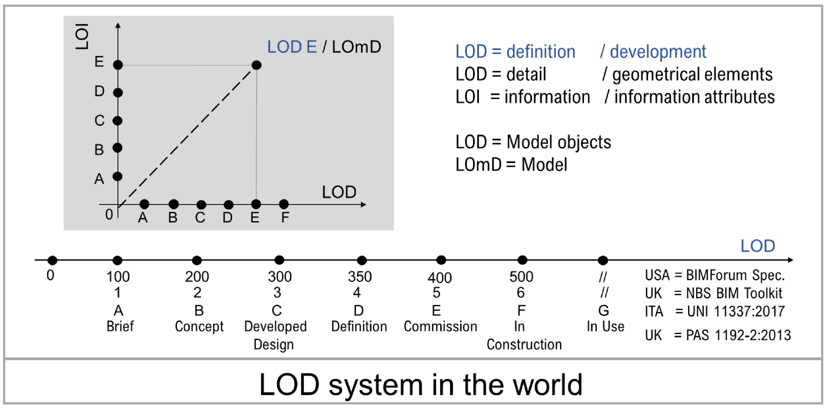
Figure 13 – Project team organization with CDE

The benefits of adopting a CDE are:

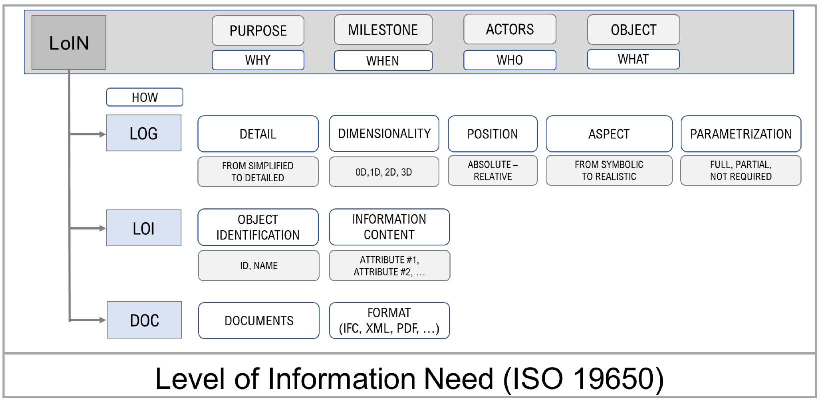
- collaboration enhancement: digital technologies have proven time and again that they can improve collaboration if used correctly. That means that all project data and information needs to flow into and be updated in one centralized system. This leads to improved coordination and teamwork, both internally and across teams.
- creation of a single source of truth: never underestimate the power of one single source of truth on a project. One reliable place for team members to access real-time plans, changes, and data leads to better decision-making and insight across projects and even company-wide.
- improvement of efficiency and quality: CDEs reduce the need to manually recreate data, which leads to reduced input errors and lost information. Consequently, the entire firm has improved access to information that empowers teams to make decisions faster.

- reduction of risk: a CDE lowers risk with better transparency and insight into the entire project landscape. Over time, this enables continuous improvement and predictability, crucial for excelling a business forward.
- Strengthening security: with a CDE, administrators and IT professionals have better control of data and information, creating more security.

Another new aspect of ISO 19650 concerns the overcoming of LOD (Level of Detail or Level of Development) through the Level of Information Need (LoIN) and with the introduction of the concept of Document (DOC) next to geometry (LOG - Level Of Geometry) and alphanumeric information (LOI - Level Of Information). While the LODs were classified through a scale of definition (Figure 14a), the LoINs have no predetermined scale (Figure 14b).



a.



b.

Figure 14 – a. LOD systems in the world; b. LoIN (ISO 19650)

As far as the Italian standard is concerned, we can identify as the national annex of ISO 19650 the technical standard UNI 11337 which, although it was adopted previously, was then updated to respond to the function of a complementary standard to ISO itself. The mainly applicative structure of the Italian standard is perfectly compatible with ISO 19650, which instead provides guidelines on information management through BIM.

The UNI 11337 is composed of several parts and currently have been published seven of them (part 1-2-3-4-5-6-7, 2021). The Italian legislator provides that it can be applied to any type of building, infrastructure and process, understood as conception production for new construction, conservation or restoration of the environment or the built environment.

The different parts, already drafted, of the UNI 11337 are:

- UNI 11337-1:2017 Construction and civil engineering works - Digital management of construction information processes - Part 1: Models, documents and informative objects for products and processes;
- UNI 11337-2:2021 Construction and civil engineering works - Digital management of construction information processes - Part 2: Designation and classification criteria for models, products and processes;
- UNI/TS 11337-3:2015 Construction and civil engineering works - Coding criteria for construction works and products, activities and resources - Part 3: Models for collecting, organizing and recording the technical information for construction products;
- UNI 11337-4:2017 Construction and civil engineering works - Digital management of construction information processes - Part 4: Evolution and development of information within models, documents and objects;
- UNI 11337-5:2017 Construction and civil engineering works - Digital management of construction information processes - Part 5: Informative flows in the digital processes;
- UNI/TR 11337-6:2017 Construction and civil engineering works - Digital management of construction information processes - Part 6: Guidance to redaction the informative specific information;
- UNI 11337-7:2018 Construction and civil engineering works - Digital management of construction information processes - Part 7: Requirements of knowledge, skills and competence for the figures involved in the digital management of the information processes;
- UNI 11337-8 and followings (under drafting).

The purpose is to gradually reorganize the entire national normative park in consideration of ISO 19650 but, more than for this, for the evolutions that have occurred in the meantime, from 2015-2021, in practice and, obviously, in technology (semantics, block-chain, etc.).

The framework of the Italian standards, which are very applicative, is in fact perfectly compatible with the structure of ISO 19650, which essentially presents guidelines, although its adoption supports the decision of a gradual overall review. Always with the intention of standardizing at a national level as a basis for discussion for the community (CEN) and international (ISO) levels.

The most important innovations will involve:

- the introduction of Level of Information Need (LoIN) instead of LOD (ex part 4), which will be reviewed in consideration, also, of the European standard currently being defined, considering that, in order to facilitate its applicability in public contracts, a reference scale will in any case be envisaged according to the higher indications deriving from “Codice degli Appalti” (Italian legislations: D. Lgs. 50/2016 and D.M. 560/2017);
- a more detailed definition of the CDE (ACDat in Italy, ex part 5) according to the scheme confirmed by 19650, and in parallel with the development of digital, organizational and national "platforms" (ex part 1). A concept that until recently was entirely Italian and that today also sees Europe active towards an EU digital platform for construction: DigiPLACE - H2020 (Figure 15);
- the finalization of the information flow now defined only in the Informative Specifications (Capitolato Informativo, ex part 6) with the application definition of OIR, PIR, AIR, EIR, AIM, PIM, etc. in the Organization Information Handbook (Figure 16);
- the writing of the parts already planned but still missing: 8 - workflows, 9 - operation phase, 10 - automated verification, 11 - data security, block-chain.

All while waiting, among other operational steps, of the (political-administrative) path underway for the opening of a European standard on BIM and digital for conservation and restoration of built heritage and listed buildings (Figure 17).

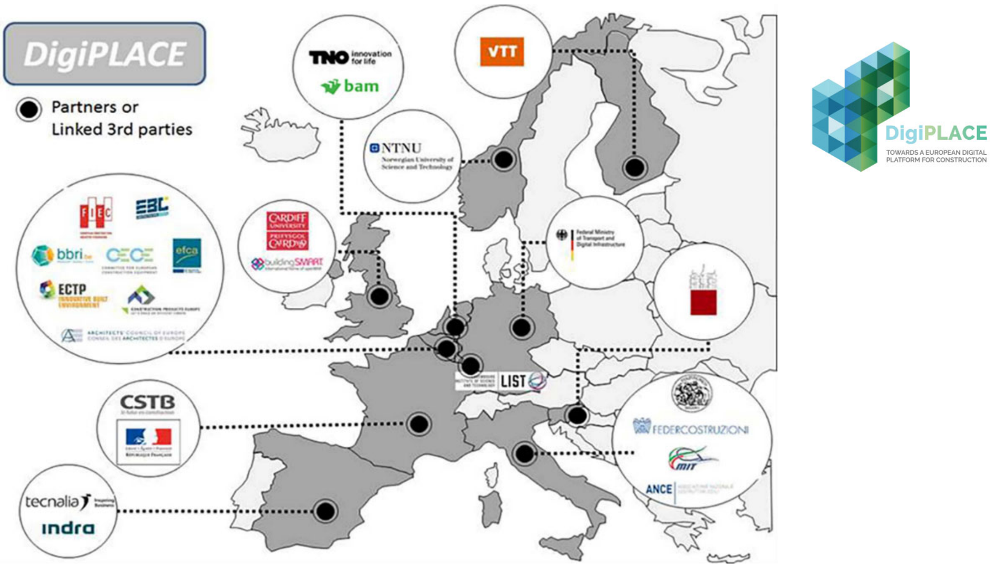


Figure 15 – DigiPLACE - H2020


1 Introduzione
1.1 Riferimenti normativi
1.1.1 Norme
1.1.2 Standard
1.2 Acronimi E glossario
2 Scopo
3 Attività
3.1 Benchmark informativo
3.2 Prodotti eeservizi
4 Organigramma relazionale
4.1 Organigramma relazionale esterno all'organizzazione
4.1.1 Soggetti coinvolti
4.1.2 Organigramma delle relazioni esterne
4.2 Organigramma relazionale interno all'organizzazione
4.2.1 Entità del gruppo
4.2.2 Funzioni/aree dell'organizzazione
4.2.3 Organigramma delle relazioni interne
5 Flussi informativi
5.1 Flussi informativi esterni dell'organizzazione
5.2 Flussi informativi interni dell'organizzazione
5.2.1 Flussi informativi tra entità del gruppo
5.2.2 Flussi informativi tra le funzioni/aree dell'organizzazione
6 Strumenti dedicati
6.1 Strumenti hardware dell'organizzazione
6.2 Strumenti software dell'organizzazione
7 Politiche di sicurezza informativa
7.1 Segretezza dati
7.2 Sicurezza dati
7.3 Garanzia di accesso nel tempo

A OIB - ORGANIZATION INFORMATION HANDBOOK (P. 12)
A1 OIR - ORGANIZATION INFORMATION REQUIREMENT
A2 OIM - ORGANIZATION INFORMATION MAPS
B AIB - ASSET INFORMATION HANDBOOK (P. 9)
B1 AIR - ASSET INFORMATION REQUIREMENTS
B2 AIM - ASSET INFORMATION MODEL
C PIB - PROJECT INFORMATION HANDBOOK (P. 6)
C1 PIR - PROJECT INFORMATION REQUIREMENTS
C2 PIM - PROJECT INFORMATION MODEL
D EIR - EXCHANGE INFORMATION REQUIREMENT (P. 6)
E IDP - INFORMATION DELIVERY PLANNING
E1 BEP - BIM EXECUTION PLAN
F PDM - PLATFORM DATA MANAGEMENT (P. 5)
F1 CDE - COMMON DATA ENVIRONMENT
F2 DR - DATA ROOM

Figure 16 – Organization Information Handbook (UNI 11337)

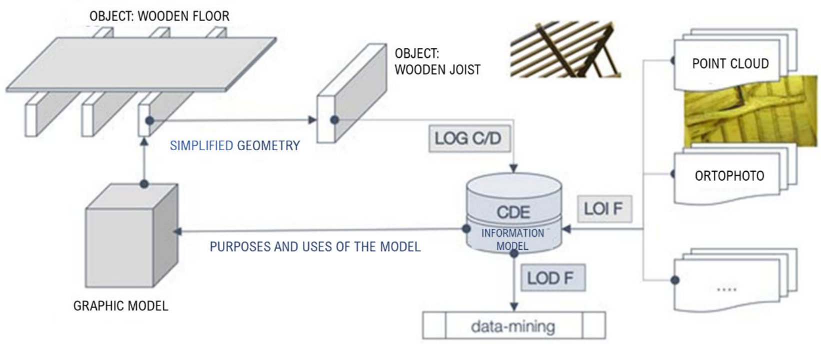


Figure 17 – Example of modeling information flow for conservation and restoration of built heritage

2.2. BIM for built heritage

The need to make the heritage conservation and enhancement processes coordinated and planned has been established at a theoretical and legislative level for several years now.
In Italy, in particular, the basis of such a methodological approach is stated in Article 29 of the D. Lgs. 42/2004[8], encouraging a conservation practice ensured by «a coherent, coordinated and planned activity of study, prevention, maintenance and restoration». In addition, Article 3 of the D.M. 154/2017[9] explicitly refers to the above-mentioned article and clarifies that public interventions on cultural heritage have to be implemented "*according to the timescales, priorities and recommendations deriving from the criterion of planned conservation*".

[8] D. Lgs. 42/2004 – Decreto Legislativo 22 gennaio 2004, n. 42 - *Codice dei Beni Culturali e del Paesaggio* (Governo Italiano)
[9] D.M. 154/2017 – Decreto Ministeriale 22 agosto 2017, n.154 - *Regolamento concernente gli appalti pubblici di lavori riguardanti i beni culturali tutelati* (Ministero dei Beni e delle attività culturali e del turismo, Governo Italiano)

Heading in this direction means developing an operative methodology able to collect, hierarchically organize, but also interconnect and manage heterogeneous data (different sources, contents, scales of representation, levels of detail and development, etc.) related to historical architectures and sites in the medium-long term, ensuring accessibility and shareability of information among stakeholders during the various phases of the conservation process. The implementation of innovative digital technologies, from survey to BIM, can offer significant chances to support both the crucial but radical change of processes and tools, which are traditionally available to the architect-restorer, and the collaboration with experts working in cross-disciplinary fields.

In recent years there has been an increasing experimentation of the BIM approach in the field of cultural heritage in order to assess its adequacy for documentation, restoration and management of historical heritage (Brumana et al., 2017; Bruno and Roncella, 2018; Della Torre et al., 2019).

To exploit the potential of Information and Communication Technology (ICT) while respecting the discipline of heritage protection and its specificities, the approach to artefacts (survey, modeling and data enrichment) has to be based on knowledge as a guiding principle; in this sense, it is possible to talk about "knowledge modeling" as several authors have recently highlighted (Acierno, 2017; Acierno et al., 2017; Fiorani, 2017).

Geomatic survey techniques are particularly relevant for accelerating spatial data collection from existing buildings (Gómez-García-Bermejo et al., 2013). Moreover, colour and material information can also be integrated or mapped. The processed data can be a starting point to give a product suitable for BIM platforms, adopted in recent years as a new paradigm for documentation and data management of existing assets, especially of the built historical monuments (Akbarnezhad et al, 2014).

BIM has been originally designed to support new buildings. This could make BIM adoption to heritage buildings challenging due to the specific characteristics of historic buildings (Barazzetti et al., 2015). For example, they have an extended time of use that usually alters some of their features: repurposed structures, reused materials and shape variations. Historic buildings usually include different architectural typologies, several historic-constructive phases and sometimes pathologies such as cracks or humidity (Green et al., 2016). Heritage stakeholders have different needs than those of regular AEC professionals and these needs to take into account in a precious and useful manner (Megahed, 2015).

The first use of BIM applied to existing buildings is represented by the works of Arayici (2008) which attempts a first 3D modelling with integration of intelligent data. In the same years the experiments of Murphy et al. (2009, 2013) to the develop the HBIM by creating libraries of parametric objects constructed from historical data and a system for mapping the parametric object. Murphy has defined HBIM as a new system of modelling historic structures creating full 2D and 3D models, which include detail behind the surface of the objects concerning its methods of construction and material makeup (Murphy et al. 2009). Recently, HBIM was also named Heritage Building Information Modelling, a broader term that includes historical data, conservation policies and significance values (Spanish Ministry of Education, Culture and Sports, 2004). Heritage BIM includes highly protected buildings that usually requires broader intervention projects and a careful life cycle management. Dore and Murphy (2017) proposed these HBIM elements: heritage documentation standards, data collection techniques, 3D modeling concepts, as-built BIM and procedural modelling.

In the interesting work of Volk et al. (2014), the limits and the poor application of BIM on existing buildings are discussed through a critical analysis of numerous contributions in the literature. Some of the issues expressed in the contributions are still current: difficulties in the modeling of non-standard forms, lack of automation in the conversion of data acquired from digital surveys into semantic objects, methods for entering information and documents. Even today, in the practice of the restoration project, BIM is still not widespread and often used as advanced CAD, neglecting its essence: information and its sharing (Coli et al. 2019).

The development of an "as-built" BIM requires the data acquisition of the current state of the relevant structure (Macher et al., 2017), the geometrical modeling of the objects, the attribution of categories and material properties to the objects and the creation of relations between them (Hichri et al., 2013).

It is important to note that the libraries and tools of the BIM platforms focus on the design and construction of new buildings with simple, regular, and standardized objects (Bryde et al., 2013). For this reason, the virtual and detailed reconstruction of cultural-historical heritage has revealed some limitations of BIM platforms, such as the unavailability of historical parametric object libraries and the lack of tools for managing complex, irregular shapes that are obtained from the geomatic survey techniques.

Historic buildings have different characteristics compared to new buildings. Each historic building is different from the other and has characteristics and singularities that make it a *unicum*.

The difference between common existing buildings and heritage ones is that heritage projects involve architectural, historic and archaeological documentation, so it involves the technical reproduction of a context, as well as an intellectual effort to describe the socio-cultural heritage setting (De Naeyer et al., 2000).

The lifecycle of an historic building is cyclical for the periodic and recurring activities for its maintenance and restoration but also for managing several multi-temporal information. In addition, the whole history of the building must be considered and added to the information about the actual state (Bruno and Roncella, 2018).

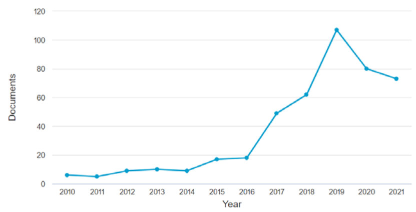
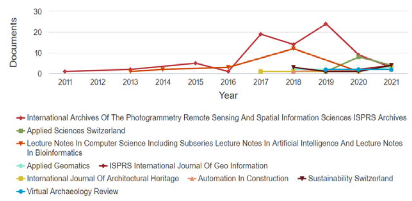
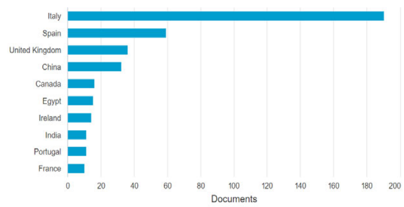
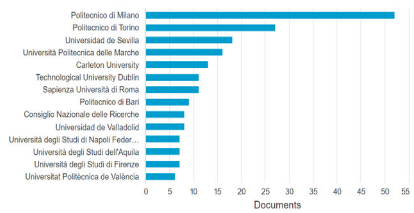
Based on these main considerations, it's clear that HBIM implementation cannot follow a standard approach, but it needs to understand the Level of Information (LOI) that can be based on acquired information and adopting a semantic description, essential for the representation of the artefact where data and entities are linked in a relational system. HBIM can be defined as a useful information system to enrich the knowledge about an existing building and it allows to manage heterogeneous data e.g. geometric, historical, thematic, etc. trying to put in order and combine them to enhance the heritage documentation. In addition, in field of restoration, a HBIM system represents an efficient tool for protection and conservation monitoring in order to prevent damage situations (Malinverni, Mariano et al., 2019).

2.2.1. Literature analysis about BIM for built heritage

To better investigate how the topic of BIM for BH has been addressed in scientific research, it is good practice to carry out a literature analysis. To this end, a state of the art search was carried out for the time period of the last decade (2010-2021) through different scientific publication sharing platforms such as Scopus, Web of Science and Science Direct. The choice fell on the use of the Scopus platform as it gathers more publications from different sources and more affiliations than the other two platforms. This operation made it possible to analyse not only the trend of scientific publications on the topic of BIM for the built heritage but also to identify operational and research trends.

The search began by looking for the terms "BIM" and "cultural heritage" in titles, abstracts and keywords list of publications. Similarly, the search was carried out with the term "HBIM" only. As this second expression was coined by the scientific community and therefore more widely used, it returned more results (445 publications, Table 1) than the first combination (324 publications). The search was also carried out by combining all three terms, confirming the same result as with term "HBIM" only.

Table 1. Search results for the term HBIM using the Scopus platform (updated 31 October 2021)

<table>
<tr><th colspan="2">Search: TITLE-ABS-KEY (hbim) AND PUBYEAR > 2010 AND PUBYEAR < 2021</th></tr>
<tr><td>445 document results

</td>
<td>Documents per year by source

</td></tr>
<tr><td>Documents by country

</td>
<td>Documents by affiliation

</td></tr>
</table>

Through the analysis of the results obtained, shown in Table 1, the following comments can be expressed:

- "HBIM" term is more used from 2017 since it was introduced in the literature in 2009 by researchers Murphy et al. (2009).
- The peak in the number of publications reached in 2019 is motivated by the fact that there have been several initiatives from the scientific community (conferences, workshops, special issues on international journals) which is not confirmed in the following years due

to the impact of the Covid-19 emergency where in-person activities such as in-situ surveys and conferences (see ISPRS publications as main repository) have disappeared, although they have been maintained in online mode. The sources of the publications shown in the graph were chosen by the author on the basis of the journals most frequently mentioned in the bibliography of the thesis.

- Since 2017, special issues on HBIM have been promoted by several journals and this has allowed to deepen the HBIM topic not only in geomatics, but by other scientific disciplines related to the topic of built heritage, historic buildings and historical centres and this makes us understand the number of actors with different skills that are involved in an HBIM project.
- Despite the fact that the concept of information system (such as BIM) was introduced earlier in other countries of the world such as UK and Canada, Italy ranks first in terms of number of publications (43%) and this is justified both by the high number of academics and researchers and institutional bodies dealing with the topic of built heritage and by the richness of the historical heritage that characterizes the Italian territory.

The literature search was then conducted by combining the term "HBIM" with other terms that are introduced in this research thesis and are shown in the following table separated into sub-categories (Table 2). The results of the search for combinations of terms have been catalogued in Appendix A.

Table 2. Search results of combination with HBIM term within Scopus platform (updated 31 October 2021)

HBIM and…	**n. publications**
documentation	120
digitization	30
conservation/preservation	209
restoration	79
management	177
knowledge	90
geomatics/geomatic survey/metric survey	22
photogrammetry	77
laser scanner/TLS/MLS/MMS	46
3D/3D model/3D modeling	229
database/relational database	60
semantics/semantic	59
ontology	20
open-BIM	14
data integration	41
data sharing	21
interoperability	36
GIS/3D GIS	36
web/semantic web	24
review	34

A first research has been carried out by combining "HBIM" with terms that refer to the main objectives of its application to the BH. It can be seen that the main purpose attributed to the use of the HBIM system is that of conservation and preservation of the BH, understood not only as an action of physical preservation of the artefact but also through the tools of digitization and virtualization. This is followed by the terms management and documentation, often combined with the concept of conservation but more related to non-geometric data aspects of the BH, useful for restoration process. HBIM is also a useful tool for the knowledge of the heritage itself, in all its forms, starting from the data managed, the information produced and the forms of sharing and dissemination to stakeholders outside the project.

Since we are in the geomatics field, the research continued with the combination of "HBIM" with metric acquisition techniques of the BH. The main techniques applied include photogrammetry and laser scanning. The former is recorded more times than the latter and this confirms the greater use of the image-based technique because it is easier and more practical to use and also allows more data to be obtained than the range-based technique such as RGB data and the material description of the artefact. The range-based technique is more useful because the point cloud obtained facilitates the 3D modeling of the object. It is also to be considered that often these two techniques are used in combination and this allows to enrich the amount of data obtained from the geomatic survey guaranteeing a greater completeness of the acquired artefact.

With regard to the elements that are generated through (H)BIM software, 3D modelling prevails over the creation of the information database. This observation reflects what was anticipated in the Introduction (Chapter 1), i.e. that the scientific research dealing with BH focuses more on obtaining parametric modelling that conforms to reality and is less concerned with the management of the information linked to the 3D model and the artefact in general that is catalogued in database. The semantic aspect of HBIM implementation is emphasised as the logical organisation of the information managed and the relationships between the data referring to the object are taken into account. On the other hand, a low number of publications deal with the topic of ontology, which represents an indispensable tool for the management of information by defining semantic domains that allow the management and conversion of data into coded expressions, guaranteeing the exchange and interoperability of the HBIM platform both internally and externally with other information systems used for BH.

At the back of the queue for issues related to data sharing, data integration also through open BIM platform. Furthermore, the concept of interoperability between a BIM system and other information systems used for the management of a built heritage, such as GIS, guaranteed through the semantic web, is still an open challenge in the scientific research scenario.

Regarding the literature review conducted on HBIM, several reviews have been performed since 2015 that are useful to define the technological, functional and research progress on information modeling and management for BH.

Chapter 3.

Data management for built heritage

The data management for the documentation of built heritage is the preliminary action to deal with characteristics and any issues related to it. The procedure of documentation requires a diverse range of data (quantitative and qualitative) to be obtained and investigated in order to achieve an accurate digital representation and archiving of the built heritage (3D model and database).

The heritage sector is usually not seen as a thriving economic sector, which makes less effort to meet the need to document every heritage building. This is confirmed by the fact that heritage buildings are often not documented or do not have accurate, sufficient and complete documentation covering every aspect of the building: geometry, historical background and condition state (Khalil et al., 2021).

BH is usually characterised by a fragile appearance, inefficient preservation methods and outdated security measures, which can compromise their existence by putting them at increased risk of damage and accidents that may lead to the loss of part or all of the heritage. In these unfortunate cases, if complete, necessary and reliable documentation is not in place, the history of the BH and its legacy may be lost forever.

Considering every aspect of BH documentation, current state-of-the-art documentation technologies are already available and able to provide accurate and reliable information when accompanied by careful planning and consideration of the documentation process and its objectives (Table 3). These technologies enable useful data to be obtained in various aspects of a heritage building and its required interventions. However, these up-to-date methods and technologies are often isolated from each other and not linked, which threatens the whole documentation process.

Current BIM tools allow the combination of different documentation data into a complete artefact model and promote the collaboration of different actors in the same workflow. In reality, however, the inherited isolation of different workflows still dominates the field. This can be seen in the research model regarding BH documentation, which is usually discipline-oriented and rarely discusses the issue of documentation itself in a broader holistic view (Laing et al., 2015; Acierno et al., 2017; Khalil and Stravoravdis, 2019). As seen from the literature analysis (Section 2.2.1) there are distinct areas of documentation such as the geometric model, and less on aspects regarding data archiving the investigation and condition state, so there is not much work on all these areas combined, which is what is needed for the documentation and preservation of a BH. However, there is no framework that can combine all technologies and tools together in a meaningful way for the digital documentation of heritage buildings.

Thus, the combination of various data sources embedded with built heritage documentation in a holistic framework would facilitate the full implementation of BIM strategies and open the door to data integration with other information techniques (e.g. GIS tools, virtual/augmented reality) aiming at truly representing the whole BH in the digital environment.

Table 3. Documentation objectives for built heritage, grouped for different type of requirements and finalities

Documentation objectives for built heritage
Historical studies Public dissemination (digitization) 3D representation/reconstruction (VR-AR-XR) Educational purposes
Conservation Preservation
Maintenance Monitoring
Restoration
Consolidation Rehabilitation
Retrofitting Adaptative reuse

3.1 Digital documentation for built heritage

BH documentation is seen as "*the systematic collection and archiving of tangible and intangible elements of historic structures and environments. Its purpose is to supply accurate information that will enable correct conservation, monitoring and maintenance for the survival of an artefact*" (Dore and Murphy, 2017). Documentation is the first phase for BH's analysis, conservation, restoration, renovations and management. It can incorporate both quantitative assets (geometric data) and qualitative assets (historical background and condition state) (Fai et al., 2011). Capture of all possible data is the first step to contribute towards fundamental modeling for BH recording and documentation (Cheng et al., 2015).

The process of digital documentation of heritage buildings can be viewed as a three-phase procedure. It begins with the acquisition of all the necessary data on various levels using a variety of tools and sources. Data capture is concerned with gathering, surveying and monitoring all the available raw data of the BH from the building itself or from external sources in order to create a pool of primary data that describe the BH in all its aspects.

The second phase of data interpretation could be carried on in order to analyze and visualize the captured data. Interpretation of captured data requires different tools and methods but share the same idea of extracting and analysing the related information concerning the BH. This step include data analysis, such as research and analytical studies of archaeological and historic data; as well as visualisation of the geometry and other documented data.

Then, the data processing and recording the surveyed raw data are converted into structured data that can help to build a basic form fo information of the BH, its history, how it was constructed, how it works, potential structural deterioration and performance deficiencies. This understanding is the keystone in decision-making, planning and managing any needed intervention.

This methodology of work of data capture, interpretation and processing and recording is often conducted in isolation by different stakeholders and for a range of purposes, leading to a lack of communication between different data types, repeated effort and incomplete documentation.

Once the objective has been identified, the cycle starts with the data capture phase, which represents the collection of all relevant data of the BH basing on the request LOD (Level of Detail) (Fai and Rafeiro, 2014) and/or LOA (Level of Accuracy) (Garagnani and Manfredini, 2013) and basing on the LoIN (Level of Information Need) (ISO 1950:2018) can be achieved. Following is the data interpretation that leads to the analysis, and visualization of the captured data. The data processing and recording consist on modeling the geometrical data and archiving within database not geometrical data; transforming all data into structured information.

3.2. Documentation data

The documentation process of BH incorporates a diverse range of data formats that span from quantitative to qualitative and from tangible to intangible (Fai et al., 2011; Di Mascio et al., 2013). It represents also numerous types of data, considering its purpose, such as geometric data, historical data and condition state data. Different stakeholders are usually interested in specialised tape of documentation data (Acierno et al. 2017); these distinctively different data types collectively represent the documentation of the BH.

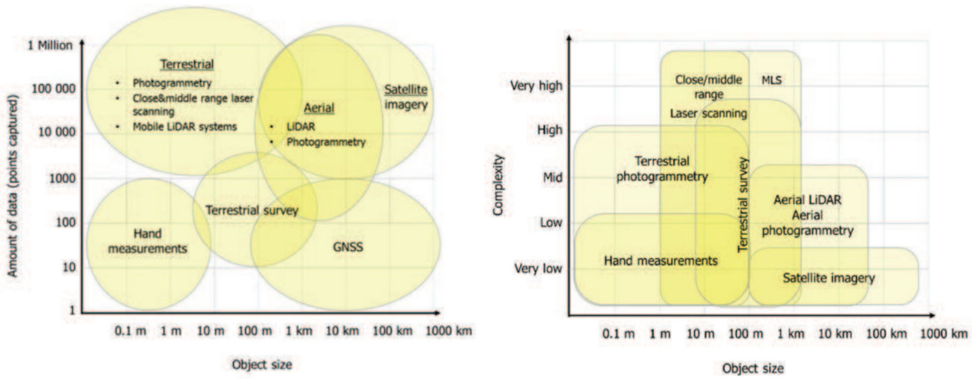
Three main data categories that span the whole BH documentation data areas are being suggested which vary geometry, investigation and lifecycle (Table 4).

Table 4. Proposed categorisation of the documentation data of built heritage and their respective data capture tools or sources

Category	**Geometry**	**Investigation**	**Lifecycle**
Sub-category	Metric survey	Indirect analysis	Condition state
Tools - sources	Geomatic techniques	Historical background Bibliographic research Multimedia	Technical documents Transformations Risk assessment

3.2.1 Geometry

Multi-source data fusion is one of the main challenges to face 3D reconstruction and visualization of BH, providing a solution for the combination of mixed data sources. For this purpose, the suitability of the different sources of metric data should be systemized according to the BH object size and its complexity (Rodriguez-Gonzalvez et al., 2017).



a. b.

Figure 18. a. Three dimensional survey techniques characterised by scale and object size (derived from Böhler et al., 2001). b. Three-dimensional survey techniques characterised by complexity and object size (Rodríguez-Gonzálezvez et al., 2017)

One of the most common classifications of CH studies (Kraak and Ormeling, 2011) is based on categorization according to the size of the element under study or scale range: the scale of built heritage dealt with in the present work is considered at architectural and urban landscape scales (Table 5). This classification may seem unsophisticated, but the addition of other variables would complicate the classification and would result in confusion when describing the approach. The different categories of BH assets are specified in order to assist inventory compilers and users in determining the appropriate procedures to be followed.

Table 5. Scale ranges for BH commonly established (revision of the adaption from Kraak and Ormeling, 2011)

BH scale	Scale ranges
Architectural (Building scale)	From 1:10 to 1:200
Urban - Landscape (Urban scale) (e.g. Archaeological area - Building aggregate – Urban area – Vernacular villages)	From 1:200 to 1:2000

The determination of position, size, shape and identity of the components of a heritage artefact is a fundamental part of any project related to the conservation or renovation of BH (Historic England, 2018). Geometry capture of heritage artefacts has witnessed a lot of research and development in the recent years. However, it is still a particularly challenging process due to the irregular geometry, non-homogeneous materials, variable morphology, undocumented changes, damage and various stages of construction that typically characterises BH.

Geometry capture and representation of heritage buildings can be conducted by means of various techniques with a wide range of accuracy, cost efficiency and time consumption.

Nowadays, two main data acquisition methods are used to generate 3D models of the current state of BH: image-based and range-based techniques, which use passive and active sensors respectively. Depending on the particular case study and the working scale different geomatic systems are recommended, as Table 5 shows.

Due to their ability to collect large volumes of 3D data in a rapid and accurate way, range-based techniques such as Terrestrial Laser Scanning (TLS), Mobile Laser Scanning (MLS) and Aerial Laser Scanning (ALS) allow the acquisition of complex and versatile data (point clouds) that can be used in different contexts in a non-contact and non-destructive manner. On the other hand, image-based techniques such as terrestrial or aerial photogrammetry (onboard airborne systems such as drones) including automated implementations of Structure from Motion (SfM) algorithms, can provide valuable spatial object models adding high-quality photographic texture information (Bagnolo et al., 2019). SfM approaches allow the reconstruction of 3D scenes (structure) and camera pose (motion) through sets of 2D images. The process mainly consists of image matching, camera orientation and self-calibration, and dense point cloud generation. These processes are based on a projective geometry and include the derivation of interior and exterior orientation parameters of the taking cameras.

Some of the geotechnologies classified as passive or active systems in Table 6 can be defined as "hybrid" systems, for example MLS which integrates navigation (GNSS/INS), range (laser scanners) and imaging (cameras) sensors, but they are kept in the active-passive dichotomy for the ease of understanding. In addition to optical sensors, radar sensors also provide useful data for large-scale documentation of a BH context.

Table 6. Set of geotechnologies appropriate to 3D data acquisition in CH environments classified according to the dimensions of the element or site under study.

BH scale / **Geomatic sensors**	**Architectural**	**Urban landscape**
Optical sensors		
Passive systems	• Close-range photogrammetry (aerial and terrestrial) • Spherical photogrammetry • GNSS	• Long/medium-range aerial photogrammetry • GNSS
Active systems	• Airborne/Aerial Laser Scanning • Close-range TLS • Total station	• Long/medium-range TLS • Total station
«Hybrid» systems	• MLS (with SLAM and camera)	• MLS (with SLAM/GNSS and camera)
Radar sensors		• SAR images

3.2.1.1 Advanced reality-based geomatic techniques

The actual technologies and methodologies for cultural heritage documentation allow the generation of realistic 3D results (in terms of geometry and texture) used for many scopes like heritage documentation (Murtiyoso et al., 2018), digitization (Masciotta et al., 2021), digital conservation (Reinoso-Gordo et al., 2018), condition assessment (Quagliarini et al., 2016), restoration purposes (Di Stefano et al., 2019a), VR/AR/XR applications (Banfi and Oreni, 2020), 3D repositories and catalogs (Santagati and Lo Turco, 2017), knowledge sharing systems (Bitelli et al., 2017), valorization (Sanchez-Aparicio et al., 2019) and visualization purposes (Pierdicca et al., 2021), etc. But despite all the possible applications and the constant pressure of international organizations, a systematic and well-judged use of 3D models in the cultural heritage field is still not yet employed as a default approach for different reasons (Remondino, 2011):

- the "high cost" of 3D, both in acquisition and processing and recording phase;
- the difficulties in achieving good 3D models by everyone;
- the consideration that it is an optional process of interpretation (an additional "aesthetic" factor) and documentation;
- the difficulty to integrate 3D worlds with other more standard 2D material.

But the availability and use of 3D computer models of heritages opens a wide spectrum of further applications and permits new analysis, studies, interpretations, conservation policies as well as digital preservation and restoration. Thus, virtual heritages should be more and more frequently used due to the great advantages that the digital technologies are giving to the heritage world and to recognize the documentation needs stated in the numerous charters and resolutions.

"*It is essential that the principles guiding the preservation and restoration of ancient buildings should be agreed and be laid down on an international basis, with each country being responsible for applying the plan within the framework of its own culture and traditions*" (Gazzola et al., 1964). Even if this was stated more than 60 years ago, the need for a clear, rational, standardized terminology and methodology, as well as an accepted professional principle and technique for interpretation, presentation, digital documentation, and presentation, is still not evident. Furthermore *"[...] Preservation of the digital heritage requires sustained efforts on the part of governments, creators, publishers, relevant industries and heritage institutions. In the face of the current digital divide, it is necessary to reinforce international cooperation and solidarity to enable all countries to ensure creation, dissemination, preservation and continued accessibility of their digital heritage*" (The UNESCO's Charter on the Preservation of the Digital Heritage, 2003).

Therefore, although digitally recorded and modeled, our heritages require more international collaborations and information sharing to digitally preserve them and make them accessible in all the possible forms and to all the possible users and clients. Nowadays, the digital documentation and 3D modeling of cultural heritage should always consist of (Di Stefano et al., 2021):

- 3D reconstruction, documentation, data source for restoration, conservation and preservation interventions and activities;
- design of 3D parametric surfaces and meshes through reverse modelling, direct modelling or generative modelling operations;
- spatial analysis and management through information system of the achieved 3D geometrical models for further applications (HBIM or 3DGIS);
- detailed archivable record, condition analysis and structural monitoring in case of changes over time due to forms of degradation or damage resulting from risk situations by anthropological and natural actions;
- digital inventories and sharing for education, research or tourism purposes and also improving accessibility, knowledge and understanding.

The continuous development of new sensors, data capture methodologies, multi-resolution 3D representations, and the improvement of existing ones are contributing significantly to the documentation, conservation, and presentation of heritage information and to the growth of research in the BH field. This is also driven by the increasing requests and needs for digital documentation of archaeological sites at different scales and resolutions.

A technique is intended as a scientific procedure (e.g., image processing) to accomplish a specific task while a methodology is a group or combination of techniques and activities combined to achieve a particular task. Reality-based techniques (e.g., photogrammetry, laser scanning, etc.) employ hardware and software to survey the reality as it is, documenting the actual or as-built situation of a site and reconstructing it from real data. Non-real approaches are instead based on computer graphics software (3D Studio, Maya, Sketchup, etc.) or procedural modeling approaches (Barazzetti et al., 2015; Schwarz et al., 2015; Banfi et al., 2018), and they allow the generation of 3D data without any particular survey or knowledge of a site.

The generation of reality-based 3D models of heritage sites and objects is nowadays performed using methodologies based on passive sensors and image data, active sensors and range data, classical surveying (e.g., total stations or GNSS), 2D maps, or an integration of the aforementioned techniques (Nex and Rinaudo, 2011, Bayram et al., 2015). The choice or integration depends on required accuracy, object dimensions, location constraints, system's portability and usability, surface characteristics, working team experience, project's budget, final goal, etc. Although aware of the potentialities of the image-based approach and its recent developments in automated and dense image matching, the usability by non-experts and the reliability of optical active sensors (with related range-based modeling software) in certain projects are still much higher, although time consuming and expensive. Nevertheless, many discussions are still opened on which approach and technique is better in which situation. So far the best answer is the combination and integration of the different sensors and techniques, in particular when surveying large and complex sites. Indeed, the generation of digital 3D models of large heritage sites for documentation and conservation purposes requires a technique with the following properties:

- Accuracy: precision and reliability are two important factors of the surveying work, unless the work is done for simple and quick visualization.
- Portability: the technique for terrestrial acquisitions should be portable due to accessibility problem of many sites, absence of electricity, location constraints, etc.
- Low cost: most archaeological and documentation missions have limited budgets, and they cannot effort expensive surveying instruments.
- Fast acquisition: most sites or excavation areas have limited time for documentation not to disturb works or visitors.
- Flexibility: due to the great variety and dimensions of sites and objects, the technique should allow different scales and it should be applicable in any possible condition.

As all these properties are often not eligible in a unique technique, most of the surveying projects related to large and complex sites integrate and combine multiple sensors and techniques in order to achieve more accurate and complete surveying, modeling, interpretation, and digital conservation results.

Geomatics experts, researchers and practitioners have witnessed a dramatic change in the way surveying is conducted over the last two decades. Point clouds are the most viable kind of data, to represent, at different scales and with different levels of complexity, every kind of object. Broadly speaking, the problem domain dictates the choice of sensors, processing techniques, computational approaches and resources, according to the products in output (e.g. 3D models, orthoimages, cartography, 2D drawings) and foremost their quality (resolution, precision vs accuracy).

For this reason, acquisition tools have been developed to provide the user with accurate and geometrically correct 3D data. Conversely, despite the indisputable value of 3D point clouds, the choice of the right tool is entrusted on several variables: in other word, the balance between costs, times, accuracy, efficiency, is hard to find.

Among the geomatic research community there is growing interest towards the adoption of those surveying methods encompassing all the needs of the domain: ease of use, reliability, efficiency, reduced costs, reduced human effort. It is well-known, in fact, that the integration of heterogeneous data, coming from different source, is somehow unavoidable dealing with complex 3D surveys.

Appendix B shows an overview of the geomatic techniques and technologies addressed during the research activity, based on different scale of built heritage context: from the landscape and urban scales, to building scale and underground one.

Photogrammetry

Image data require a mathematical formulation to transform the 2D image measurements into 3D information. Generally, at least two images are required, and 3D data can be derived using perspective or projective geometry formulations (Remondino and El-Hakim, 2006). Image-based modeling techniques are generally preferred in cases of lost objects, monuments or architectures with regular geometric shapes, small objects with free-form shape, mapping applications, deformation analyses, low budgets, good experience of the working team, and time or location constraints for the data acquisition and processing (Luhmann and Tecklenburg, 2004).

Between the available image acquisition platforms (space, airborne, and terrestrial), of particular interest are the UAVs (Unmanned Aerial Vehicles – Achille et al., 2015, Carnevali et al., 2018, Karachaliou et al., 2019) which can fly in an autonomous mode, using integrated GPS/INS, stabilizer platform, and digital cameras (or even a small range sensor) and which can be used to get data from otherwise hardly accessible areas.

Image-based 3D modeling generally requires some user's interaction in the different steps of the 3D reconstruction and modeling pipeline, reducing its use mainly to experts. The pipeline (Figure 19) is generally composed of different steps which can be performed in an automated or interactive way, according to the user requirements and project specifications.

Accurate feature extraction from aerial images is still a manually driven procedure. In terrestrial applications, more automation is available for scene reconstruction. Fully automated methods based on a SfM approach are getting quite common in the 3D heritage community, although mainly useful for visualization, object-based navigation, annotation transfer, or image browsing purposes and not for metric and accurate 3D reconstruction and documentation. However, the automation of the procedures has reached a significant maturity with the capability to orient huge numbers of images, and open source programs are also available. But the complete automation in image-based modeling is still an open research topic, in particular for the 3D surveying and modeling of architectural scenes and man-made objects (Aliberti and Iglesias Picazo, 2019; Azzola et al., 2019). Nevertheless, the camera calibration and image orientation steps can be achieved fully automatically as well as the surface measurement and the texturing for a large number of free-form objects (Adami et al., 2018), but the user interaction is still necessary in the geo-referencing and for the quality control part.

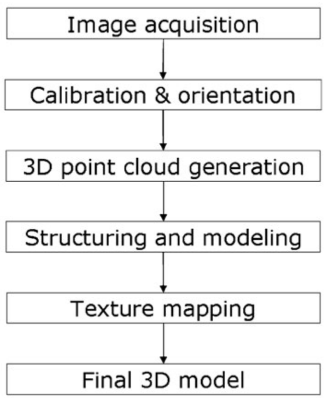


Figure 19. Typical image-based 3D modelling workflow

Photogrammetry is considered the primary technique for the processing of image data, being able to deliver at any scale of application accurate and detailed 3D information with estimates of precision and reliability of the unknown parameters from measured image correspondences (tie points). The correspondences can be extracted automatically or semi-automatically according to the object and project requirements.

As can be seen from the previous rows but also from the literature (Appendix A), due to a series of advantages, the most used technique for surveying in the BH field is photogrammetry, often combined with 3D BIM modeling. There are two main types of photogrammetric acquisition, aerial and terrestrial, whose main characteristics are summarised in the following table (Table 7). There is a third methodology which is spherical photogrammetry that allows the acquisition of 360° panoramic photos (Fangi, 2007; Fangi and Nardinocchi, 2013) (Appendix B – Case study n. 3).

Table 7. Photogrammetry techniques applied to BH field

	Aerial photogrammetry (UAV – drone)	**Terrestrial photogrammetry (close-range)**	**Spherical photogrammetry**
Planning	Automatic/manual	manual	manual
Data acquisition	Automatic/assisted/manual	Automatic/assisted/manual	Automatic/assisted/manual
GSD – image resolution	cm-m	mm-cm	mm-cm
Size of the area	mq-kmq	mmq-mq	mmq-mq
Distance to the object	m-km	cm-100m	cm-50m
Typical absolut accuracy	cm-10m	mm-m	mm-cm
Orientation	Normal/oblique	Normal/oblique	360°
Field of view	Aerial-azimuth	Terrestrial	Spherical
Applications and features	▪ Small and large-scale areas: 3D modelling of building outdoor, roof ▪ Applications in inaccessible areas and dangerous situations ▪ Large site prospecting and mapping ▪ Real-time applications (monitoring)	▪ Small-scale areas: 3D modelling of building outdoor and indoor ▪ Architectural photogrammetry ▪ Material classification and properties (decay mapping)	▪ Small-scale areas: 3D modelling of building outdoor and indoor ▪ Architectural photogrammetry ▪ Virtual tour

UAV: Unmanned Aerial Vehicle
GSD: Ground Sample Distance

Laser Scanning

Optical range sensors (Table 8) (Pu and Vosselman, 2009; Ruether et al., 2012; Shaoner and Abed, 2018) like pulsed, phase-shift, triangulation-based laser scanners have received in the recent years a great attention, also from non-experts, for 3D documentation and modeling purposes. Range sensors deliver directly ranges (i.e., distances thus 3D information in form of unstructured point clouds) and are getting quite common in the heritage field, despite their high costs, weight and the usual lack of good texture.

During the surveying with Terrestrial Laser Scanner (TLS), the instrument should be placed in different locations or the object needs to be moved in a way that the instrument can see it under different viewpoints. Successively, the 3D raw data need errors and outliers removal, noise reduction, and sometimes holes filling before the alignment or registration of the data into a unique reference system is performed in order to produce a single point cloud of the surveyed scene or object. The registration is generally done in two steps: (a) manual or automatic raw alignment using targets or the data itself and (b) final global alignment based on iterative closest points or least squares method procedures. After the global alignment, redundant points should be removed before a surface model is produced and textured. The range-based modeling pipeline is quite straightforward, and many commercial or open source packages are available.

In addition to range sensors used in static mode, there are also those used with dynamic platforms in moving solutions, referred to as Mobile or Aerial Laser Scanners (MLS, ALS) (Makkonen et al., 2017; Malinverni et al., 2018; Di Stefano et al., 2021a).

A Mobile Mapping System (MMS) describes a mobile platform that can be either aerial or terrestrial, in which measurement systems and sensors are integrated for the acquisition of geo-referenced metric data. Hence, an MMS is an integration of three main hardware components: optical sensors, navigation/positioning sensors and a control unit (Toschi et al. 2015). This technology, if combined with a Light Detection and Ranging (LiDAR) unit, can be referred as Mobile Laser Scanner (MLS) which is a widely used acronym in recent literature. This approach has the great advantage to be time efficient if compared with the other survey's methods. In this case, the laser scanners have been placed on moving platforms in order to obtain multiple scan positions with artificial targets for high detection rates and avoiding, as much as possible, shadowing effect and non-detection areas. It is a further technology improvement which combines a moving sensor with position estimation to obtain continuous registration and unlimited viewing angles (Zlot et al., 2014). For what concerns the quality of the data obtained with the MLS surveys, it depends on the devices used but it generally reaches a centimetric accuracy and a resolution that is related to the data acquisition speed and the distance of the detected objects (Di Stefano et al., 2020a).

In BH field, depending on the type of context, the degree of accuracy and the level of detail, mobile devices are used in different ways. Thanks to the versatility and handiness of portable devices such as hand-held and backpack, it is possible to survey any type of environment in a very short time by making short and closed paths (Di Filippo et al., 2018). These are mainly used in indoor environments of historical buildings (Tucci et al., 2018; Bronzino et al., 2019), underground built heritage (Di Stefano et al., 2021b) (Appendix B – Case study n. 5) or to detect outdoor environments where it is not possible to operate with wheel-based Laser Scanner for different factors such as restricted access for reasons of cultural heritage safeguard or the presence of narrow passages to cross (Smuleac et al., 2020) When it is necessary to detect objects along a long perimeter such as bas-reliefs (Zheng et al., 2015) or large-scale cultural heritage sites or objects such as the ancient walls of a city (Rodriguez-Gonzalvez et al., 2017) or artefacts in archaeological sites (Borrmann et al., 2015), the wheel-based solution is more likely to be adopted with MLS system, composed by TLS used in kinematic manner, on rails or mounted on trolley or vehicles that travel long or medium distances in the vicinity of the object of interest.

Aerial or airborne laser scanners are used here to survey very large areas of land at various altitudes where remains of ancient cities, mound complex or archaeological sites (Vilbig et al., 2020; Iriarte et al., 2020) can be identified, allowing the possibility of creating a topographic and semantic mapping of the identified objects (Campana, 2017). Range sensors, coupled with GPS/INS sensors, can also be used on airborne platforms

(Shan and Toth, 2008), mainly for digital terrain model (DTM) and digital surface model (DSM) generation and city modeling.

According to Beraldin et al. (2007), the 3D scanning results are a function of:

- intrinsic characteristics of the instrument (calibration, measurement principle, etc.);
- characteristics of the scanned material in terms of reflection, light diffusion, and absorption (amplitude response);
- features of the working environment;
- coherence of the backscattered light (phase randomization).

Dependence from the chromatic content of the scanned material (frequency response) range sensors works from very short ranges (few centimeters) up to few kilometers, in accordance with surface proprieties and environment characteristics, delivering 3D data with positioning accuracy from some hundreds of microns up to some centimeters.

Table 8. 3D range sensors applied to BH field (according to Historic England, 2018)

	TLS – Time of Flight (pulses)	TLS – Phase shift	MLS (ground-based)	ALS
Technical Support	Tripod	Tripod	• Human-based platform (handheld-backpack) • Wheel-based platform (vehicle, trolley, UGS)	UAS-drone
Mode of use	Static	Static	Dynamic	Dynamic
Operating range [m]	0.5-1000	up to 50-100	0.5–50 (handheld,backpack, trolley?) 10-200 (vehicle)	10-100 (UAS) 100-3500 (Airborne)
Typical accuracy [mm]	1–6	2–10	0.03–30 (handheld,backpack, trolley?) 10–50 (vehicle)	20–200 (UAS) 50–300 (Airborne)
Adding components	Camera	Camera	• Camera • GNSS and/or other localization recording systems (SLAM) • Trajectory recording and correction systems	• Camera • Trajectory recording and correction systems
Level of detail of the point cloud (scale of representation)	1:100-1:200	1:50-1:200	1:200	1:100-1:200 1:500-1:2000
Applications and features	▪ 3D modelling of building exteriors (facades) and interiors ▪ Surface models and analysis (defomations) ▪ Drawings	▪ 3D modelling of building outdoor (facades) and interiors ▪ Surface models and analysis (deformations) ▪ Drawings ▪ Particularly where rapid data acquisition and high point density are required	▪ 3D modelling of building outdoor (facades) and interiors ▪ Awkward locations, e.g. building interior, caves. ▪ City models ▪ As-built documentation ▪ Monitoring environmental changes ▪ Drawings	▪ 3D modelling of building roofscapes ▪ Aerial view ▪ Large site prospecting and mapping (DTM, DSM)

TLS: Terrestrial Laser Scanning; MLS: Mobile Laser Scanning; ALS: Aerial Laser Scanning;
UGS: Unmanned Ground System; UAS: Unmanned Aerial System
GNSS: Global Navigation Satellite System; SLAM: Simultanously Localization And Mapping
DTM: Digital Terrain Model; DSM: Digital Surface Model

As seen from the literature research analysis, photogrammetry and laser scanning are the common surveying techniques used to acquire metric data useful for obtaining 3D models of the object. Table 9 summarising the main features comparing them.

Table 9. Comparison between Photogrammetry and Laser Scanning (according to Remondino, 2011)

Characteristics	Photogrammetry (image-based modeling)	Laser Scanner (range-based modeling)
Cost of instruments (HW and SW)	Low	High
Manageability/Portability	Good	Sufficient (TLS) – Excellent (MLS)
Time of data acquisition	Quite short	High (TLS) – Short (MLS)
Time for modelling	Quite short, experience required	Often long (TLS) – Short (MLS)
Output	Photos	Point clouds (TLS) - Point clouds and trajectory (MLS)
3D information	To be derived	Direct
Distance's dependence	Quite Independent (often based on GSD)	Dependent
Dimension's dependence	Independent	Dependent
Material's dependence	Almost independent	Dependent
Light's dependence	Dependent	Independent (TLS) – Almost independent (MLS)
Geometry's dependence	Quite dependent	Independent
Texture's dependence	Dependent	Independent
Scale	Absent	Implicit (1:1 – real scale)
Data volume	Dependent on the resolution of the images and the measurements	Dense point cloud
Detail's modeling	Good/excellent	Generally excellent
Texture	Included	Absent - Low resolution (MLS)
Edges	Excellent	Quite problematic
Statistics/Qualitative analysis	For each calculated point	Global
Open-source SW	Some	A few

HW: hardware; SW: software;
TLS: Terrestrial Laser Scanner; MLS: Mobile Laser Scanner

Topographic survey

While photogrammetry and laser scanning enable data to be obtained on the object as a whole, topographic surveying is based on point-wise analysis by acquiring a few points but which serve to obtain spatial data and attribute geographical coordinates to the object itself. The optical instruments that are used for this purpose are the total station as active sensor and the GNSS (Global Navigation Satellite System) as passive sensor, because it uses satellites to receive data.

In addition to defining the geolocalization of a BH artefact, i.e. its position in a reference system such as the geographic one, using targets placed in the survey scene, the data acquired from the topographic survey are also useful for conducting more accurate monitoring operations and analysis both of the terrain and of the structures standing on it (landscape scale and architectural scale).

Multi-sensor data integration

Nowadays, the state-of-the-art approach for the 3D documentation and modeling of large and complex sites uses and integrates multiple sensors and technologies (photogrammetry, laser scanning, topographic surveying, etc.) to:

- exploit the intrinsic potentials and advantages of each technique,
- compensate for the individual weaknesses of each method alone,
- derive different geometric LOD and LOA of the scene under investigation,

- achieve more accurate and complete geometric surveying for modeling, interpretation, representation, and digital conservation issues.

3D modeling based on multi-scale data and multi-sensors integration is indeed providing the best 3D results in terms of appearance and geometric detail. Each LOD and LOA is showing only the necessary information while each technique is used where best suited. Sensor and data fusion were then applied also in the BH domain, mainly at terrestrial level, although some projects mixed and integrated satellite, aerial, and ground information for a more complete and multi-resolution 3D survey (Appendix B – Case studies n. 2 and 4).

The multi-sensor and multi-resolution concept should be distinguished between (Figure 20):

- geometric modeling (3D shape acquisition, registration, and further processing) where multiple resolutions and sensors are seamlessly combined to model features with the most adequate sampling step and derive different geometric LOD and LOA of the scene under investigation
- appearance modeling (texturing, blending, simplification, and rendering) where photo-realistic representations are sought taking into consideration variations in lighting, surface specularity, seamless blending of the textures, user's viewpoint, simplification, and LOD.

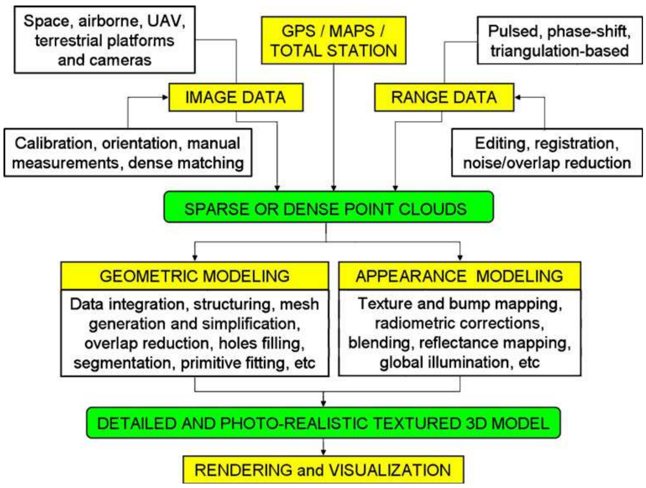


Figure 20. The multi-sensor and multi-resolution 3D modeling pipeline based on the integration of different techniques for the generation of point clouds and textured 3D models

Remote sensing – satellite data

With the launch of orbiting space satellites, it is possible to acquire data even at remote distances in the form of both large-scale images (optical sensors) and radar signals.

Also in the field of BH remote sensing techniques are adopted and data can be obtained through these processes:

- processing of images (multispectral or panchromatic) to operate a mapping in which elements are highlighted for documentation purposes (Del Pozo et al., 2017) and especially for recognition of the same in areas of difficult access (Chiappini et al., 2020);
- processing of radar signals to perform context analysis through monitoring operations (Crosetto et al., 2005).

Synthetic Aperture Radar

Satellite radar techniques also include SAR (Synthetic Aperture Radar) technology, which is a very valuable technique for mapping and monitoring in contexts where the BH is threatened by natural or anthropogenic events and hazards. This remote sensing technique, compared to topoghaphic levelling, can provide higher spatial point density, wider spatial coverage, and low-cost acquisitions (Ager, 2021).

SAR based techniques allow processing areas from regional/national scale up to very detailed scale such as single buildings, providing a high number of displacement measurements at low cost (Crosetto et al., 2016). Their applications are also reported for post-seismic analysis (Saganeiti at al., 2020), which can serve also as input for geotechnical and geomechanical survey techniques (Wang et al., 2021).

Among the various orbiting stations dealing with SAR data, the most common in Europe is the ESA (European Space Agency), which, with the launch of the Sentinel-1 pair of satellites (Table 10), provides information that is also useful for verifying the status of certain landscape and urban contexts, also with historical value such as vernacular villages, included in the BH category (Appendix B – Case study n. 1).

Table 10. Characteristics of Sentinel-1 SAR system

	Launch	Sensors	Acquisition technique	Frequency Polarization	Acquisition mode			Repeated cycle
					Type	Swath [km]	Spatial resolution [m]	
Sentinel-1 (ESA)	Sentinel-1 A 3 april 2014 Sentinel-1 B 25 april 2016	Radar microwaves (antennas)	Time of Flight (pulses) and Side-Looking illumination	C-Band with VV or VV-VH polarization (over land)	Stripmap (SM)	375 km	5x5	12 days (each satellite every 6 days)
					Interferometric Wide swath (IW)	**250 km**	5x20	
					Extra wide swath (EW)	400 km	20x40	

3.2.1.2 3D modeling

Once a point cloud is available, a polygonal model needs to be generated to produce the best digital representation of the surveyed object or scene (Lopez et al., 2017, Rodriguez-Moreno et al., 2018). For BH scenes and objects, generally described with sparse point clouds, a segmentation and structuring phase is necessary before producing a mesh model (Macher et al., 2014; Yang et al., 2019). Dense point clouds derived with automated image matching methods or measured with range sensors can be directly converted into meshes, following some possible editing and cleaning. Then some repairing to close holes, fix incorrect faces, or non-manifold parts are often demanding (and time-consuming) (Grussenmeyer et al., 2016). Those errors are visually unpleasant, might cause lighting blemishes due to the incorrect normals and the computer model will also be unsuitable for reverse engineering or physical replicas. Moreover, over-sampled areas should be simplified while under-sampled regions should be subdivided, and then risk losing expected or required LOD and LOA (Anton et al., 2018).

Finally, photo-realism, defined as having no difference between a view rendered from the model and a photograph taken from the same viewpoint, is generally required and achieved with the texture mapping phase, e.g., projecting one or more images (or orthophotos) onto the 3D geometry. Generally, problems might rise from the time-consuming image-to-geometry registration or because of variations in lighting, surface specularity, and camera settings. Often the images are exposed with the illumination at imaging time, but it may need to be replaced by illumination consistent with the rendering point of view and the reflectance properties (bidirectional reflectance distribution function) of the object. High dynamic range (HDR) images might also be acquired to recover all scene details while color discontinuities and aliasing effects must be removed.

The ability to easily interact with a huge 3D model is a continuing and increasing problem, in particular with the new demand of sharing and offering online and real-time visualizations. Indeed, model sizes (both in geometry and texture) are increasing at faster rate than computer hardware and software advances, and this limits the possibilities for interactive and real-time visualization of the 3D results. Due to the generally large amount of data and its complexity, the rendering of large 3D models is done with a multi-resolution approach displaying large textured meshes with different levels of detail and simplification approaches (Quattrini et al., 2015).

3D geometric modeling for BH using BIM requires a different procedure to that used for BIM modeling for new constructions (Figure 21). While for the latter BIM software are provided with libraries of parametric object to manage, for BH artefact the need to talk of reverse engineering (De Luca et al., 2006) through two techniques most common in the literature: creation of a surface mesh from 3D point clouds, or with direct for example scan-to-BIM process (Thomson and Boehm, 2015; Banfi et al., 2019) and generative modeling with dedicated software (Berndt et al., 2005; Fassi et al., 2011, Chevrier et al., 2010, Ludwig et al., 2013).

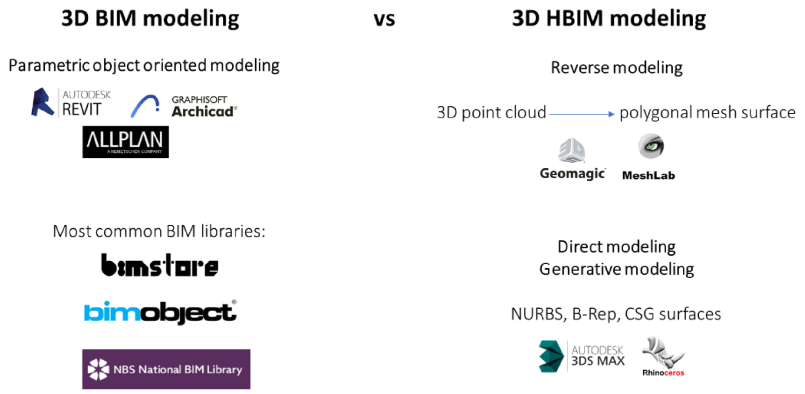


Figure 21. 3D modeling methods in BIM and HBIM

3.2.2 Investigation

Investigation documentation data category focuses on the analytical study of the BH historical background, its historical context and the variation of its form and function through it lifetime. This not only helps archaeologists and historians understand the history of the BH and its context but also leads to a better understanding of the architecture ideologies and styles, construction technologies and building materials of the building's era that were incorporated into its fabric. It also shows how the building functioned and served its various roles through its lifespan (Historic England 2006).

Historic documentation can combine the tangible geometry of the building (including previous drawings, form changes, building materials) with many of its intangible aspects such as historic texts, archaeological figures, oral histories, sketches and photos. These data sources can create a better understanding about the BH in its current status as well as its historic morphology over time. They can also contribute towards understanding the construction systems of the building and its development through the building's history, as well as BH an idea about the materials and technologies used in its construction. This can be also used to disseminate the BH and its historic development for the wider audience visualisation of the different phases of the BH's history. In this sense, more advanced visualisation and presentation can be achieved through VR/AR/XR technologies. (Osello et al., 2018) (Barazzetti and Banfi, 2017).

3.2.3 Lifecycle

Investigating and documenting the condition state of BH has a significant impact on the decision-making and process of their conservation. Condition assessments focus on studying the quality of the materials and structural system of the building; they also study original materials and construction methods, structural system, material degradation, historic fabric developments (Historic England 2017; Bruno and Fatiguso, 2018) and forms of decay that can result from structural design errors, erroneous interventions or neglect (Theodossopoulos and Sinha 2008). Therefore, risk assessment can be categorised into two areas: material pathology and structural pathology. It can be conducted using various tools; however, the geometry capturing tools remain the most used tools to investigate buildings condition state, unless subsurface investigations are required (Sanchez-Aparicio, 2016; Di Stefano et al., 2020b). The condition state of the BH is described through technical documentation that serves as support for the architectural and structural analysis, such as the AeDES sheets that are compiled by the Italian Civil Protection following seismic events (Baggio et al., 2007) according to NTC 2018[10].

The condition state data category represents a wide range of data concerning the operability and performance of the building. It aims to understand how the building is operating, investigate potential performance deficiencies in various aspects and predict its performance in a range of scenarios. This can help to optimise solutions for the various aspects of its operability and planning its maintenance.

3.3 Documentation methods integration

The aforementioned distinct categories of data related to the documentation of BH are often conducted and utilised by different stakeholders, which have different aims. This often leads to the isolation of information and stakeholders can work on their own. But this is not always the case, as there are examples where data can be used interchangeably across categories. For instance, condition state data can be obtained from accurate geometry surveys and can benefit from available historical data.

In some cases, when historic data is scarce, a reverse process starting with the geometric survey and the development of 3D models of the heritage building can be useful for the interpretation of the monument itself and its historical construction and development over time (Felicetti and Lorenzini, 2011; Brumana et al., 2013).

Based on the set objectives, the integration of the BH documentation methods tries to meet the requirements and the degree of interest from the stakeholders as much as possible based on factors such as LOD, LOA and LoIN (Table 11).

This preliminary documentation phase through the use of geomatics tools, historical data research and assessment of the BH state of affairs is of primary importance on which the subsequent information management phase will be based once these data have been structured.

Table 11: Degree of interest in documentation data categories (referring to Table 4)

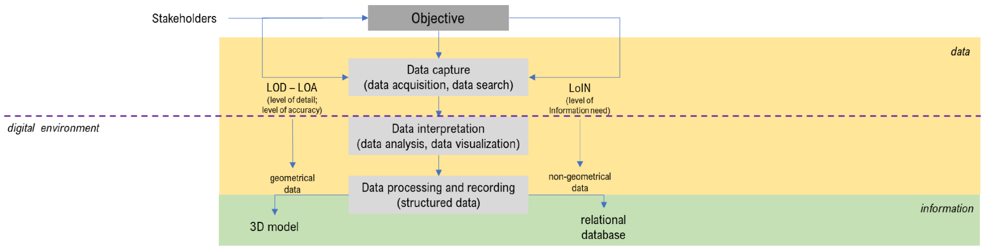
Documentation data / Stakeholders (SHs)	Geometry	Investigation (historical background)	Lifecycle (condition state)
Internal SHs			
Project actors			
• Owner/client	B	F	F
• Architects	F	B	F
• Restorers/Conservators	B	F	F
• Structural Engineers	F	B	F
Building users	B	B	B
External SHs			
Istitutional SH			
• Cultural authorities	B	F	F
• Public administrations	B	B	F
Facility managers	B		F
Culture SHs			
• Academics/researchers	F	F	F
• Heritage historians	B	F	B
• Museum	B	F	B
• Educational activities	B	B	
Tourism SHs			
• Dissemination	B	F	B

F=full interest; B=basic interest

[10] NTC 2018. Norme Tecniche delle Costruzioni 2018, Circolare 21 gennaio 2019, n. 7 C.S.LL.PP. *Istruzioni per l'applicazione dell'Aggiornamento delle "Norme tecniche per le costruzioni" di cui al decreto ministeriale 17 gennaio 2018.* Gazzetta Ufficiale della Repubblica Italiana.

Graphical summary

Once the objective has been identified, the cycle starts with the data capture phase, which represents the collection of all relevant data of the BH basing on the request LOD (Level of Detail) and/or LOA (Level of Accuracy) and basing on the LoIN (Level of Information Need) can be achieved. Following is the data interpretation that leads to the analysis, and visualization of the captured data. The data processing and recording consist on modeling the geometrical data and archiving within database not geometrical data; transforming all data into structured information.



Chapter 4.

Information management through (H)BIM implementation

As explained in the Introduction (Chapter 1), the main focus of the following research thesis is that of information management linked to a BH 3D model through an information system. The aim is therefore to illustrate the methodology that illustrates the main steps for the implementation of an HBIM, as BH information management system, starting from the available data and according to the objective proposed.

4.1. Structured data

Once the documentation part, as the preliminary data management phase, has been completed, these data must then be well structured and archived in order to be used to define an information model of the object.

A first phase concerns the logical structuring of the data obtained, mostly linked to the geometric composition of the object, and this makes it possible to identify a system of identification of the architectural component at the various scales of representation. This geometric decomposition is useful for cataloguing the non-geometric data referring to the architectural elements. For this purpose, the best data management system is the relational database. A further development in data management is the definition of a semantic ontology that defines the domains that can be implemented in an information system such as BIM that lacks such data structuring and also guarantees the interchange and interoperability of the data with other information systems.

Appendix C is dedicated to summarising the various insights made into information management through case studies.

4.1.1 Conceptual schema

A first form of data structuring useful to give a logical representation may be the conceptual schema. From a conceptual point of view, the BH object can be decomposed in various modes and under different level of in-depth analysis. A BH can be defined in different ways (functional, structural, stratigraphic, technological, etc.) and with different components (building, macro-areas, areas, technological systems, architectural elements, etc.), depending on the hierarchical classification and considering the graphical representation of each entity.

Regarding the geometric classification of the components of a BH, different approaches can be used to create a conceptual schema.

A first approach is to adopt a three levels of geometry classification: the first for the representation of the built heritage object in the urban context, the second for the functional areas, the latter one basing on the classification of architectural components. So, in deep, the level 1 coincides with the whole artefact. The spatial distribution allows to make a volumetric decomposition, identifying the areas for the functional classification of level 2. The third level is a division based on macro-elements, and in the case of a building you have for example: walls, floor, vault, etc. A subclass of this level describes the single components of each element, the micro-elements defining characteristics of the architectural style (Figure 22) (Malinverni et al., 2019b).

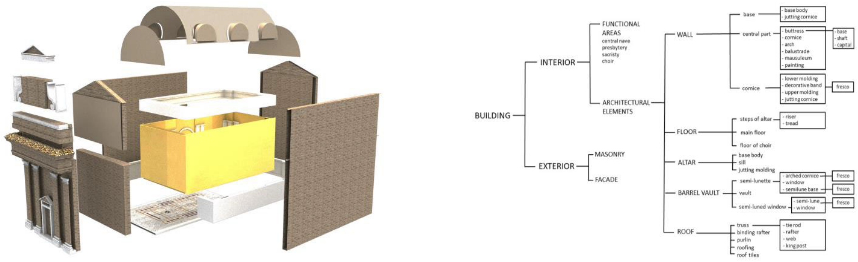


Figure 22. Example of conceptual decomposition of built heritage: a. exploded axonometry of the 3D model showing the architectural components and b. tree graph of the geometrical classification and the architectural elements.

An other way to decompose a BH is based on decreasing semantic LODs were identified, described as follow: BH in its complex (LOD 1), functional distribution of the BH (LOD 2), the main architectural elements which characterizing the functional areas (LOD 3), the architectural sub elements which defining the volumetric architectural object (LOD 4), and specific detailed architectural elements such as decorations, components of columns, etc. (LOD 5) (Figure 23).

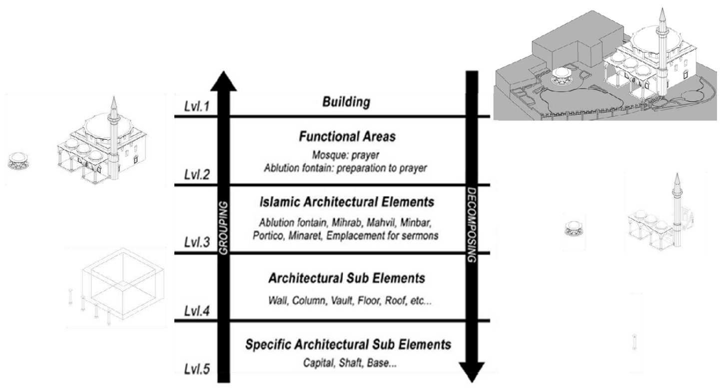


Figure 23. Example of conceptual decomposition of a BH: semantic LoD classification

The logical design of the conceptual map, which serves for the database architecture, has a primary importance on the representation of a HBIM 3D model, because the complexity and the usefulness of the information structure depends on it. According to the choice of LOD, the information structure of the BH is based on the geometrical decomposition as illustrated above in the graphs shown. In the graphs the classification explains better the functional logical process to the 3D modelling. This schema is useful to understand how decomposing the BH and can be used as the basis of the next semantic classification.

The tools that can be used to create these conceptual graphs are various: there are several software tools that allow one to draw this first BH-related classification, including free and open-source online software.

4.1.2 Relational database

In the field of BH, in addition to the geometrical representation, it’s important to consider and manipulate all the documentation data, e.g. historical data, material composition, structural components, construction phases, forms of decay, etc. So, to organize all this information and make useful for the conservation, valorisation and restoration interventions, one becomes crucial collect them in an “ad hoc” well-structured database possible to be linked to the 3D model. A unique and flexible relational database appropriate to record and organize more features of each designed object can be realised. This kind of database works on the system entity-relationship: first identifying the entities in each record and then arrange the digital information defining the relations among different entities belonging to the same object. Moreover the relational database is characterized by a simple and good functionality, allowing a fast collection of information in input and for retrieving it, a multimedia data management and, in particular, the possibility to enrich it in any case, uploading new data.

The typical structure of the relational database is that of a table composed of tuples (Figure 24). Thanks to the existence of dedicated data management software (e.g. Microsoft Excel, Access and similar software packages) these tuples can contain data of various types, ranging from the insertion of numbers, words, text, images, to documents in interchange format and links to external links or web addresses. The main one is the possibility to flexibly mix additional data created by operators via data enrichment, thus being able to perform cross-model queries (Bianco et al., 2013; Fangi et al., 2017).

Basing on a hierarchy of classes and subclasses of the conceptual map, the implementation of a relational database organizes the BH components assigning a not changeable ID numerical code easier to identify them by queries (Figure 25a). The ID code may represent a combination of numbers, for example basing on the abovementioned LOD classification. This classification system gives in output an ID code relating to any object, that contains information about the recognized object and also, if present, information about recognized sub-objects. This code can be then allocated in the relational database, linking to the related object and it could help to understand the relation and the link among the object composing the 3D model in the BIM environment. Referring to the example shown in Figure 23, each single object can be identified from the last number (LoD 5) to the first one

(LoD 1) of the same combination to understand to which part of the building belong to (Figure 25b) (Di Stefano et al., 2019b).

BIM software automatic schema (category-family-type) — Historical data - Interventions — Images

CATEGORIA	FAMIGLIA	TIPO	ID ELEMENTO	INTERVENTO 1	INTERVENT0 4	INTERVENTO 6	INTERVENTO 7	INTERVENTO 10	INTERVENTO 11	INTERVENTO 14	IMMAGINI STORICHE
Attrezzature speciali	abluzione	base	I.02.01.06.00	1683 restauro	1950 restauro	1959 restauro e conservazione	1960 restauro e conservazione	1981 restauro e conservazione	1982 restauro e conservazione	2013/14 restauro conservazione	x
Apparecchi idraulici	abluzione	grata	I.02.01.13.00							2013/14 applicazione	x
Attrezzature speciali	abluzione	fontana1	I.02.01.12.00	1683 restauro	1950 restauro e sostuzione rubinetti	1959 restauro e conservazione	1960 restauro e conservazione	1981 restauro e conservazione	1982 restauro e conservazione	2013/14 restauro conservazione	x
Apparecchi idraulici	abluzione	fontana2	I.02.01.12.00	1683 restauro	1950 restauro	1960 restauro e conservazione	1960 restauro e conservazione	1981 restauro e conservazione	1982 restauro e conservazione	2013/14 restauro conservazione	x
Arredi	abluzione	sgabello	I.02.01.13.00	1683 restauro	1950 sostituzione	1961 restauro e conservazione	1960 restauro e conservazione	1981 restauro e conservazione	1982 restauro e conservazione	2013/14 restauro conservazione	x
Pilastri	abluzione	base_colonna	I.02.01.08.01	1683 restauro	1950 restauro	1962 restauro e conservazione	1960 restauro e conservazione	1981 restauro e conservazione	1982 restauro e conservazione	2013/14 restauro conservazione	x
Pilastri	abluzione	fusto_colonna	I.02.01.08.02	1683 restauro	1950 restauro	1963 restauro e conservazione	1960 restauro e conservazione	1981 restauro e conservazione	1982 restauro e conservazione	2013/14 restauro conservazione	x
Pilastri	abluzione	capitello_colonna	I.02.01.08.03	1683 restauro	1950 sostituzione	1964 restauro e conservazione	1960 restauro e conservazione	1981 restauro e conservazione	1982 restauro e conservazione	2013/14 restauro conservazione	x
Attrezzature speciali	abluzione	architreve	I.02.01.09.00	1683 restauro	1950 sostituzione	1965 restauro e conservazione	1960 restauro e conservazione	1981 restauro e conservazione	1982 restauro e conservazione	2013/14 restauro conservazione	x
Attrezzature speciali	abluzione	cornice	I.02.01.02.00	1683 restauro	1950 sostituzione	1966 restauro e conservazione	1960 restauro e conservazione	1981 restauro e conservazione	1982 restauro e conservazione	2013/14 restauro conservazione	x
Attrezzature speciali	abluzione	cupola	I.02.01.03.00	1683 restauro	1950 sostituzione	1967 restauro e conservazione	1960 restauro e conservazione	1981 restauro e conservazione	1982 restauro e conservazione	2013/14 restauro conservazione	x

ID-code

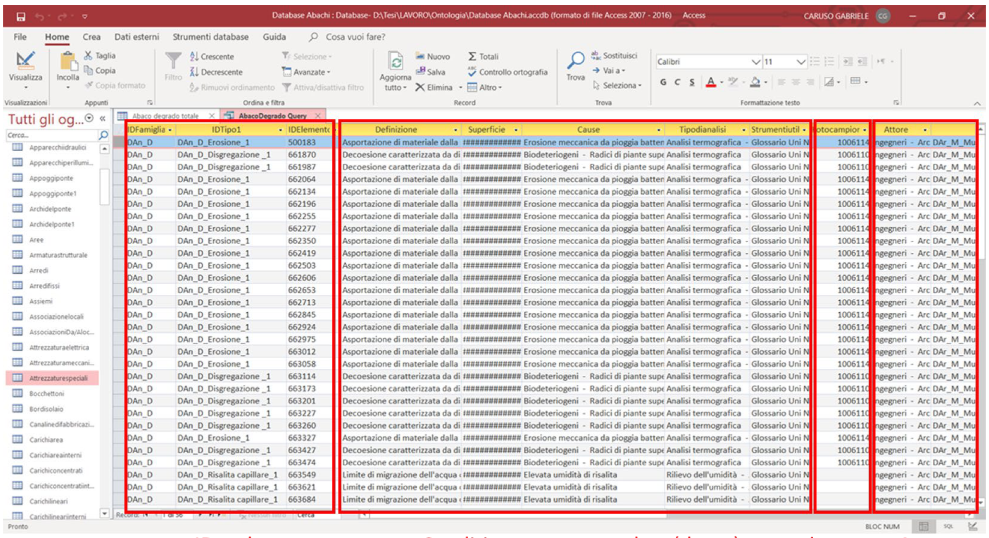
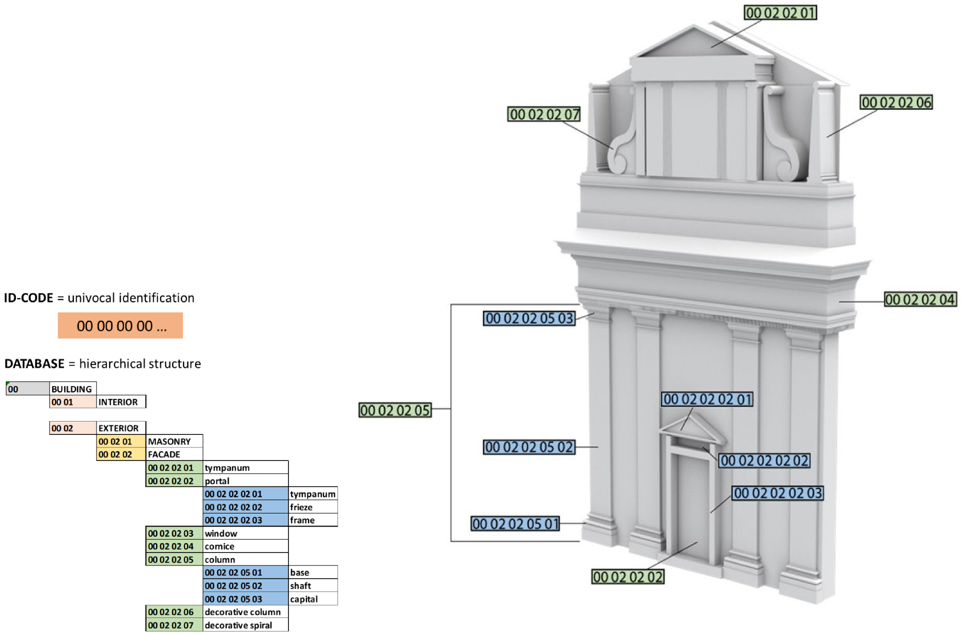
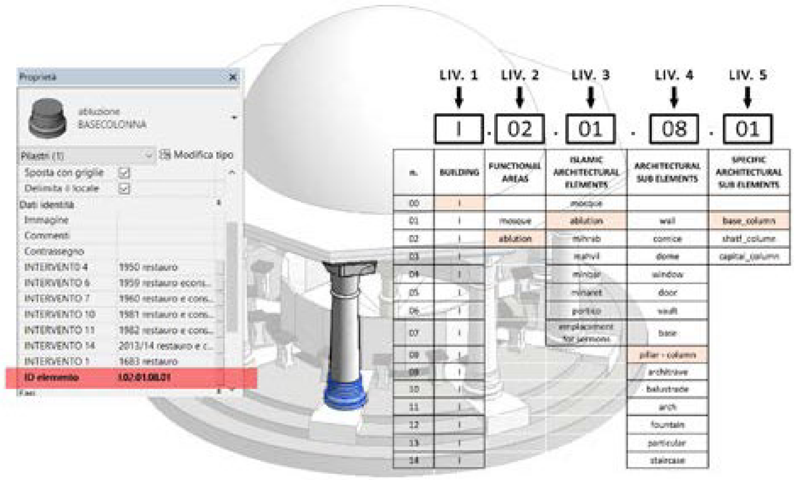


Figure 24. Examples of section of the relational database for BH documentation data management



a.



b.

Figure 25. Examples of ID code assignment: a. in reference of Figure 22 b. based on LOD classification, in reference to Figure 23

4.1.3 Semantic ontology

An ontology is «*a conceptual grid which we superimpose to various possible states of affairs*» (Guarino and Giaretta, 1995), a hermeneutic process to collect information about a particular reality in orderly and logically linked forms.

Today ontologies have found a wide range of applications. The analysis of the state of the art acknowledged the presence of previous researches aimed at establishing an ontology-based framework for modeling architectural knowledge (Noardo, 2016; Fiorani and Acierno, 2017; Garozzo et al., 2017) starting from the most elaborated ontology for the integration of cultural heritage information, that is the CIDOC-Conceptual Reference Module, now ISO 21127:2014 (Lo Turco et al., 2019; Doerr er al., 2020). As seen, the new ISO 19650:2018 standard that introduced the LoIN offers an additional information structuring (Figure 14b) that serves as a further support for the definition of an ontology applied to the BH in cases where the previously mentioned ontology schemes do not provide in the management of certain domains.

According to the above-mentioned references, the semantic domains for BH can be identified are essentially four: the artefact (geometry), the investigation process, its lifecycle (condition state) within each of which there are classes, properties and relationships proper of any ontology. In addition the domain concerns the actors involved within the project is define fostering the cooperation and collaboration among the stakeholders.

The ontological schema is commonly represented as a graph structure that refers to the logical composition of the conceptual schema, also taking into account the relationships between the elements with reference to the relational database. These semantic domains thus make it possible to manage heterogeneous data from the same BH (Figure 26) (Di Stefano et al., 2020b).

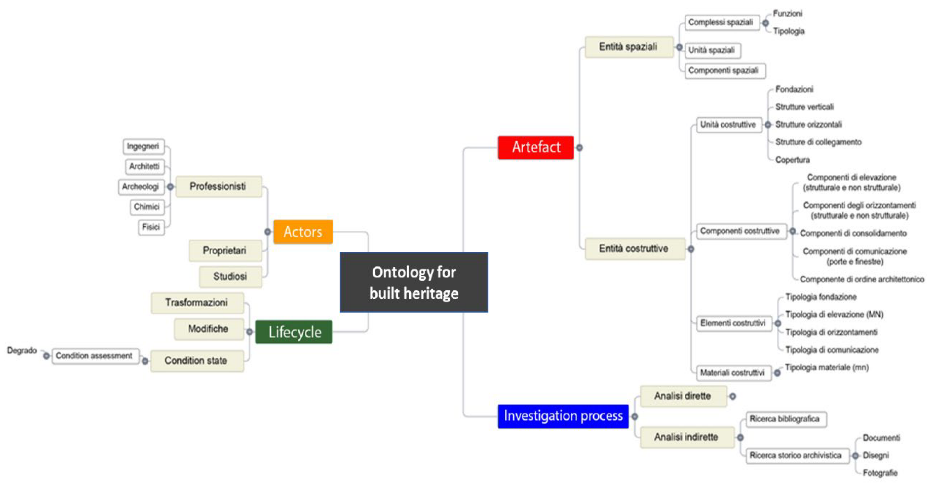


Figure 26. Semantic ontology for BH (Di Stefano et al., 2020b)

The semantic domains of a BH ontology allow the definition of coded names attributed to the various structured data, and this not only allows the data to be quickly identified but also to allow these codes to be converted into strings that are easy for programming languages to use. This makes us realise that there are dedicated software or systems with digital libraries of already encoded data or which allow new data to be identified, such as an enriched CIDOC-CRM system for cultural heritage or open-source ontology-editor such as Protegè (Quattrini et al., 2017).

After this introduction of which methods are relied upon for data documentation, Table 12 below summarises and compares the various data management systems for BH.

Table 12. Data management systems for BH

Data management system	Typical structure	Expression form of data	Main functions	Strenghts	Weaknesses
Conceptual schema	• Node-link diagram • Tree chart	names, annotations	• Data classification • Data hierarchy	• Logical stucture of data • Mostly used for geometrical decomposing of the built heritage (architectural structure) and some descriptive features	• No multimedia data • No exchange data
Relational database	• Entity-relationship system • Tuples (table)	names, annotations, numbers, strings, texts, documents, links	• Data identification • Data archiving • Data aggregation • Data instantiation	• Relational structure of data (object-attributes) • Used for descriptive features of geometrical elements and not geometrical data • Management of multimedia data and exchange data • Links and hyperlinks between data (internal and external) • Ensuring data sharing among project stakeholders • Data enrichment; updating data anytime • Data querying and extraction	• Lack of a semantic approach • No interoperability
Semantic ontology	• Semantic domains • Graphs (nodes-edges)	coded names (linked to specific domain) easily to use for programming language	• Definition of data management syntax • Data collector • Data coding	• Semantic structure of data • Heterogeneous data management and homogeneous representation of knowledge • Promoting process of data connection and transfer between information systems (interoperability)	• Many forms of ontology schemas in BH application, difficult to stardardise

4.2. Information management within BIM tools for BH

In the last few years, the use of BIM technology in the AEC industry has improved several working processes including design, construction and management for new buildings, but its application in the field of existing buildings (Arayici, 2008; Volk et al., 2014), and in particular of historical architecture (Li et al., 2014; Simeone et al., 2014; Pocobelli et al., 2018; Gargaro et al., 2019), still shows some limitations (Jordan-Palomar et al., 2018; Yang et al., 2020).

In fact, the new ICTs offer undisputed advantages to the collection and management of different kinds of information and data; nevertheless, they also have crucial limitations and can cause undesired consequences, which are often inherent to the development of digital virtual models that struggle to detect and represent real complex architectural structures, especially if they are ancient and belonging to the BH.

Working on the architectural heritage requires the control of both analytical-scientific phases, such as the analysis of its geometry, material consistency, construction techniques or decay phenomena, and critical-interpretative phases related to the understanding of its material and immaterial values – for instance, its authenticity, identity and integrity to name but a few. These latter are aspects that more than others risk being sacrificed when, in (H)BIM environment, experts use parametric software with default functionalities from which it is not easy to deviate.

Such a condition implies on the one hand the impossibility of representing the uniqueness of the BH, deeply related to its history and historical events, on the other hand the lack of semantically enriching the virtual model with its interpretative context that can be deduced only through a well-structured system of knowledge-led investigations.

Since HBIM was first introduced (Murphy et al., 2009; Dore, Murphy, 2012), attempts to overcome these matters have multiplied, bringing this research topic to the centre of the current scientific debate. Nowadays, a significant literature has been produced documenting the state of the art on this subject (Del Giudice and Osello, 2013; Logothetis et al., 2015; Garcia-Valldecabres, 2016; Antonopoulou and Bryan, 2017; Dore and Murphy, 2017): existing and ongoing studies prove the need to make this technology perfectible by updating and adapting it to the features of BH in order to meet specific programmatic objectives.

Over the years, some research projects have been focused on optimizing modeling times (Biagini et al., 2016), integrating data from metric survey into BIM also by the creation of parametric objects directly from the 3D point cloud, on defining the most suitable levels of accuracy of the parametric model and characterizing it with data related to materials, construction techniques and stratigraphy (Garagnani and Manferdini, 2013; Spallone et al., 2016; Malinverni et al., 2019), on testing the possibilities for a new storytelling (Di Giulio et al., 2019; Banfi and Oreni, 2020) and, last but not least, on building adequate forms of semantic enrichment both on an architectural and urban scale through the use of ontologies (Quattrini et al., 2017; Chiabrando et al., 2018; Acierno and Fiorani, 2019).

Compared to the aim of this research, the most interesting researches are those which have tried to overcome the idea of HBIM as a simple repository of complex data, conceiving it rather as «*a hub for supporting integrated documentation of heritage artefacts*» (Simeone et al., 2019). From this point of view, a crucial challenge is to replace the default semantics of BIM with a more appropriate one allowing experts to organize and relate the heterogeneous data of historical buildings while taking into account all phases of the restoration/conservation process (Bruno and Roncella, 2019). Ontologies make an essential contribution in this regard.

Since the ontology-based modeling is conceptual and not visual, it is more appropriate than ever to integrate it with the (H)BIM modeling, which has a distinctly graphic and visual-descriptive vocation. Anyway, the problem of the automatic connection between the ontology-based modeling and the BIM one, which is essential due to the complexity of the BH, is still an open topic today, although the implementation of a specific platform able to translate the two modeling systems into a homogenous format enabling correspondences between them is currently in progress (Pili, 2019; Simeone et al., 2019).

Therefore, the present research aims to provide its own contribution in this specific issue, developing a possible way to synchronize these two ways (ontology-based and BIM visual-descriptive) of representing BH by supporting interoperability between software in full compliance with documentation needs (Figure 27).

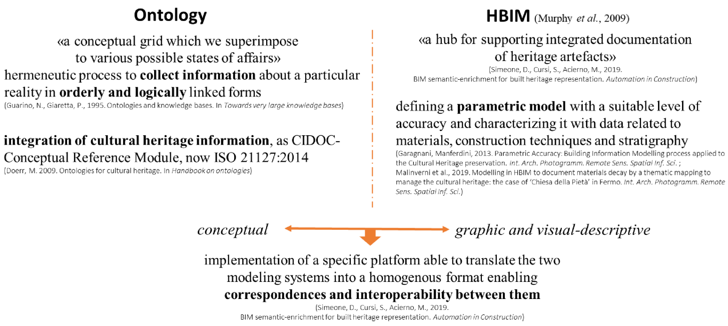


Figure 27. Ontology and HBIM definitions

4.2.1 Ontology-based (H)BIM

The proposed ontology draws inspiration from those found in other research (Fiorani 2017; Acierno, 2017; Messaoudi et al., 2017; Zalamea et al., 2018) and aimed at reproducing, as consistently as possible, the logical structure characterizing the conservation process in the HBIM environment. The idea was therefore to formalize the knowledge of the BH by reproposing, on a conceptual level, all propaedeutic steps for understanding, preserving and managing heritage site in the medium-long term.

As already stated above, four semantic domains were defined: the artefact, the lifecycle, the investigation process and the involved actors; they can be deduced from the reference studies by introducing minimum adjustments.

The artefact consists of twofold classes: spatial and construction classes. On the one hand, the first ones characterize function, typology and organization of the architectural space and are divided into spatial complexes, spatial units and spatial components. On the other hand, construction classes feature the building from a technological point of view consisting of construction units (i.e. foundations, vertical, horizontal and connecting structures), in turn articulated in construction components (i.e. structural/nonstructural vertical and horizontal components, reinforcing components, but also communication components such as stairs, doors and windows, and architectural components), each of which made of construction elements (describing all types of technological elements) as well as of construction materials (e.g. brick, sand, lime, concrete and so on). The structure of the construction classes here presented also reflects that established by the Guidelines for the preventive and planned conservation of the architectural heritage (Della Torre, 2002).

The investigation process includes cognitive and interpretative activities for an exhaustive knowledge of the artefact. This domain is described by two key classes, namely that of direct analysis (geometric survey, material, stratigraphic, diagnostic and decay analysis) for each of which methods, tools and results are also stated, and that of indirect analysis (bibliographic, archival and iconographic research, etc.).

Furthermore, the lifecycle represents the physical and functional transformations of the artefact, its condition state; in this way space, materials, and time are directly connected according to the event-centred methodological approach of the CIDOC-CRM (Doerr et al., 2020).

Finally, the actors domain (professionals, building owners, scholars and so on) concerns subjects that were or will be involved in the lifecycle of the BH, as regards transformation, study, restoration and management phases.

4.2.1.1 Application of ontology-based (H)BIM

Literature research has shown that HBIM is being adopted for a variety of purposes, the main ones being purely documentation (Cheng et al., 2015; Maietti et al., 2018), knowlegde dissemination (Quattrini et al., 2017; Garcia et al., 2018; Parisi et al., 2019), condition assessment (Bruno et al., 2018), conservation (Masciotta et al., 2021; Mora et al., 2021) and maintenance (Garcia-Valldecabres et al., 2021), restoration (Oreni et al., 2014; Di Stefano et al., 2020) and experimental applications (Scianna et al., 2014). This ontological scheme described above is suitable for all contexts where we then take into account those factors that are of most interest for a given predetermined objective.

It has been mentioned that the BIM system is not easily adapted to manage a model referring to the BH due to software limitations. We have seen this with reference to 3D modelling which has to resort to the parameterization of new geometric shapes and which best reflects the volumetric reality. The same is true for model information: there are no parameters referring to BH information so new families have to be created to manage it. Furthermore, BIM does not provide an ontological schema and therefore, as explained before, this information system has to be customised by trying to import the semantic domains that allow the information linked to the BH 3D model to be structured in the best possible way.

At the end of the ontology schema definition, the problem of merging this conceptual schema with the (H)BIM working space came up. As interoperability between ontology and BIM software is not yet an automatic process, the ontology schema is implemented directly in BIM environment (e.g. Autodesk Revit), leveraging the general three-level hierarchy of both modeling system: *class* > *sub-class* > *entity* for the ontology schema and *family* > *family type* > *instance* for the BIM one, as it is described in Figure 28. In this way, the ontology-based modeling was not imported into BIM software but served as a guiding principle for the 3D modeling and the subsequent phase of data enrichment (Simeone et al., 2019).

Figure 28. Three level hierarchy of ontology and BIM software

As soon as the ontology structure was defined, the next step consisted in creating a HBIM model of the BH, modeling each geometrical component individually and using processed data from geomatics survey as well as information from historical research and BH condition assessment as references.

The ontology-based data enrichment was carried out in a second phase, that will be later explained. The result was an early integrated and complex model, including both geometrical and non-geometrical data, resulting in a real 3D database for supporting heritage documentation process.

Once the first modeling phase was completed in BIM software (Autodesk Revit), the modelled elements were inserted by means of 'loadable families'; for instance, they are windows or doors and damaged parts due to the passage of time. In Revit, 'loadable families' tool permits to satisfy any customization that the project requires, for this reason it is fundamental for representing architectural heritage. These types of families are not a default setting in the Revit project environment; therefore, they have to be loaded from external libraries and edited in the 'family editor'. This latter allows to select an unlimited number of parameters and relationships as well as to define building geometry, appearance and features for a very complete customization. Leveraging this tool, the geometrical model was refined and reproduced in order to make it coherent with the artefact current state of conservation (Figure 29). Subsequently, textures from photogrammetric survey could be applied.

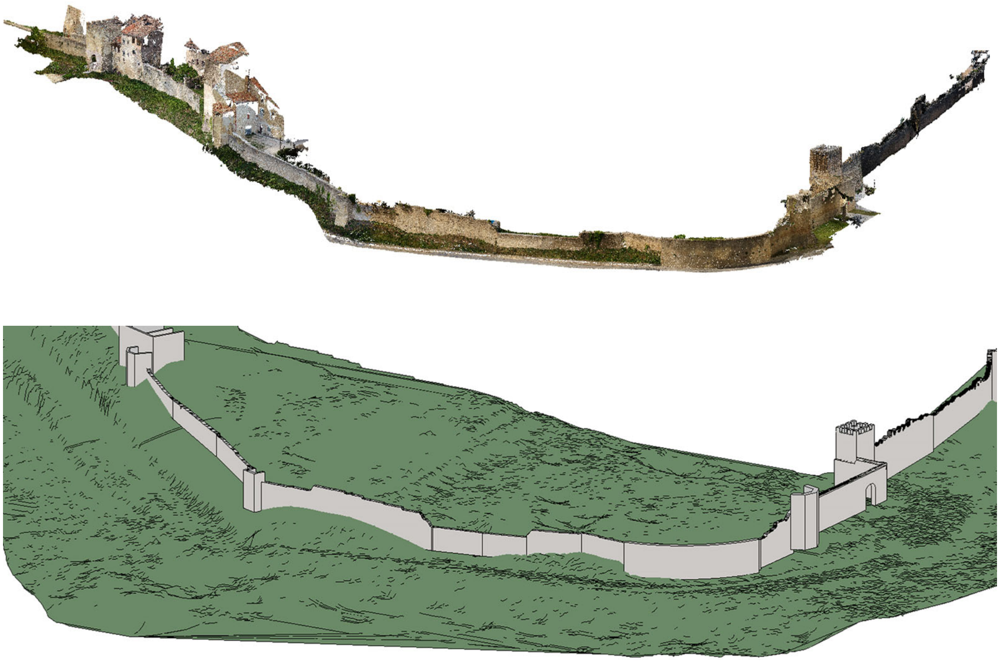


Figure 29. Geometrical appearance in BIM software generated form 3D point cloud

The described 3D model could be considered well-structured and quite truthful, but it was defined only by geometric and dimensional information adding material attributes as deduced from the images captured. The main goal of this research project is rather to obtain a 3D model able to record all heterogeneous data collected within the ontology schema. Thus, on the one hand a knowledge-rich ontology was designed, but on the other the model developed in Revit did not allow a direct link to this complex system of data (Garozzo et al., 2017). In the literature there are no examples or cases where it occurs, this is because Revit, but more generally BIM software, has a very different purpose than describing the ontological structure of an existing artefacts. So, an alternative solution to overcome this limitation was studied.

To test the integration of the ontology-based model into BIM, the selected focus was on the decay analysis, for BH restoration purpose, within which crucial relationships emerge, such as the link between materials, degradation phenomena (including causes and effects) and subsequent interventions (Di Stefano et al., 2020).

The representation of decay phenomena in BIM environment could be addressed in different ways (Brumana et al., 2017; Malinverni et al., 2019). Since one of the key issues of this work was the creation of queryable objects, which serve as a collection of interoperable semantic data also available via the 3D model, the strategy was to define ad hoc families able to adapt the 3D model and ontology by varying its parameters.

Due to the complex geometry and repetitiveness of decay phenomena, the 'decay family' was not represented as a single family in Revit. For this reason, the use of a 'nested family' capable to group the individual modelled families was the key. This option not only allows users to generate a family containing others, but it is useful for creating general parameters applied to all individual elements and for formulating future queries within software.

In addition, these types of families representing the decay analysis were then placed on another geometrical family hosting it (e.g. 'wall family'). Being part of a hosting family, they are directly linked to and affected by it. For example, if the wall is erased, the decay on it disappears. This relationship between families could be subsequently verified in data-tables in which construction information regarding the wall (materials and techniques) and decay information describing its current state of conservation were systematized. Graphically, elements concerning the 'decay family' were displayed as thematic mapping through a transparent veil on the 3D model of BH object, as the following figure make it clear (Figure 30).

In order to implement the described ontology, two plug-ins were used: DB Link and Dynamo allowing Autodesk Revit to perform functionalities unsupported by default commands (Figure 31). Revit DB Link is an add-in developed by Autodesk that supports bidirectional interoperability, moving data from and into Autodesk Revit. Dynamo, on the other hand, is an extremely flexible open source visual programming environment capable to formulate customized algorithms (procedures or formulas to solve problems) for data processing and the creation of geometries by means of graphical user interface blocks. Dynamo is often used for several purposes, especially to obtain the automatic creation of shared parameters and therefore to facilitate and speed up the parameter creation process.

The final achievement in using these two plug-ins is a faithful representation of the architectural heritage decay, as it is described within the ontology. To make it possible, the tripartite hierarchical structure of both conceptual and 3D representation systems is essential. Stressing this homologous three-level structure, the ontology information hierarchy (*class* > *sub-class* > *entity*) is manually transferred in Autodesk Revit (*family* > *family type* > *instance*).

First of all, semantic contents of the "artefact" domain are modelled, in particular "construction classes". For example, the vertical structures of the wall ("construction unit" in the ontology scheme) became a *family* in Revit within which several *types* and *instances* made it possible to respectively distinguish the ontology "construction elements" and "materials". Then, as already illustrated, the described and data enriched '*wall family*' hosted the '*decay nested family*' expressing the fundamental relationship between materials and decay phenomena with all specificities of this analysis. All these semantics contents are uploaded using '*shared parameters*' acting as carriers of information.

In this perspective, a unique identification code (ID) is additionally assigned to all ontological data; at the same time, references to the host family are added. To better explain how data are constructed, it is useful to consider a very practical example of a decay family element which, in turn, is part ('*host'*) of the wall family. Its ID is designed in order to transfer specific properties of the element, as well as the ontology domain to which it belongs (Di Stefano *et al.*, 2019).

For instance: 'DInvPro_DAn_erosion' is the decay element ID, informing users that it belongs to the *investigation process domain* (DInvPro), results from the *decay analysis* (DAn) and identifies an *erosion*; while 'DAr_M_Square sandstone blocks' is its host wall ID, informing users that it belongs to the *artefact domain* (DAr) and it is a *masonry* (M) made of *square sandstone blocks*.

Working in this way means that data belonging to all described elements could be also recognized even once exported from Autodesk Revit. Using exported tables, in fact, it is possible to identify the ontology logic workflow. Therefore, these parameters have to be compiled according to the ontology-based modeling.

Being a mechanical process within a BIM workspace, it could take a long time and be conditioned by human error during the compilation phases. To overcome this problem, the solution is to compile it outside Autodesk Revit. The selected add-in tool is DB Link plug-in allowing users to export the Autodesk Revit parameters and making them available in an external database such as Microsoft Excel or Microsoft Access. Once the database is compiled according to the ontology, the final file is imported again by DB Link into the BIM software which updated the externally operated changes also in the Autodesk Revit project (Figures 33, 34).

All parameters, thus compiled and collected within the project, became also easily accessible from the 3D model. However, in order to make them more readable they were grouped in schedules or otherwise externally exported.

Working outside Autodesk Revit also demonstrated the advantage of enabling external users, who have no specific expertise in BIM software, to collaborate with other stakeholders in a simpler and more intuitive work environment, such as a spreadsheet or Microsoft Access database. Moreover, query, spreadsheet and database functions could be performed using data coming from the 3D model.

To summarise, the procedure followed to import an ontological schema into BIM, referring to the analysis of degradation for a restoration project of the BH taken as an example, is outlined and illustrated below:

- definition of the ontological classes and of the identification code (ID) of both the object elements and the degradation forms through a tripartite structure to adapt to the one present in the BIM system (Figure 30);
- creation of families in BIM: the host family (object) is connected to the nested families (decay) (Figure 31);
- through the use of plug-ins such as DBLink and Dynamo (Autodesk Revit) the data collected in external databases are imported and these become "shared parameters" (Figure 32, 33);
- implementation of the ontology of decay families in BIM (Figure 34) and graphical representation of degradation in the 3D model in the form of thematic mapping (Figures 35);
- automatic collection of data in the schedules and possibility to modify and enrich information through internal tools or export/import data through external databases (Figure 36);
- export of the project for sharing with other stakeholders (Figure 37).

FAMIGLIA	TIPO	ISTANZE
Muro di base	DAr_M_Muratura in pietra squadrata_1	Altezza
		Spessore
		Materiale legante
		Materiale legato
		Datazione
		interventi pregressi
		ID Famiglia
		ID tipo
	DAr_M_Merli_1	Altezza
		Larghezza
		Anno di costruzione
		Materiale legante
		Materiale legato
		ID Famiglia
		ID tipo
Tetto di base	DAr_T_Copertura piana_1	Superficie
		Spessore
		Tipologia elemento costruttivo
		Materiale legante
		Materiale legato
		ID Famiglia
		ID tipo

DAr_M_Type_n

Domain Artefact_Masonry_Square sandstone blocks_1

a.

FAMIGLIA	TIPO	ISTANZE
Degrado	DAn_D_Efflorescenza_1	Descrizione
		Superficie
		Cause
		Tipo di analisi
		Strumenti utilizzati
		Attore
		Foto campione
		ID Famiglia
		ID tipo
	DAn_D_Crosta_1	Descrizione
		Superficie
		Cause
		Tipo di analisi
		Strumenti utilizzati
		Attore
		Foto campione
		ID Famiglia
		ID tipo
	DAn_D_Colatura e dilavamento_1	Descrizione
		Superficie
		Cause
		Tipo di analisi
		Strumenti utilizzati
		Attore
		Foto campione
		ID Famiglia
		ID tipo

DAn_D_Type of decay_n
Domain Analysis_Decay_Erosion_1

b.

Figure 30. BH object (a.) and decay (b.) identification code according to the ontological schema

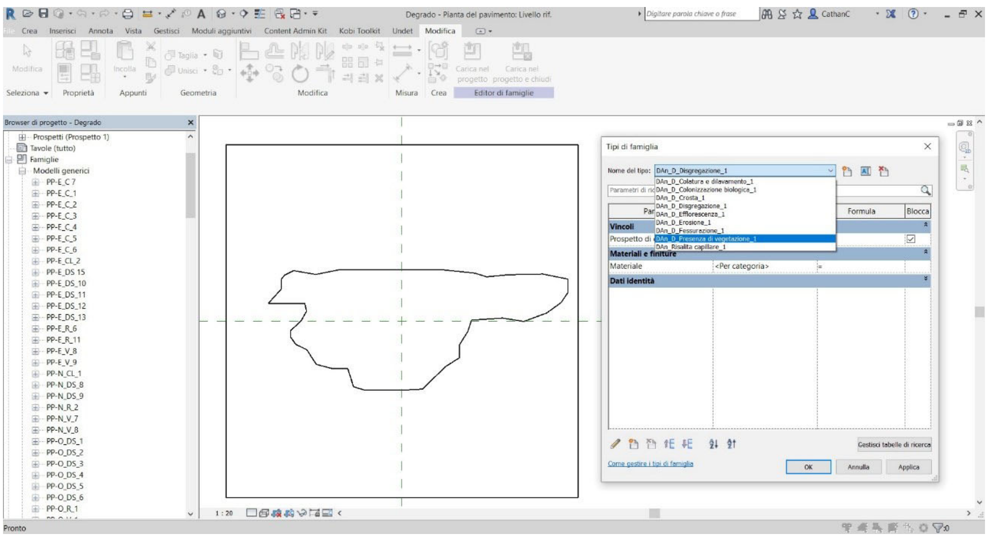


Figure 31. Rapresentation of decay as nested family hosted in "wall family"

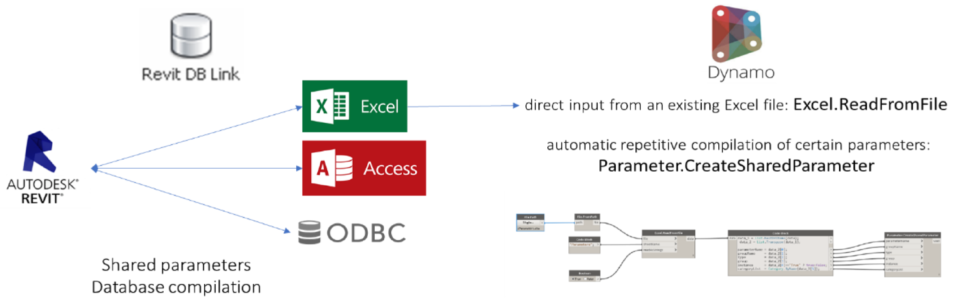


Figure 32. Revit DB Link allowing to import external database into BIM system and Dynamo for the shared parameters definition

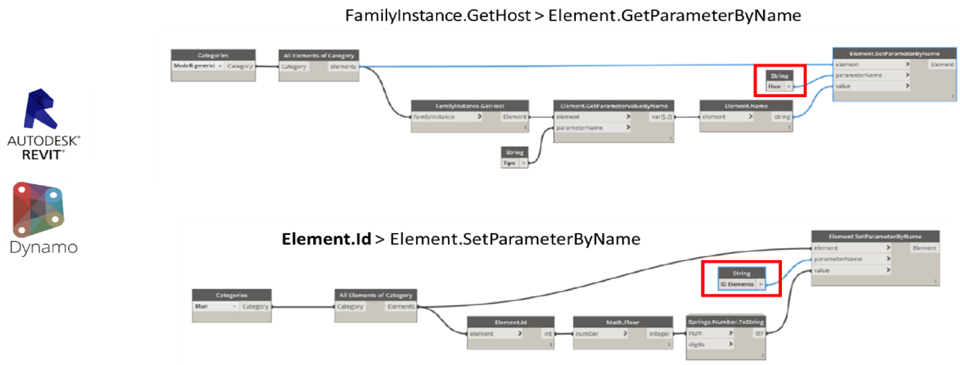


Figure 33. Ricognition system through Dynamo plug-in within Autodesk Revit software

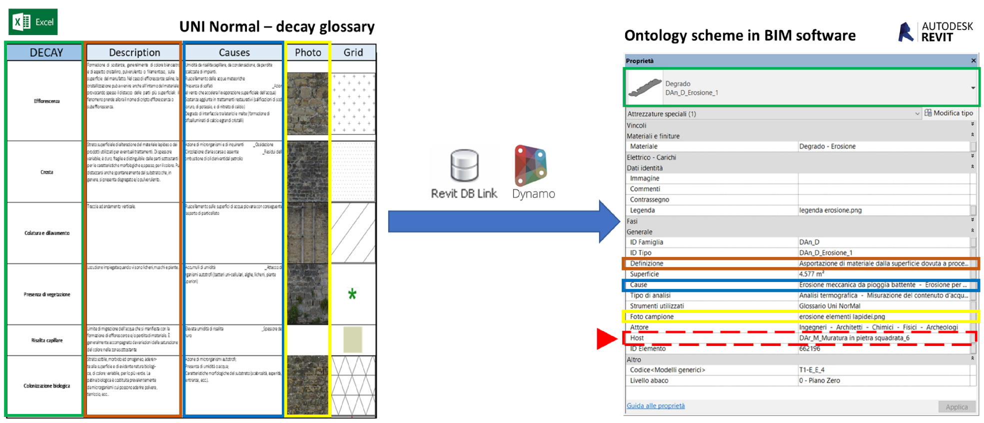
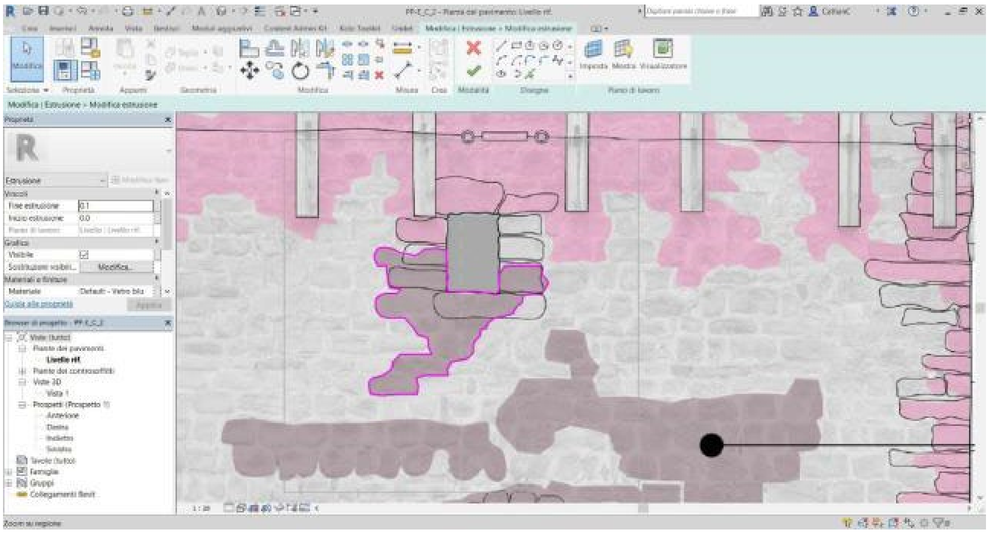
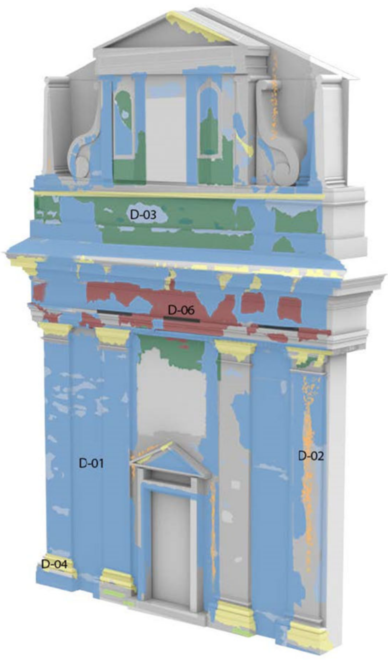


Figure 34. Ontology of decay classification importing in BIM software





ID-code	DECAY	COLOR ATTRIBUTES
D-01	SURFACE DEPOSIT	blue
D-02	SURFACE WASHOUT	orange
D-03	LAITENCE	light blue
D-04	LEAKAGE	yellow
D-05	ABSENCE	black
D-06	CONCRETION	bordeaux
D-07	INCONGRUOUS ELEMENTS	red

Figure 35. Thematic mapping in BIM software of the decay on the 3D model of the BH object

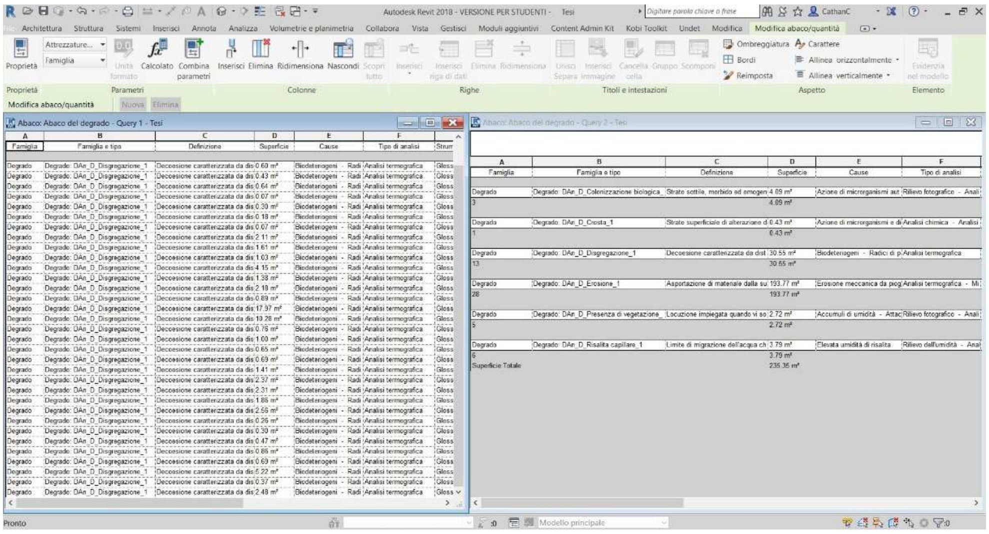


Figure 36. Abacus of all data managed within the 3D model

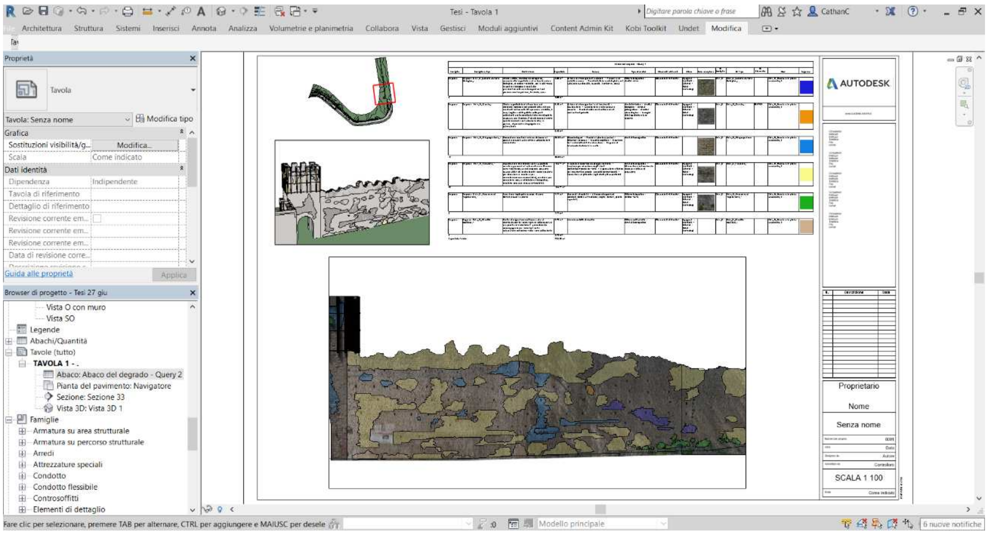


Figure 37. Information sharing system within BIM; exportation of data for external stakeholders

At the end of this process, a complete database regarding the state of conservation of a selected BH is developed. This is and will be a crucial tool for planning future conservation interventions as well as for constantly monitoring that historical site in compliance with architectural heritage ontological standards.

4.2.2 Open (H)BIM

Thanks to the IT tools of the web, it is possible to share the BIM project through cloud platforms without any special data conversion processes, thus a kind of open data repository (Figures 38, 39). This ensures interoperability, collaboration and information exchange between the various stakeholders, flexibility and sustainability. Open BIM processes can be defined as sharable project information (IFC format) that supports seamless collaboration for all project participants.

This sharing tool is useful in cases where there is a great disparity in terms of knowledge and technological competence of the BIM system and standards among the various figures involved or interested in the project.

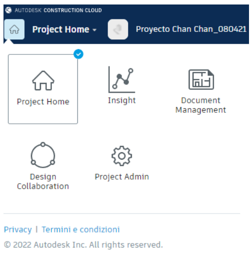


Figure 38. Open BIM platform structure

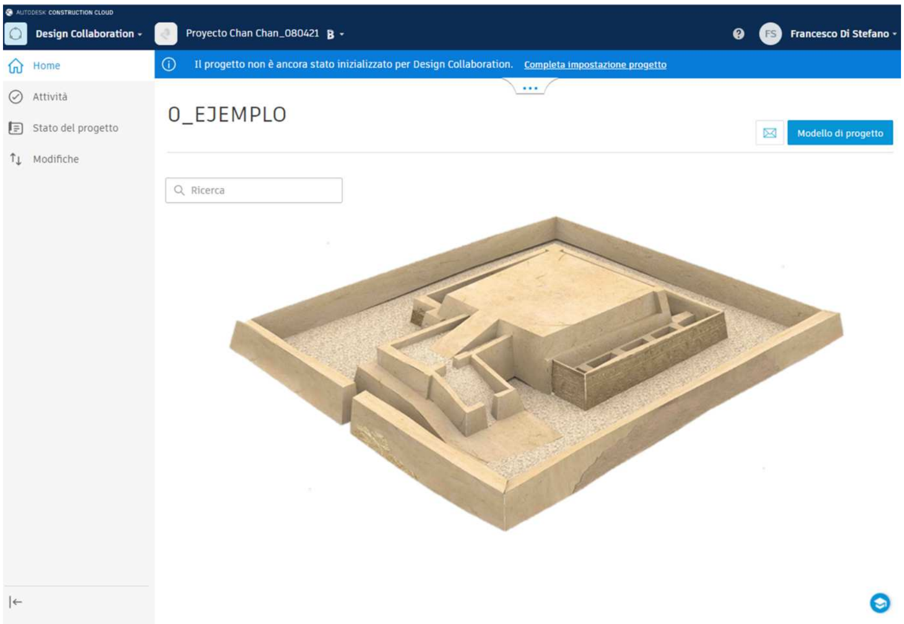
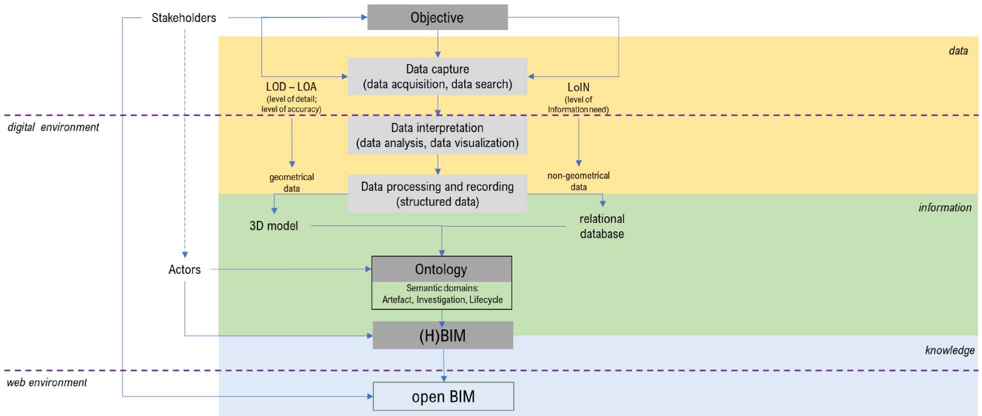


Figure 39. 3D modeling in open shared BIM

Graphical summary

The ontology aimed at reproducing the logical structure in the HBIM environment with the purpose to formalize the knowledge of the BH. Four semantic domains were defined: the artefact, the lifecycle, the investigation process and the involved actors. As interoperability between ontology and BIM software is not yet an automatic process, the ontology schema is implemented directly in BIM environment. Thanks to the IT tools of the web, it is possible to share the BIM project through cloud platforms, thus a kind of open data repository.



Chapter 5.

Knowledge management: integration of (H)BIM with other information systems

5.1 Other information system for built heritage

In AEC sector, among the information systems and technologies, GIS (Geographic Information System) is a useful tool for building and landscape data management. It gives the possibilities to combine heterogeneous data: geometric shapes, quantitative analysis, enrichment of semantic knowledge, application of different technologies and multi-scale management (Ma and Ren, 2017; Fosu et al., 2015; Yamamura et al., 2016; Malinverni et al., 2019). Moreover, GIS provides to be an additional support system for the historical building or sites management, offering a new way of co-working for the preservation, conservation, monitoring and restoration activities of BH (Pisu et al., 2013; Yang et al., 2016).

5.1.1 GIS for the built heritage

Although GIS was originally used to manage geospatial data in 2D scale, it provides a robust data storage system (Vacca et al., 2018) based on a sort of hierarchy of classes and subclasses identified by the levels of detail of CityGML schema. The latter permits the definition of topological and semantic relationships between the objects. By the development of 3D GIS it makes possible the creation of 3D geospatial modelling, allowing the data management of specific building, offering a precise visualization of the geographical contextualisation and permitting the formulation of spatial queries (Rinaudo et al., 2007; Malinverni et al., 2018a). So, the 3D building model can be raised on a modelled terrain in a relative urban context with its surroundings. The GIS platform is well suited for data management at the urban scale in a given geographical area (Malinverni et al., 2019c).

Moreover, 3D GIS software gives a 3D model of the topographic representation of the landscape with the geolocalization of the BH objects in the form of volumes (DTM – Digital Terrain Model; DSM – Digital Surface Model) (Figure 40) at the various LODs (Level of Details) (Almeida et al., 2016). It incorporates 3D territorial and BH information giving a stronger, richer and clearer visual impact compared with a simple 2D GIS mapping. A 3D GIS can be used as a reference 3D map for any urban planning management activities (Lenticchia and Coïsson, 2017). In particular, GIS is suggested as a suitable tool for the risk mapping or better the spatial extent of risk in which document the effects of hazard situations, according to the ISO/IEC 31010:2009 and the

Recommendations for National Risk Assessment (Poljanšek et al., 2019). In addition, the web GIS extension, the open and online GIS platform, is also used, which differs from a GIS project in its specific purpose of communicating and sharing information with other users (Sanchez-Aparicio et al., 2020).

It's possible to convert the 3D GIS modeling in an open data system thanks to the CityGML standard (OGC, Open Geospatial Consortium). CityGML is a common semantic information model for the representation of 3D urban objects that can be shared over different applications. It is an open-source data model and eXtensible Markup Language (XML)-based format for the creation of city models (Gröger, Kolbe, Nagel, & Häfele, 2012). CityGML is widely used in GIS city modelling and represents an open recognized standard and well-defined ontology. The hierarchical structure of data is provided by CityGML that thanks to its schema allows to have a semantic representation that defines relationships between the various entities composing the 3D city model (Malinverni et al., 2020). CityGML-based approach that leads to define a knowledge modeling where not only spatial but also external information, like topological, architectonical, technical data, is managed (Agugiaro, 2016). The benefits of using a centralized GIS-based information system, developed in CityGML environment, may guarantee an efficient, well-structured BH information management system (Banerjee et al., 2020).

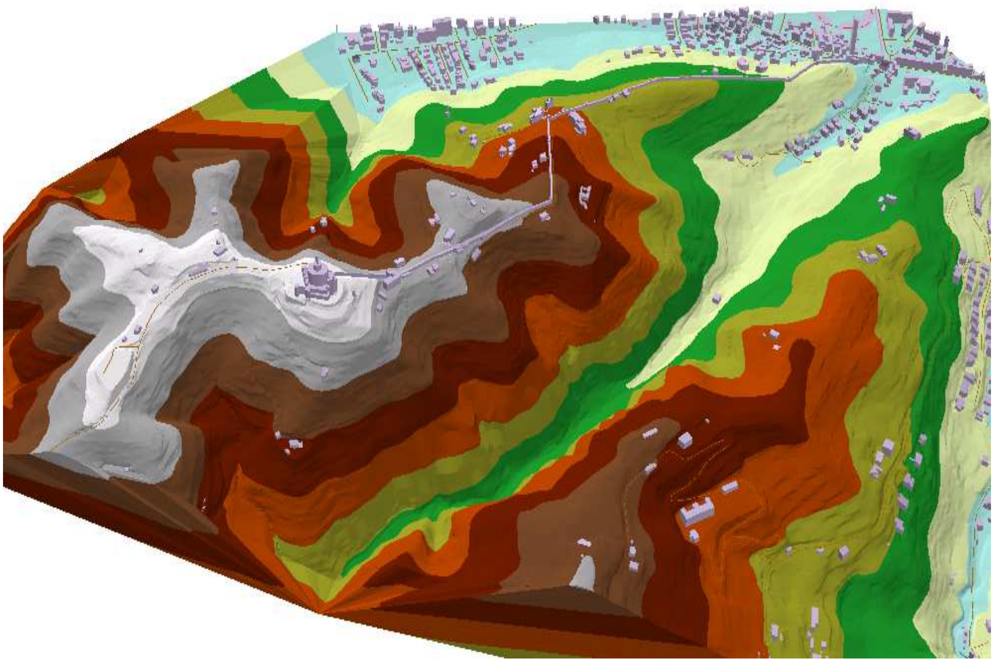


Figure 40. Example of 3D GIS model concerning an urban area

Table 13: Positive and negative aspects of BIM and GIS systems for BH

	Positive	Negative
BIM	• Management of data on a measurable model • High geometrical detail • Better 3D editing functionalities • Temporal (4D) representation	• Without any semantic ontology and difficulty in importing an ontology schema in BIM system • Works on a single object, architectural scale only • Demanding and costly for multiple large built heritage complex
GIS	• Larger scale analysis, urban/landscape scale – spatial data • Strong connection between the BH object and the landscape • Robust data storage • Multi-layered conceptual themes in 3D • Ontology schema proposed by CityGML (based on LOD)	• Not used for single object • Mostly 2D representation of object features

CityGML

Nowadays there is a variety of international standards for each field of application. Open Geospatial Consortium (OGC 2019) is an international organization which develops and maintains open standards (more than 60 have been published, 2021). Among all them available, the most extended and used in city modelling is CityGML, issued also by the ISO/TC 211 regulation (ISO/TC 211 2019). CityGML is a common semantic information model for the representation of 3D urban objects that can be shared over different applications. The geometry is stored using the Geography Markup Language version 3.1.1 (GML3), which is also XML-based format and is usually employed in geographical information archive (Figure 41). Furthermore, CityGML enables lossless information exchange between GIS software and users. It defines classes and relations regarding their geometrical, topological, semantical and appearance properties (Kolbe and Nagel, 2012). It is applicable for large areas and small regions and can represent the terrain and 3D objects in different levels of detail (LOD) simultaneously. For example, simple models without topology and few semantics in one LOD, instead of very complex detailed models with topology and fully semantical, can be represented in different LODs. LODs in CityGML indicate the accuracy of geometries and the potential elements that are included in the model. LODs range from 0 to 4: LOD0 is the coarsest model, and it is mainly a 2D model with a DTM; e.g., building would be represented as a 2D polygon laying on the DTM. LOD1 includes buildings with its height. LOD2 defines the structure of roofs and building installations. LOD3 represents the real geometry with accuracy, and LOD4 is the realist model in which all details of the building are modelled. CityGML specification defines for each object model the information needed for each LOD. As has been previously indicated, CityGML is chosen because it is widely used in GIS city modelling and represents an open recognized standard and well-defined ontology.

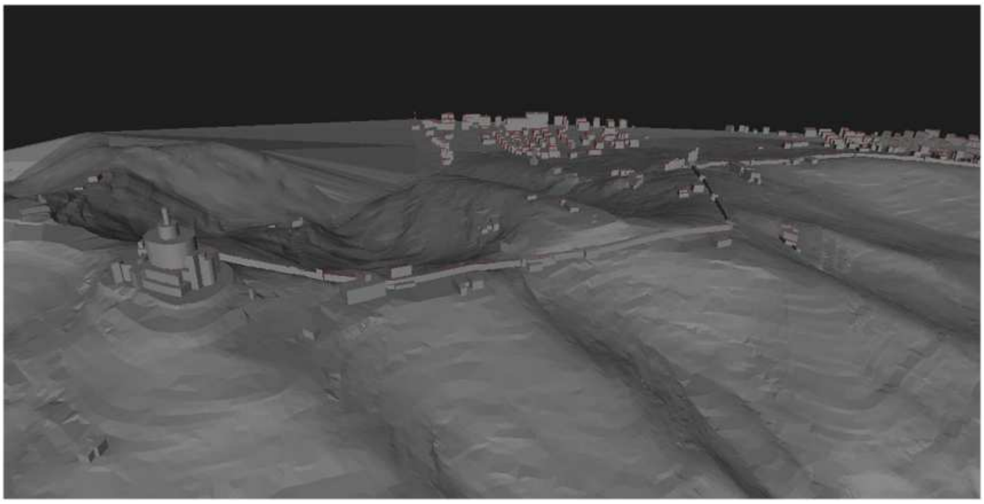


Figure 41: CityGML model of the corresponding 3D GIS model (Figure 40)

5.2 Heterogeneous information management

5.1.1 Interoperability between BIM and other information systems

The data integration process between information systems represents an innovative approach offering substantial benefits, and this combination has to take into account the strong points from each system (Zhang et al. 2009). Considering for example the most used systems like BIM and GIS, their integration represents an efficient tool for AEC projects. In short, BIM describes geometry, semantic relationships and identifies the building components. GIS provides a well-structured database and a geospatial model with topological and semantic relationships. But there are some dissimilarities between them, such as spatial scale, level of representation of geometric models and structure of database (Saygi et al., 2013; Song et al., 2017; Mirarchi et al., 2018; Matrone et al., 2019; Tsilimantou et al., 2020).

By literature, the topic of data transfer between GIS and other information systems, BIM in particular, has been already dealt with, and it is still an ongoing research, but it led to a specific solution, not simple to understand or to propose again for different case studies. Especially, it is to be highlighted that some software producers started a collaboration trying to get easier and to overcome the complexity of the data conversion and sharing between information systems (Table 14), so it is already possible to import BIM data into a GIS environment. Although this has shown good performance, it must be said that this data conversion has a limitation because it only proceeds in unidirectional way, from BIM to GIS.

Analysing research activities focusing on the topic of integrated information system, the interoperability between BIM and GIS can be presented in different ways: syntactic interoperability and semantic interoperability (Bishr, 1998).

The syntactic interoperability refers to use common data format to exchange information between BIM and GIS systems, using a domain of one of the information systems. Examples of syntactic interoperability are systems that combine building data with landscape maps, data formats of BIM object on GIS environment, and solutions to convert BIM data from IFC (Industry Foundation Class) to CityGML (Karimi and Akinci, 2009). The approach of IFC to GIS (IFG) project has been developed to provide geographic information between the frameworks of IFC, in order to get a more efficient planning (Kolbe et al., 2005). Other examples of syntactic way are based on the use of CityGML schema. The GeoBIM extension from BIMServer allows conversion from IFC files to CityGML files by defining additional information in CityGML entities (Van Berlo and De Laat, 2011). Nagel et al. (2009) proposed a conceptual method of transitioning from a KML graphics model to BIM through CityGML. The authors developed mapping rules to allow transforming CityGML model to IFC model. Another attempt, tried by Hagedorn et al. (2009), was to create a conceptual dual graph for representing topological relationships among indoor entities of a building, but not the whole one with the geospatial context. All these examples chosen to explain this type of interoperability show a common characteristic: they follow a unidirectional way of translation and do not consider the semantic information mapping in the process. A bidirectional approach is needed (Deng et al. 2016), if we want to get a dual interoperability between BIM and GIS.

The highest level of interoperability is guaranteed by the semantic aspect of data integration. The key point of semantic interoperability is to make sure that features and relations between information management systems are maintained during data conversion (Peachavanish et al., 2006). Objects as entities and their relationships are defined under a domain called unified ontology that makes possible the representation, the sharing and the management of the knowledge (El-Diraby et al., 2005; Malinverni et al., 2020). The information should be described and classified in a standard way.

Table 14. Type of integration between information management systems

Heterogeneous information management	Domain for information management	Structure of management information system	Strenghts	Weaknesses
Simple integration system	Without any specific domain	Information container: separated information coming from different information systems	• Simple structure and easy to manage	• No interoperability (data trasnfer and conversion)
Syntactic interoperability	One main ontological domain	One information management system use as main platform and data coming from other information systems are imported into	• Use of common data format	• Lack of any information during data conversion and transfer (due to incompatibility between information systems) • Unidirectional way of data transfer
Semantic interoperability	Unified ontology (combination of domains)	Graph database (RDF) in semantic web environment	• Bidirectional approach • Data conversion in specific sherable format • Lossless data transfer • Homogeneous representation	• Specific knowledge of programming languages required (for conversion and information transfer and query forumlation)

5.3 Semantic web environment

The semantic web technology represents new efficient online platform to make possible this kind of interoperability. The web ontology language (OWL) expresses the data in terms of classes. A collection of these classes, their attributes and relations can be stored as RDF (Resource Description Framework) triples describing each individual object, its properties and features, which can be understood as a graph based on nodes (entities) and vertices (relationships) (Hor et al., 2016).

Semantic web technologies have been used by several researchers to facilitate construction project information sharing (Pauwels et al., 2013). Anumba et al. (2008) explored the use of semantic web technologies to meet the challenges of collaborative project information management. Akinci et al. (2008) developed a web-based approach to enable semantic interoperability between CAD and GIS platforms. Beetz (2009) demonstrated the feasibility of semantic web tool to address information exchange and integration problems in AEC interoperability between BIM and GIS. Other recent attemps are described also for BH applications (Quattrini et al., 2017; Rodrigues Goncalves et al., 2018; Rodrigues et al., 2019)

5.3.1 Graph database

Taking this approach into account, it becomes possible to move forward a graph database direction, useful also for a BIM data interaction providing so a complete interoperability in the web environment and so allowing an eventually bidirectional way of data transfer between information systems.

As we previously discussed the main obstacle of the integration between different information systems is the lack of interoperability across both domains, which could be solved using the semantic web. The semantic web is a set of technologies used for the representation, publication and browsing of structural data on online platforms. It is used in this study to convey meaning, which is interpretable by construction project stakeholders as well as BIM and GIS applications processing the transferred data (Ebrahim and Irizarry, 2015; Karan et al., 2016).

The main elements belonging to a semantic web platform (Hor 2015) are as follows:

- Uniform Resource Identifiers (URIs), a string of characters that identifies a particular resource;
- Web Ontology Language (OWL), a type of knowledge representation languages form authoring ontologies forrepresenting the conceptual schema;
- Resource Description Framework (RDF), a family of World Wide Web Consortium (W3C) specifications originally designed as a metadata model for defining the data according to the schema;
- SPARQL, a SQL-type language for carrying out queries in data.

RDF, RDFS (Resource Description Framework Schema) and OWL are languages with clearly defined semantics or mathematical basis for the meaning of each construct. Since concepts in RDFS and OWL ontologies are expressed formally, they can be processed by computer programs.

The ontology is the key element of the semantic web. It classifies objects, data, etc. (entities), with their attributes and the relationships among them inside a domain of knowledge.

In other words, it can be defined as a data structure that represents a model of semantic representation of reality. The shared language used to describe the semantics of the data is the uniform way to facilitate the communication among different users to understand each other (Mohammad 2010).

Ontologies are used to overcome the barriers to heterogeneous semantic data sharing. They are commonly used for many purposes such as network management, data exchange on the World Wide Web and information retrieval (Hor 2015).

There are several examples in literature where ontology is required before the data conversion (El-Diraby et al. 2005; Hor et al. 2016). Also, it remarks the importance to maintain the ontology of a model in order not to lose the meaning of each feature during the data format conversion.

As is described in Kolbe and Nagel (2012), main elements of RDF are triples composed by three elements: subject, predicate and object. They can be represented in a graph (upper of Figure 42) with three linked nodes. The meaning of predicate could be interpreted as property and the meaning of object as value. The final interpretation of the triple will depend on the data stored, e.g., if the predicate is "hasChild", the meaning of the object could be a value if a boolean data (yes or no) is stored, or another object if all data regarding the child is linked. Other manner to create this RDF graph is using two nodes (subject and object) connected by an edge (predicate) (bottom of Figure 42).

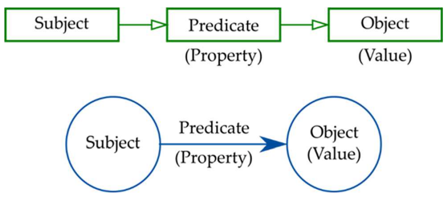


Figure 42. RDF triples

The use of open source standard facilitates end users to understand every model. But these standards are usually disconnected among them as is the case of CityGML (GIS) or IFC (BIM). As previously expressed, some solutions exist and the approach used here is useful to create a common system where an entire model can be incorporated. This common system is represented by a graph database with RDF triples.

Graph databases belong to NoSQL databases. These types of database are useful when they have to store unstructured information. Furthermore, they allow to carry out fast transversal queries. Nowadays, there are a variety of software in this field such as ArangoDB (Fernandes and Bernardino, 2018), MongoDB (Fernandes and Bernardino, 2018), or Neo4j (Fernandes and Bernardino, 2018; Hor et al., 2018). The choice fell on ArangoDB for its speed carrying out traversal queries, but any other could be used.

These databases have multi-model structure because they can collect information in different ways. This methodology is based on the use of documents and graphs (ArangoDB 2019). Documents store information, whereas graphs define relationships between data. Both are used by ArangoDB. ArangoDB uses JSON (JavaScript Object Notation) format to store information in documents. Each one of them can contain different type and quantity of attributes. Documents are stored into collections assigning them, automatically or manually, a univocal key value. There are two types of collections: vertices and edges. The main difference between them is that edge collection has two special attributes that vertex collection does not have: _from and _to. These two attributes are used to create relations among documents of any vertex collection stored in the database. The diagram of Figure 42 shows that these graph databases can be defined graphically, with vertices and edges, where vertices are documents and edges are relations (Figure 43). It allows to use RDF graphs triples to define the data in ArangoDB where Predicates (from RDF) represent edges, whereas Objects and Subjects are vertices (or documents).

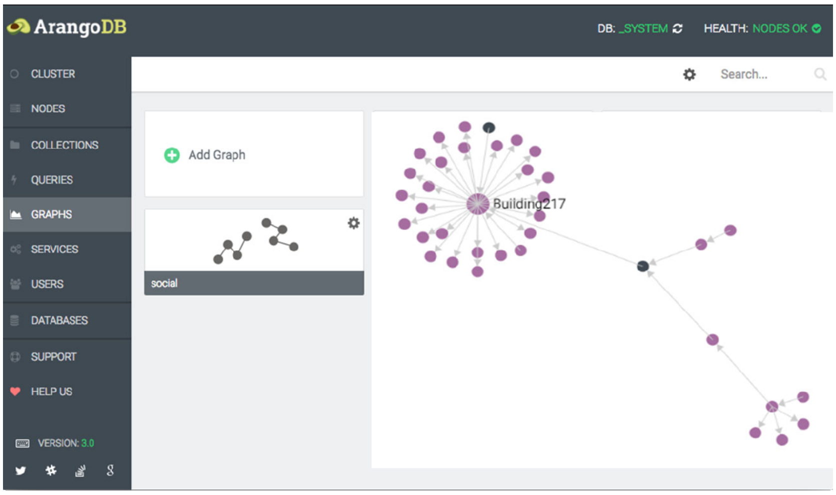


Figure 43. ArangoDB graph editor, example of graph database referring to a building

Semantic web services technologies and RDF graphs will bring the benefits of both BIM and GIS technologies together into one integrated model called integrated geospatial information model. This model uses BIM capabilities to accurately provide existing information about the architectural scale (BH object) and the GIS to support the wide range of spatial analysis and management of BH within its surrounding. The semantic web services and RDF graphs will be used to convey meaning and support the integration of all the spatial, attributes and relational information coming from both sources and provide interoperability of data. The application based on RDFs and OWL define a unified integrated system as one integrated knowledgebase and one semantic schema (Figure 44).

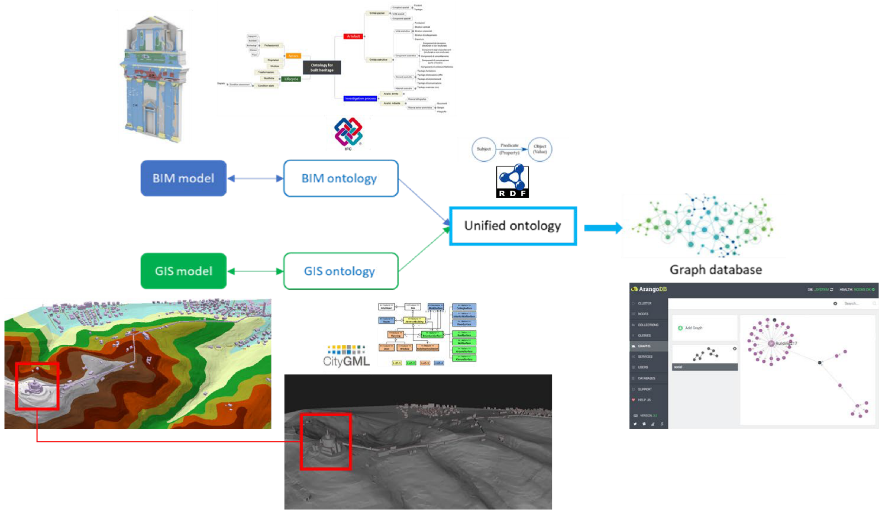


Figure 44. Interoperability and data exchange between BIM and other information management systems through semantic web environment

5.4 Beyond BIM, the BKMM

After getting to know the functionalities of BIM, trying to understand how its limitations in being able to manage more data through an ontology-based approach can be overcome, confirmed the possibility of integrating data with other information systems such as GIS at a larger scale than the architectural one thanks to the interoperability guaranteed by the semantic web, all that remains is to be able to introduce a new paradigm of information management that promotes shared knowledge, the BKMM or BKM^2 (Building Knowledge Modeling and Management) (Figure 45).

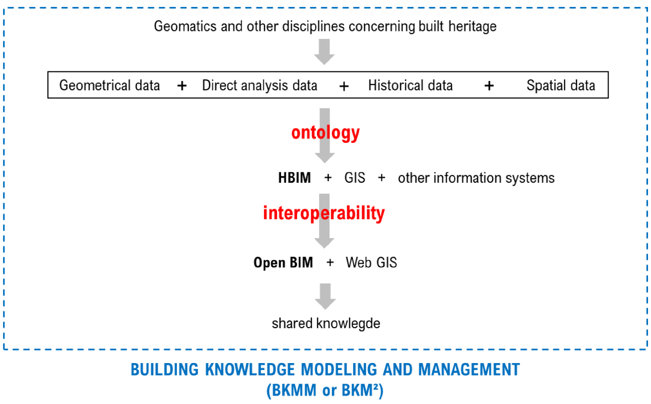
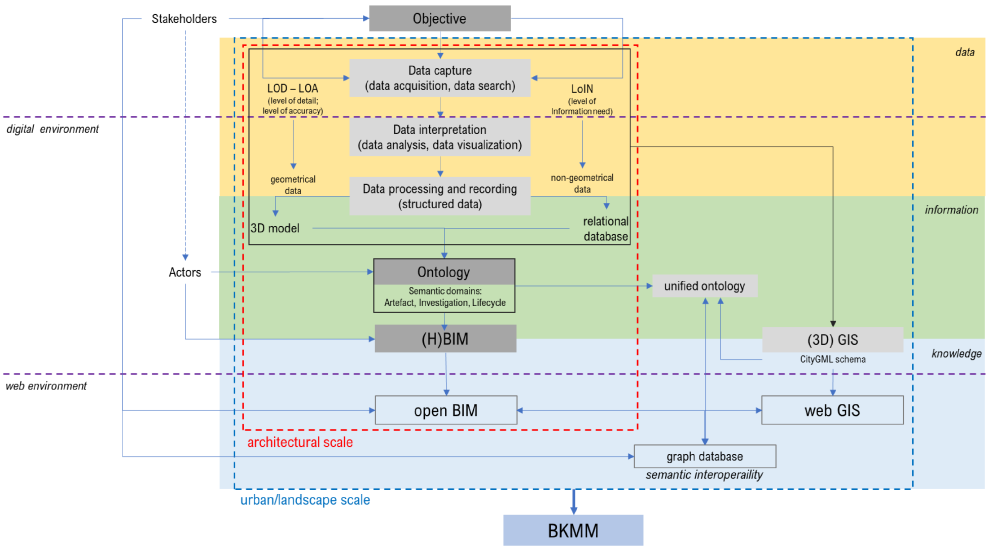


Figure 45. Building Knowledge Modeling and Management

Graphical summary

The interoperability is guaranteed by the semantic aspect of data integration between BIM and other information systems, such as GIS for BH at urban/landscape scale. The key point of semantic interoperability is to make sure that features and relations between information management systems are maintained during data conversion. Objects as entities and their relationships are defined under a unified ontology that makes possible the representation, the sharing and the management of the knowledge. The information should be described and classified in a standard way. The semantic web services and graphs database will be used to convey meaning and support the integration of all the spatial, attributes and relational information coming from both sources and provide interoperability of data. A new paradigm of information management promotes shared knowledge, the BKMM or BKM[2] (Building Knowledge Modeling and Management).



Discussion

Here the research questions previously addressed (Chatper 1) are discussed.

Data

Which kind of data of a BH can be managed through an information system?

→ Thanks to the technological progress of information systems, more and more data related to a BH can be managed. It is not only data that is obtained with geomatic techniques and technologies, but also through the integration of data from other disciplines in the BH sector, providing a better understanding not only of the geometry, but also of its historical background and condition assessment.

What are the factors to be taken into account when capturing data for BH?

→ Before starting a process of documenting a BH it is good to be clear about the purpose of the BH project. Therefore, the factors to be taken into account are not only the demands and requirements expressed by the stakeholders, but also the levels that can be achieved through the data capturing phase, which we know as the level of detail, accuracy and information need. However, this is also influenced by other intrinsic factors such as the time and cost available and the knowledge and skills of the actors involved.

At the end of the preliminary acquisition and research phase, how can be structured these data?

→ Geometric and non-geometric data are obtained through the data capturing phase. The geometric data will be used to define the volume of the object, while the non-geometric data will be collected in databases. A preliminary conceptual map allows the components of the object to be decomposed and identified, which will be used to manage the attributes associated with them according to the entity-relationship structure of the relational database.

Information

Referring to the BH, how should an information model be built for the collection and integration of various type of data? Is there a basic structure that can lead to the implementation of an information management system?

→ Before implementing an information model, it is necessary to define an ontological schema that defines the semantic domains on which to base data management. There is no basic ontology to refer to, there are several reference models in the literature and in known data management systems. What we intend to do with this research contribution is to offer a basic structuring of the ontology for a BH to best indicate the main domains to be taken into account, then their semantic structuring depends on project purposes.

For the 3D modelling of a BH object we often rely on the level of detail or development that we can/should achieve, but as far as the level of information contained in a 3D model is concerned, how is this measured?

Regarding the measurability of the level of information in the literature there have been several attempts to classify it as the level of achievement of a certain knowledge. What we would like to suggest is to also consider the normative contribution in order to standardize the formula for defining the level of information reached.

What are the strengths and weaknesses of using a BIM system for BH (or HBIM)?

The functionalities and strengths of BIM are known to experts in the AEC sector. The research activity focused on using the BIM system for BH has shown some shortcomings and weaknesses such as the lack of an ontological structure, the difficulty of modelling complex geometric shapes, and the single architectural scale on which to work. This should not downgrade the BIM system but serve as a future development and improvement of knowledge management, especially for BH projects.

Opening a bracket on the definition of the level of knowledge, mentioned in one of the answers above, it must be stated that there is no standardized classification that can ascertain the achievement of a given level. What is certain is that the level of knowledge is measured on the basis of the available and necessary information related to that specific object and that depends on that specific objective for which it is documented on that object and for the purposes of an architectural project related to it. In the literature there have been various and free interpretations in promoting a level of knowledge of the object (Banfi, 2017; Castellano-Roman and Pinto-Puerto, 2019; Lo Turco et al., 2019), but what it is good to take into account is both the normative contribution that there is at the base to be able to test the achievement of a certain level (such as the LOD) and also the possibility to better standardize this classification. The level of knowledge (LOK, Figure 46) therefore cannot be other than based on the level of information needed (LoIN - ISO 19650:2018) which is defined in turn by the level of geometry (LOG) of the object which is based on obtaining on a certain level of detail (LOD) and accuracy (LOA), by convention classified from 100 to 500, a choice that falls on the classification promoted by the BIM Forum Level of Development Specification 2020, by the level of information (LOI) that we would say defined on a scale similar to the geometric one and finally by the amount of documents (DOC), historical, technical and third party, in various file formats, that have been obtained.

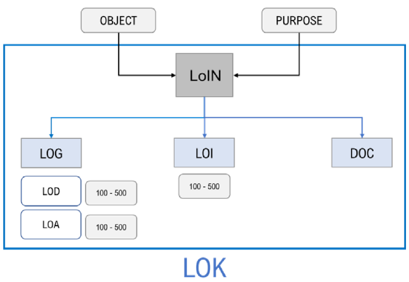


Figure 46. Level of Knowledge

Knowledge

Through which tools is the exchange and sharing of information between different information systems applied to BH ensured?

→ In AEC there are two main information systems, in addition to BIM there is also GIS which has some positive aspects that differentiate it from BIM, such as multi-scale and mutli-layer 3D modelling of the object with its context, robust data structuring and the web version has an ontology base (CityGML).
These two information systems when used together not only compensate the gaps but offer a richer and broader knowledge model, but between them data exchange and sharing must be guaranteed and this is possible thanks to domain-based interoperability (syntactic or semantic).

What does semantic ontology provide for knowledge management for BH?

→ The semantic ontology between information systems enables information standardization and guarantees data exchange operations by defining the syntax of the programming language. Furthermore, a unified semantic ontology between BIM and GIS based on interoperable standards is the basis for semantic interoperability between the two information systems through the creation of a graph database in a web environment.

Which benefits would be the implementation of an adopted BKMM (Building Knowledge Management and Modeling) for BH?

→ The BKMM is interpreted here as a new paradigm of integrated management of multiple information systems that can offer a broader vision regarding the BH, not only in the form of data, ontologies and interoperability but that guarantees a multidisciplinary methodological approach and collaboration between stakeholders favouring the enrichment and accessibility of information.

Conclusion

The aim of this thesis is to define a methodological approach for the management of information related to a BH in order to create a knowledge model.

Through the analysis of the scientific literature of the last decade (2010-2021) in the field of BIM applied to the BH, it is clear that there are still some open questions that research in the field of AEC is pursuing by highlighting the problems and trying to advance solutions. BIM will become a compulsory tool for new constructions and behind it there is a large regulatory apparatus trying to direct the correct use of it. As far as the built heritage is concerned, there are regulations that promote its documentation, preservation and conservation through the definition of interventions to be adopted. There is no real talk of BIM for the built heritage, it is merely a matter of implementing a robust information system to support projects related to it. It is therefore still an open challenge that of BIM for the BH. In the case of built heritage there are many factors and indicators that need to be taken into account in order to initiate an information process and these depend not only on the objective set and the demands made by the stakeholders, but also on the possibility of being able to obtain a necessary amount of data with the tools and resources that are available.

Geomatics as a discipline dealing with surveying techniques and the management of topological and spatial data is involved in this rapid technological, digital and informational progress characterized by the introduction of increasingly innovative tools. These tools also promote the multi- and interdiscplinary nature of geomatics by touching aspects of other scientific and non-scientific disciplines and among the various fields is precisely that of the BH. In this regard, geomatic technologies allow to obtain useful data to generate 3D models of objects and to acquire information that can be processed and stored in special information databases, integrating them with other data from other external sources.

In order to be able to record such geometric data and non-geometric information into an information system, it is best to first make use of an ontology that defines the semantics of the information in the form of domains and syntactically represents the relationships between data and attributes. This thematic aspect is less dealt with in scientific research, on the one hand because a current of research focuses more on the management of metric data and the achievement of a certain level of detail and accuracy of the model, on the other hand the lack of a basic structuring for the management of non-geometric data due to the vastness of the semantics of the BH finds less application for the definition of an ontological schema. As it is pointed out in this thesis, the ontology represents the core of knowledge and however wide the context of the built heritage may be, it is good to try to find the right dimension of the semantic aspect and to define a standardised and common language.

BIM is not characterised by an ontological approach and this limitation has been addressed in this thesis where an ontological schema is imported into the information system and managed based on the predefined structure (e.g. tripartite structure). To test this implementation it was done on a case study dedicated to the preliminary phase of a restoration project where, in addition to the 3D model, the ontology dedicated to decay classification and its graphic representation in the form of thematic mapping on the model itself was created.

It has been mentioned about semantic domains, ontology allows to define data and information in the form of coded names and this not only guarantees the possibility to transfer the management of the BIM system in an open platform thanks to the web environment but also to promote the interoperability with other information systems such as GIS. While BIM operates only at the architectural scale, GIS is a data management tool at the landscape, and therefore urban, scale where the BH is located. The combination of these two information systems represents a further advantage for the enrichment and sharing of different information for the same built heritage. But GIS and BIM do not communicate easily and the transfer of data between the two information systems in direct form causes misunderstandings and loss of information also due to the fact of the different internal data management. Compared to BIM, GIS is characterised by a robust data cataloguing system, a multi-layer model representation and its corresponding open standard exchange format has an ontological structure (CityGML). The solution to this difficult integration of the information systems is the definition of a unified ontological schema that guarantees dual semantic interoperability, i.e. dual direction of exchange, through the definition of a common information standard whose structure forms the basis of a graph database implemented in a semantic web environment.

The combination of these elements, from data, information, to the information system through ontology and interoperability between information systems defines a new paradigm of modelling and knowledge management, abbreviated as BKMM.

Some of the aspects addressed in this thesis deserve further thematic and methodological study, but an attempt has been made to outline and rearrange the guidelines to be followed and the elements to be taken into account for the management of a BIM system for the BH. Unfortunately, on the one hand, the low economic support for Italian research and the difficulty of activating conventions with companies outside the academic environment penalises research itself in being able to exploit certain funds in order to obtain concrete results. Moreover, in some aspects, the contribution of experts from the world of IT would be a further resource for testing these innovative results. Regarding to the theme of the thesis, as a future perspective it is suggested to try to understand the mechanism and perform the processes of computer automation to ensure the semantic interoperability between information systems and promote the development of a knowledge model as a theme of a future European academic cooperation project that could encompass the targets promoted in the 2030 Agenda of the Sustainable Development Goals.

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Appendix A.

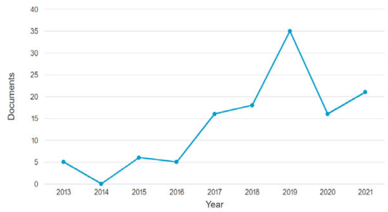
Literature search about BIM for built heritage

Referring to Table 2 in Section 2.2.1, the literature search (on Scopus platform) went deeper by adding other terms (keywords) associated with the expression “HBIM” to analyse the trend of published papers (updated 31 October 2021).

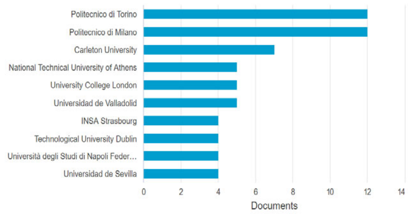
• “HBIM” and “documentation”

Search: **(TITLE-ABS-KEY (hbim) AND TITLE-ABS-KEY (documentation)) AND PUBYEAR > 2010 AND PUBYEAR < 2021**

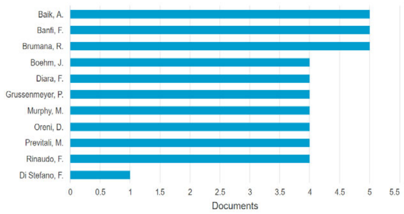
120 document results



Documents by affiliation



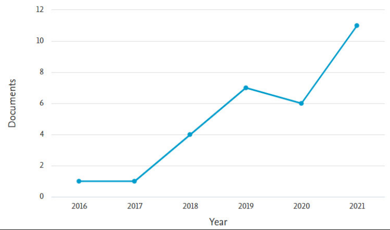
Documents by author



• “HBIM” and “digitization”

Search: **(TITLE-ABS-KEY (hbim) AND TITLE-ABS-KEY (digitization)) AND PUBYEAR > 2010 AND PUBYEAR < 2021**

30 documents results



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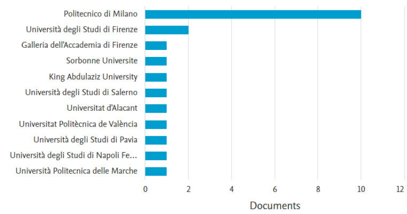
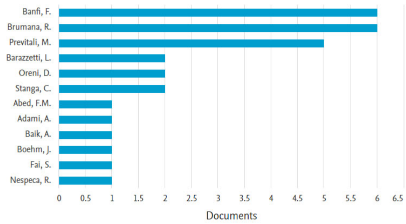


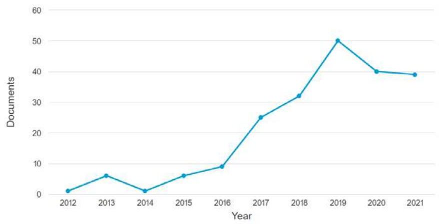
Documents by author



• “HBIM” and “conservation /preservation”

Search: **(TITLE-ABS-KEY (hbim) AND TITLE-ABS-KEY (conservation) AND TITLE-ABS-KEY (preservation)) AND PUBYEAR > 2010 AND PUBYEAR < 2021**

209 document results



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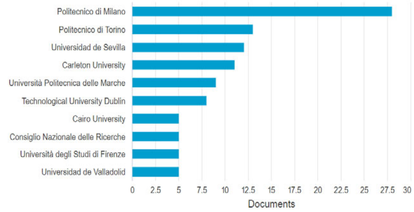

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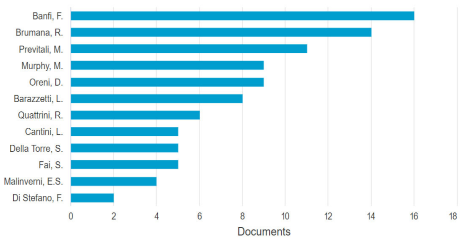

• "HBIM" and "restoration"

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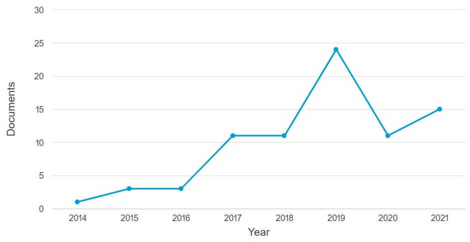
79 document results



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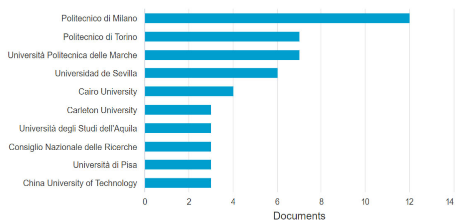

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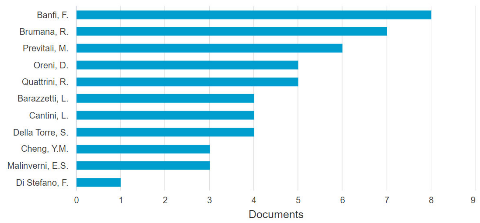
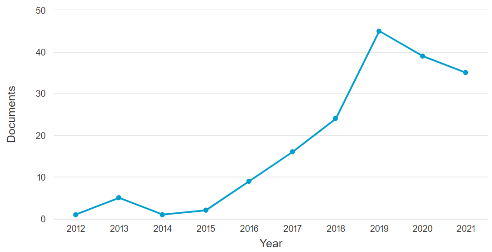


• "HBIM" and "management"

Search: **(TITLE-ABS-KEY (hbim) AND TITLE-ABS-KEY (management)) AND PUBYEAR > 2010 AND PUBYEAR < 2021**

177 document results



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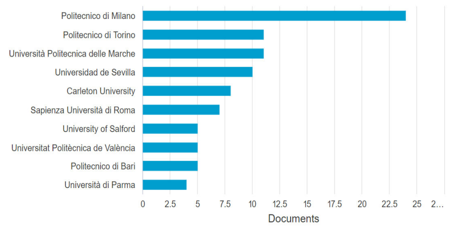

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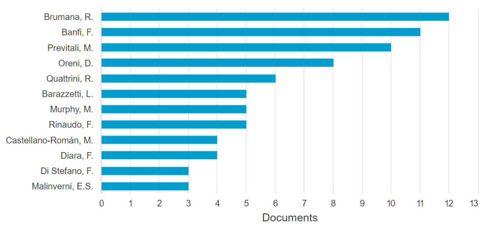
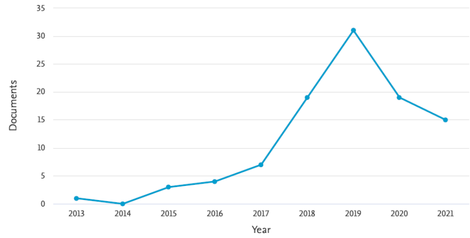


• “HBIM” and “knowledge”

Search: **(TITLE-ABS-KEY (hbim) AND TITLE-ABS-KEY (knowledge)) AND PUBYEAR > 2010 AND PUBYEAR < 2021**

90 document results



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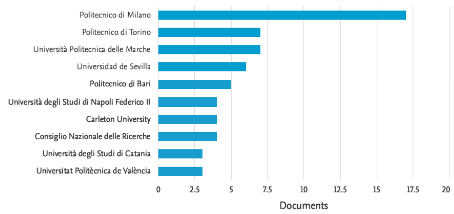

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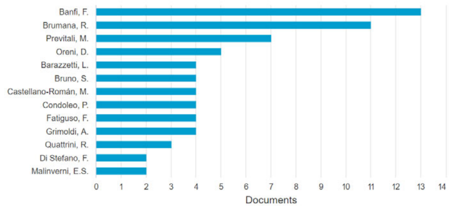
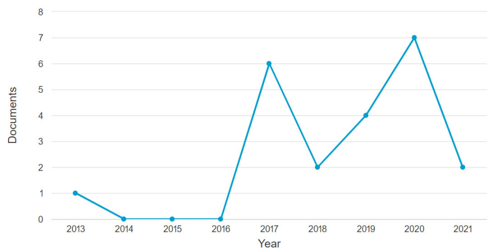


• “HBIM” and “geomatics/geomatic survey/metric survey”

Search: **(TITLE-ABS-KEY (hbim) AND TITLE-ABS-KEY (geomatics) OR TITLE-ABS-KEY (geomatic AND survey) OR TITLE-ABS-KEY (metric AND survey)) AND PUBYEAR > 2010 AND PUBYEAR < 2021**

22 document results



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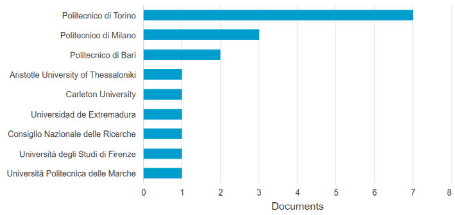
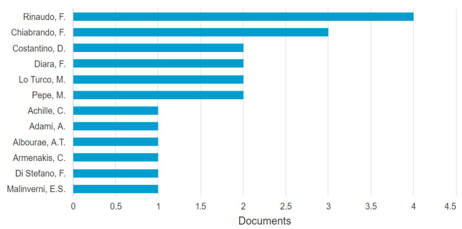


Documents by author



• “HBIM” and “photogrammetry”

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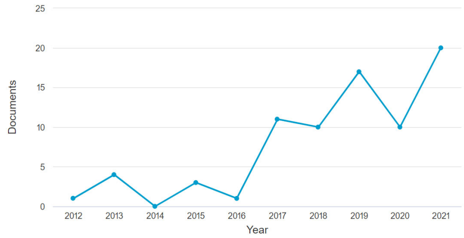
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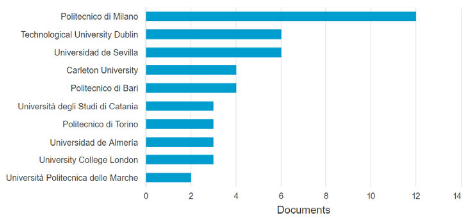
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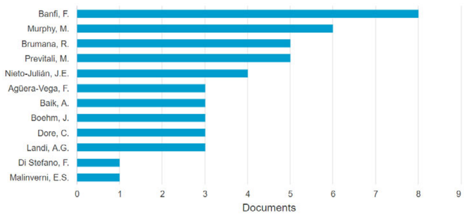
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• “HBIM” and “laser scanner/TLS/MLS/MMS”

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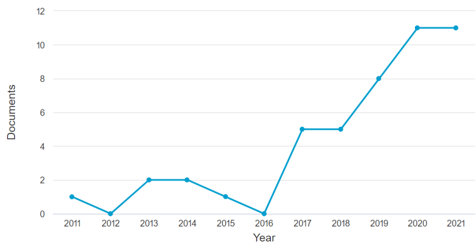
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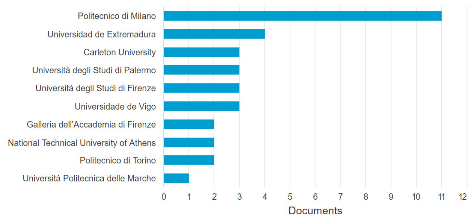
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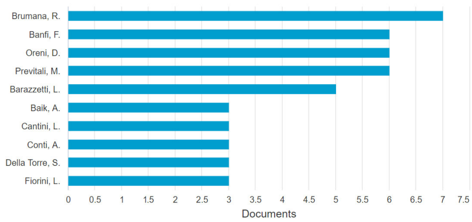
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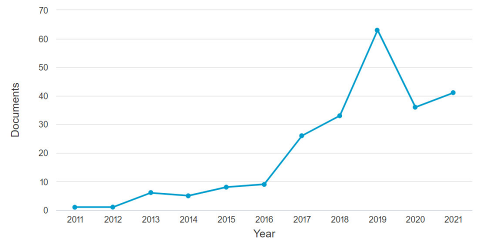
• "HBIM" and "3D/3D model/3Dmodeling"

Search: **(TITLE-ABS-KEY (hbim) AND TITLE-ABS-KEY (3d) OR TITLE-ABS-KEY (3d AND model) OR TITLE-ABS-KEY (3d AND modeling)) AND PUBYEAR > 2010 AND PUBYEAR < 2021**

229 document results



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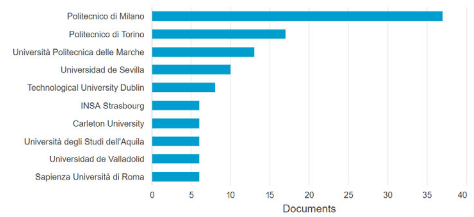

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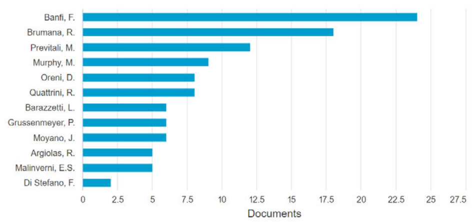
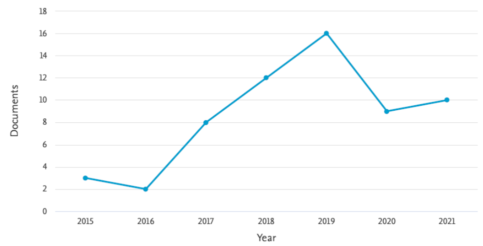


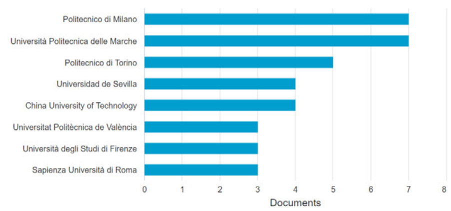
• "HBIM" and "database"

Search: **(TITLE-ABS-KEY (hbim) AND TITLE-ABS-KEY (database)) AND PUBYEAR > 2010 AND PUBYEAR < 2021**

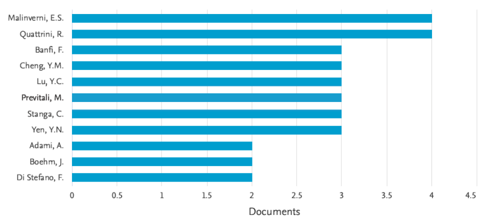
60 document results



Documents by affiliation



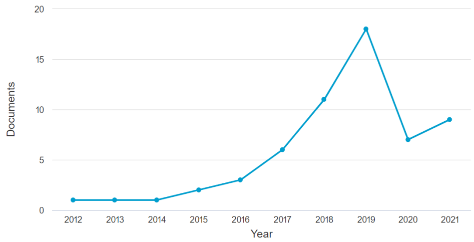
Documents by author



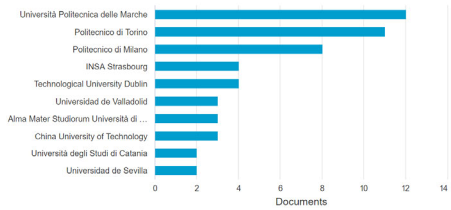
• “HBIM” and “semantics/semantic”

Search: **(TITLE-ABS-KEY (hbim) AND TITLE-ABS-KEY (semantics) OR TITLE-ABS-KEY (semantic)) AND PUBYEAR > 2010 AND PUBYEAR < 2021**

59 document results



Documents by affiliation



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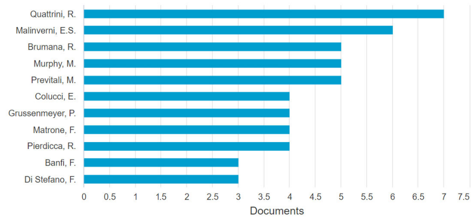
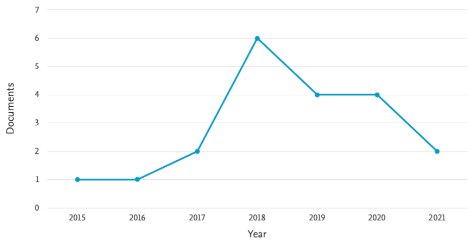


• “HBIM” and “ontology”

Search: **(TITLE-ABS-KEY (hbim) AND TITLE-ABS-KEY (ontology)) AND PUBYEAR > 2010 AND PUBYEAR < 2021**

20 document results



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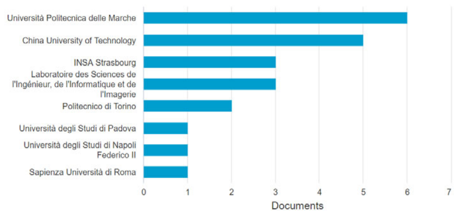

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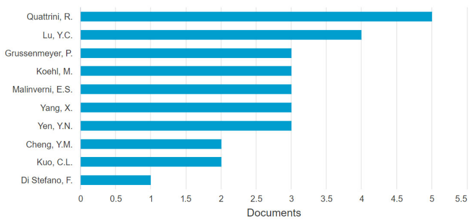
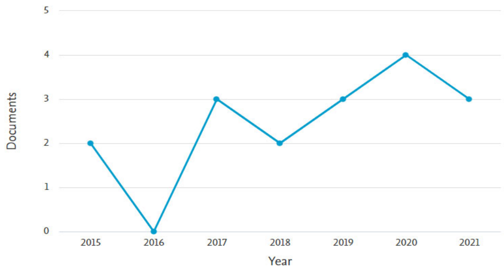


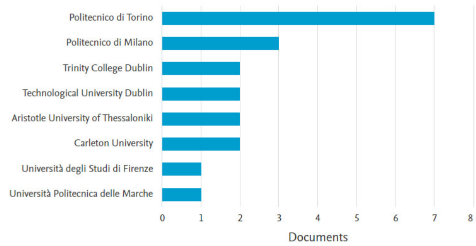
- “HBIM” and “open BIM”

Search: **(TITLE-ABS-KEY (hbim) AND TITLE-ABS-KEY (open AND bim)) AND PUBYEAR > 2010 AND PUBYEAR < 2021**

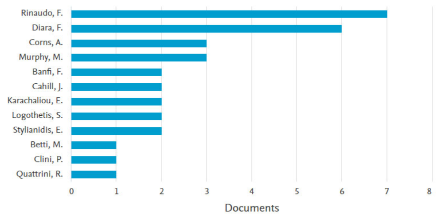
14 document results



Documents by affiliation



Documents by author



- “HBIM” and “data integration”

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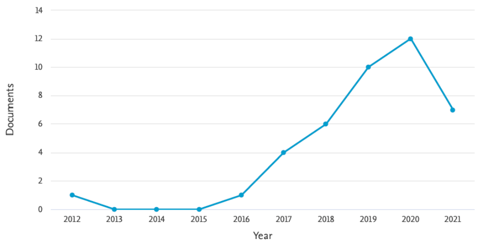
41 document results



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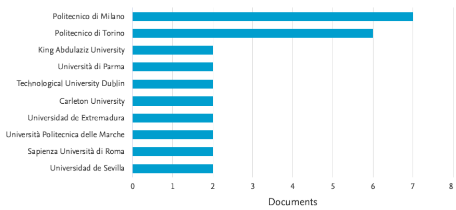
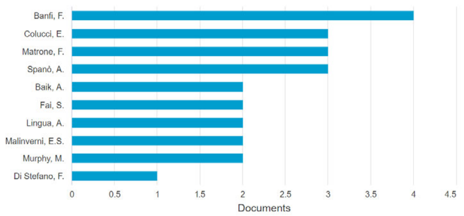


Documents by author



- “HBIM” and “data sharing”

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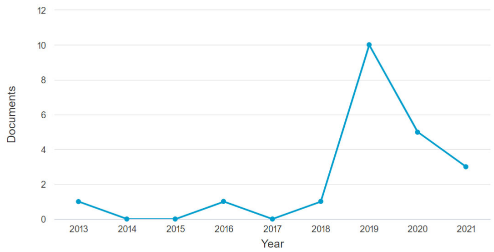
21 document results



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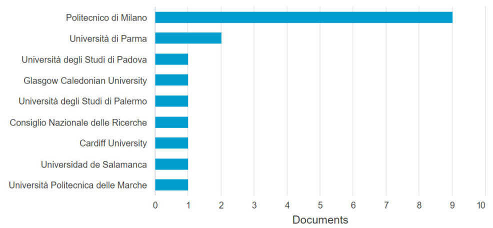
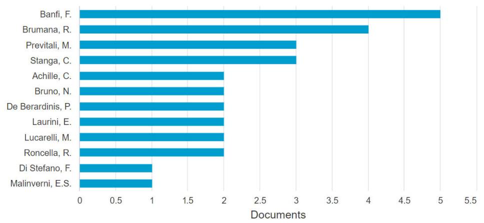


Documents by author



- “HBIM” and “interoperability”

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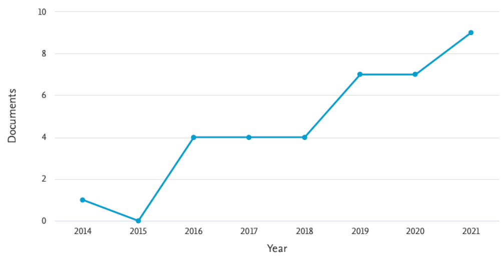
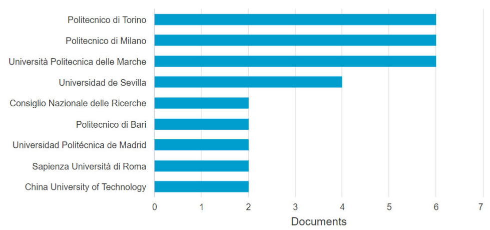
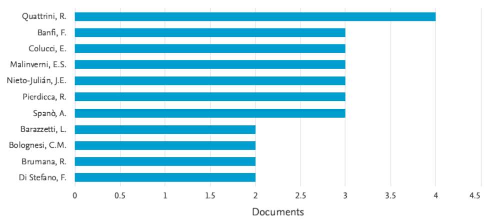
36 document results



Documents by affiliation



Documents by author



• "HBIM" and "GIS/3D GIS"

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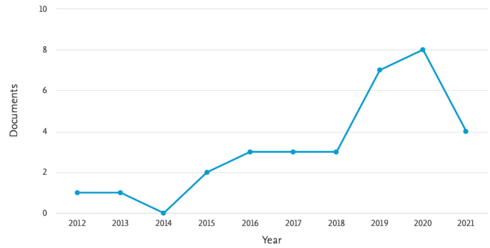
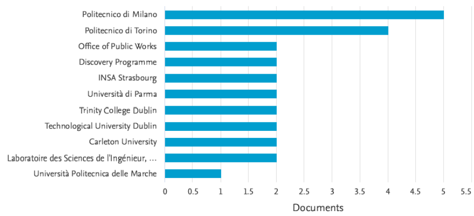
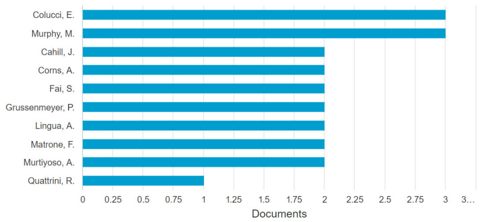
32 document results



Documents by affiliation



Documents by author



• "HBIM" and "web/semantic web"

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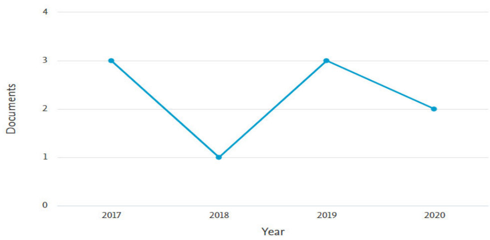
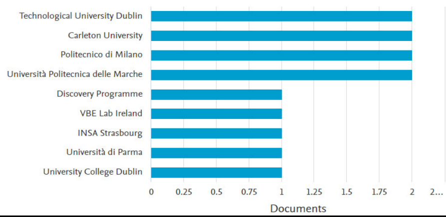
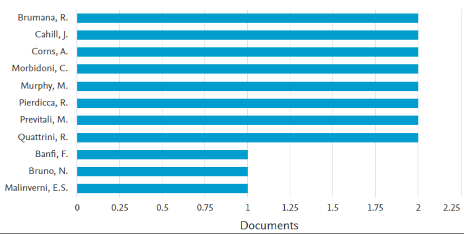
9 document results



Documents by affiliation



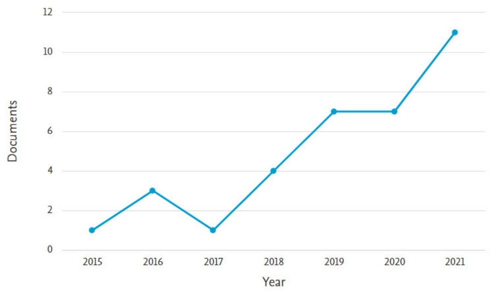
Documents by author



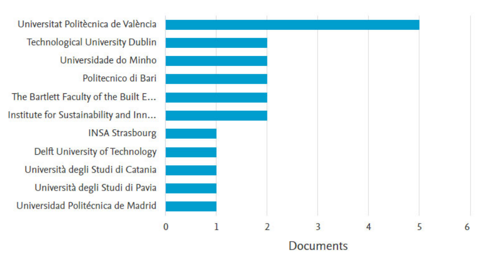
• “HBIM” and “review”

Search: **(TITLE-ABS-KEY (hbim) AND TITLE-ABS-KEY (review)) AND PUBYEAR > 2010 AND PUBYEAR < 2021**

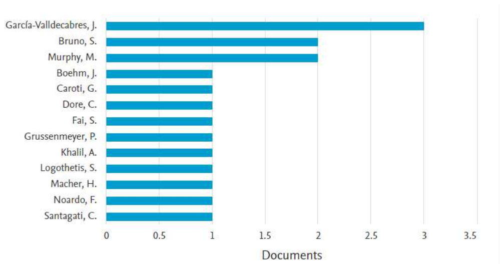
34 document results



Documents by affiliation



Documents by author

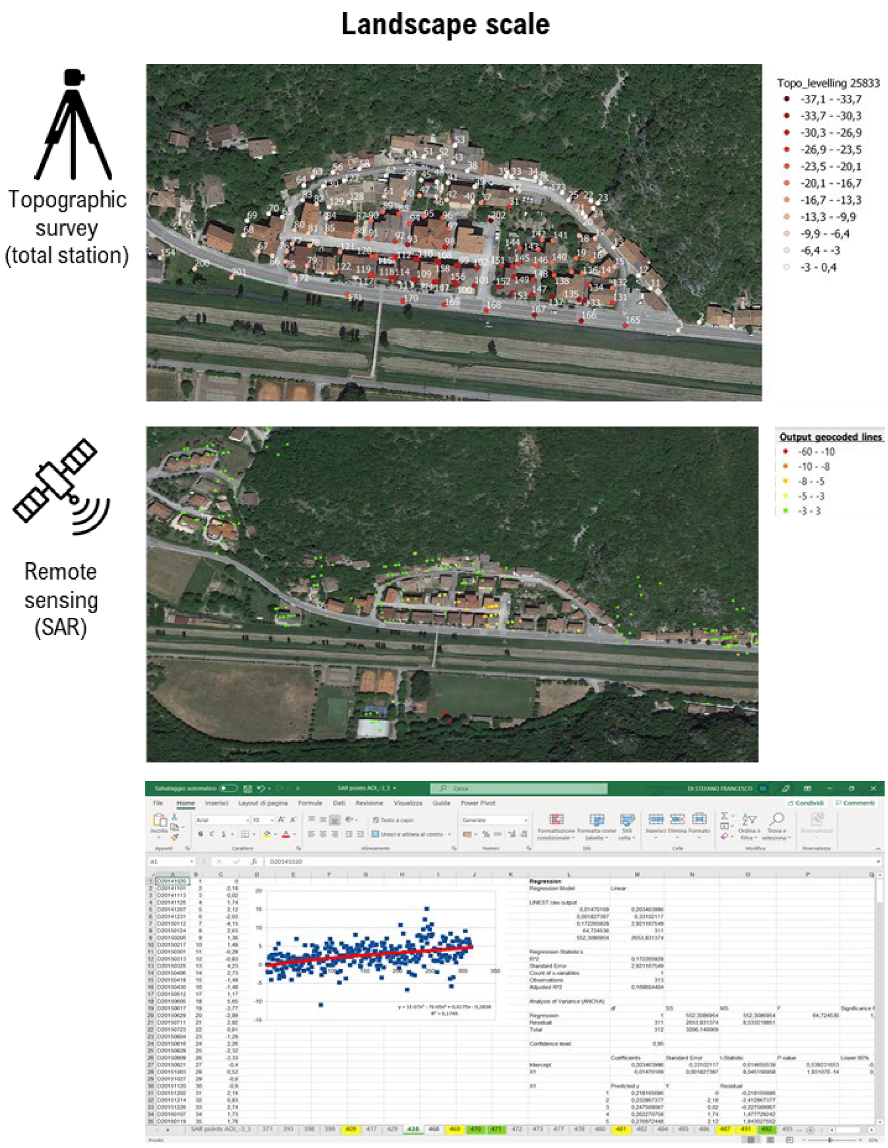


Appendix B.

Geomatics techniques and technologies

These geomatic techniques and technologies have been applied to the various scales that define a built heritage. Starting from the landscape scale (Case study n. 1) where topographic survey and satellite data allow monitoring operations, for example of a vernacular village. At the urban scale, the use of a mobile laser scanner integrated with photogrammetry and topographic survey for georeferencing data was tested (Case study n. 2). At the building scale, close-range techniques were adopted such as classical spherical photogrammetry (Case study n. 3) and terrestrial laser scanning (Case study n. 4), which allow 3D models of a good level of detail to be obtained. Finally, mobile laser scanner techniques with SLAM (Simultanously Localization and Mapping) technology were tested in an underground context (Case study n. 5).

Case study n.1



ASSESSING LEVELLING AND DInSAR FOR DEFORMATION MONITORING IN SEISMIC REGION

F. Di Stefano, M. Cuevas-Gonzalez, G. Luzi, E. S. Malinverni (2022), ASSESSING LEVELLING AND DInSAR FOR DEFORMATION MONITORING IN SEISMIC REGION, , in press.

Abstract:

In highly seismic zones it is good practice to carry out monitoring surveys both for the assessment of land deformation and the evaluation of building structures standing on it.
The most accurate and widespread technique for measuring displacement is topographic levelling. This is a point-wise survey methodology that typically allows the acquisition of dozens of discrete sub-millimetre in situ measurements per squared kilometre. Another technique used for mapping ground deformation is the InSAR (Interferometric Synthetic Aperture Radar) method, which is based on SAR images acquired from orbiting satellites. This remote sensing technique, compared to levelling, can provide higher spatial point density, wider spatial coverage, and low-cost acquisitions.

To do so, an experiment was carried out on a small urban area of Pioraco (Italy), located in the seismic crater, following the earthquakes that struck central Italy in the years 2016-2017.

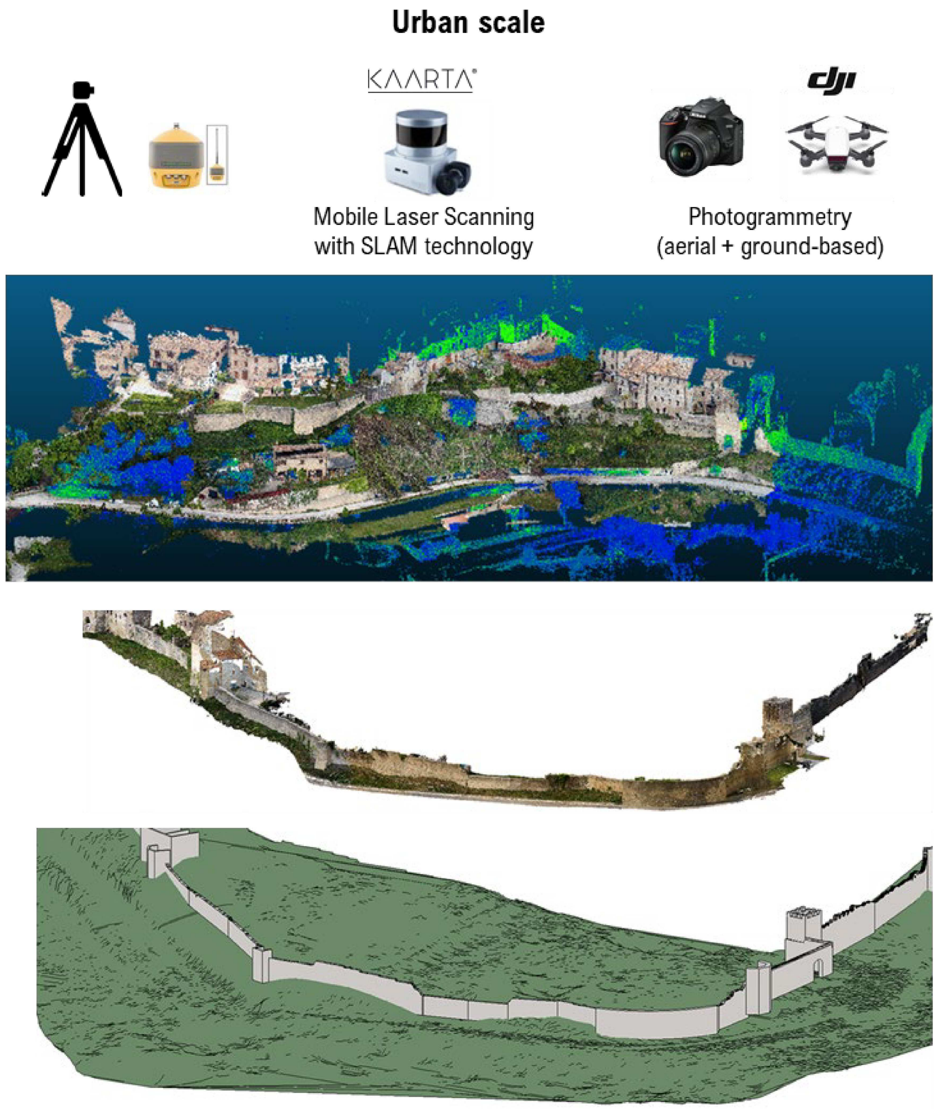
The area of interest had already been under observation through ground-based monitoring surveys, by means of targets attached to façades of buildings detected by total station, since 1998 (following the previous seismic event in 1997) until 2021. The InSAR analysis was carried out exploiting Sentinel-1A/B data during the period 2015-2021. The goal of the InSAR processing stage of the procedure is to derive the deformation information of the area of interest from SAR data. The Persistent Scatterer Interferometry chain of the Geomatics (PSIG) Division of the CTTC has been used in this study. A zero date has been set for both survey methods in order to define similar time series for comparison analysis.

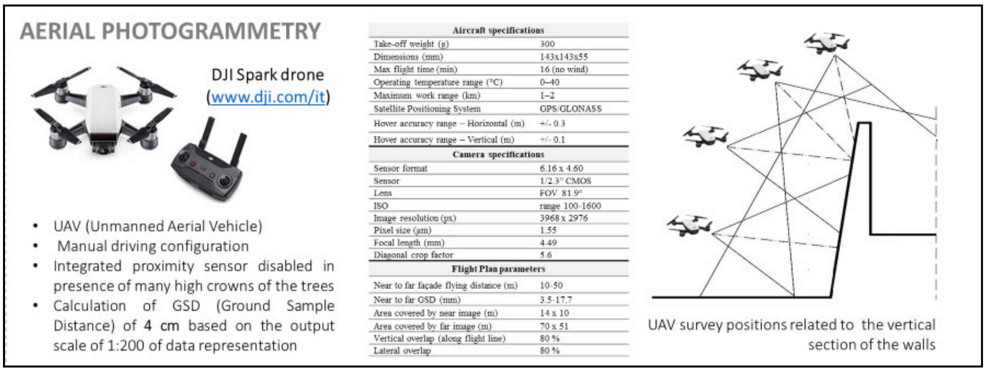
An important aspect to consider is the type of measurements obtained: with topographic levelling, the metric subsidence of the terrain is calculated on its vertical component, while with InSAR, the displacement is calculated by means of differential estimation of the velocity vector for each point identified. Another factor to consider is data processing. Levelling data are obtained directly and catalogued in database form. SAR data require a specific workflow that starts from the download of images in the temporal period to be analysed, followed by the generation of interferograms and the analysis of coherence to the estimation of the linear velocity and finally the deformation activity map in the form of points identified through geocoding process.

Finally, the displacements of the points that are evaluated on the basis of fixed targets, as reference points, are then compared to assess the value of subsidence through both techniques implemented. The reference points of the levelling are already known and fixed on elements considered to be stable, such as the rock face close to the urban area. On the contrary, the reference points for the estimation of the subsidence by means of InSAR are to be identified and are determined according to different factors including the statistical analysis of the square regression of the distribution of the value of the subsidence for each point.

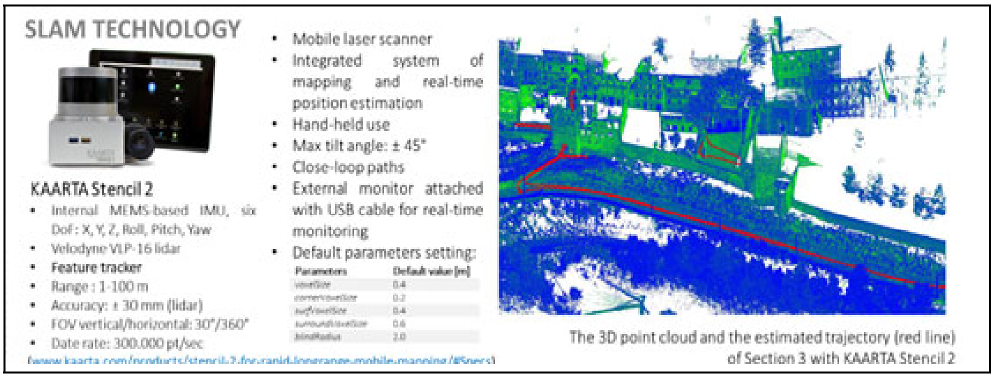
The comparison of the analysis, made on QGIS software, showed that ground displacements measured by levelling and InSAR have similar trends in the results. On the geographical aspect, the same distribution map of curves of relative subsidence rate is found in both techniques.

Case study n. 2



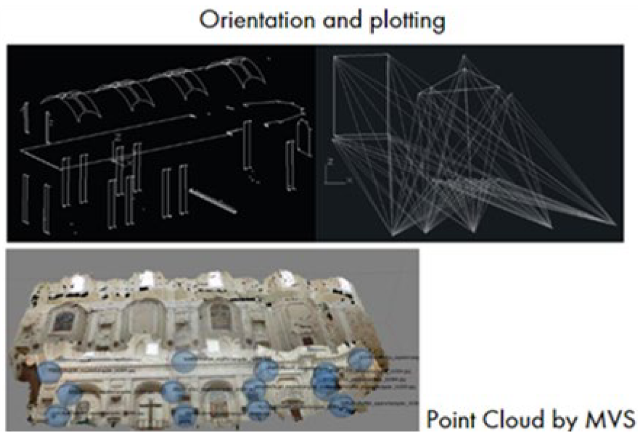


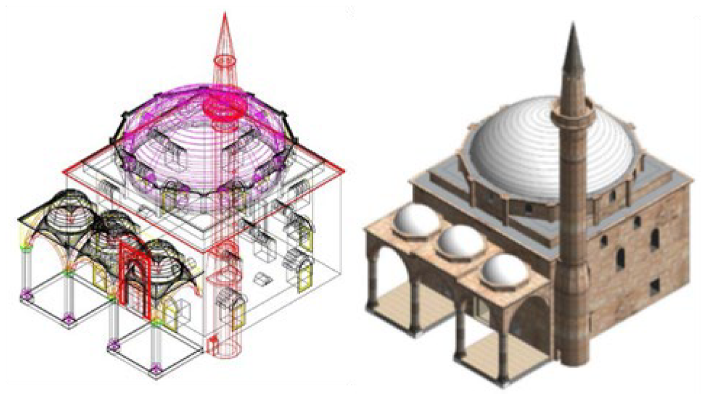
Aircraft specifications	
Take-off weight (g)	300
Dimensions (mm)	143x143x55
Max flight time (min)	16 (no wind)
Operating temperature range (°C)	0–40
Maximum work range (km)	1–2
Satellite Positioning System	GPS/GLONASS
Hover accuracy range – Horizontal (m)	+/- 0.3
Hover accuracy range – Vertical (m)	+/- 0.1
Camera specifications	
Sensor format	6.16 x 4.60
Sensor	1/2.3" CMOS
Lens	FOV 81.9°
ISO	range 100-1600
Image resolution (px)	3968 x 2976
Pixel size (μm)	1.55
Focal length (mm)	4.49
Diagonal crop factor	5.6
Flight Plan parameters	
Near to far façade flying distance (m)	10-50
Near to far GSD (mm)	3.5-17.7
Area covered by near image (m)	14 x 10
Area covered by far image (m)	70 x 51
Vertical overlap (along flight line)	80 %
Lateral overlap	80 %



Di Stefano, F., Chiappini, S., Piccinini, F., & Pierdicca, R. (2019). Integration and Assessment Between 3D Data from Different Geomatics Techniques. Case Study: The Ancient City Walls of San Ginesio (Italy). In International Workshop on R3 in Geomatics: Research, Results and Review (pp. 186-197). Springer, Cham. https://doi.org/10.1007/978-3-030-62800-0_15

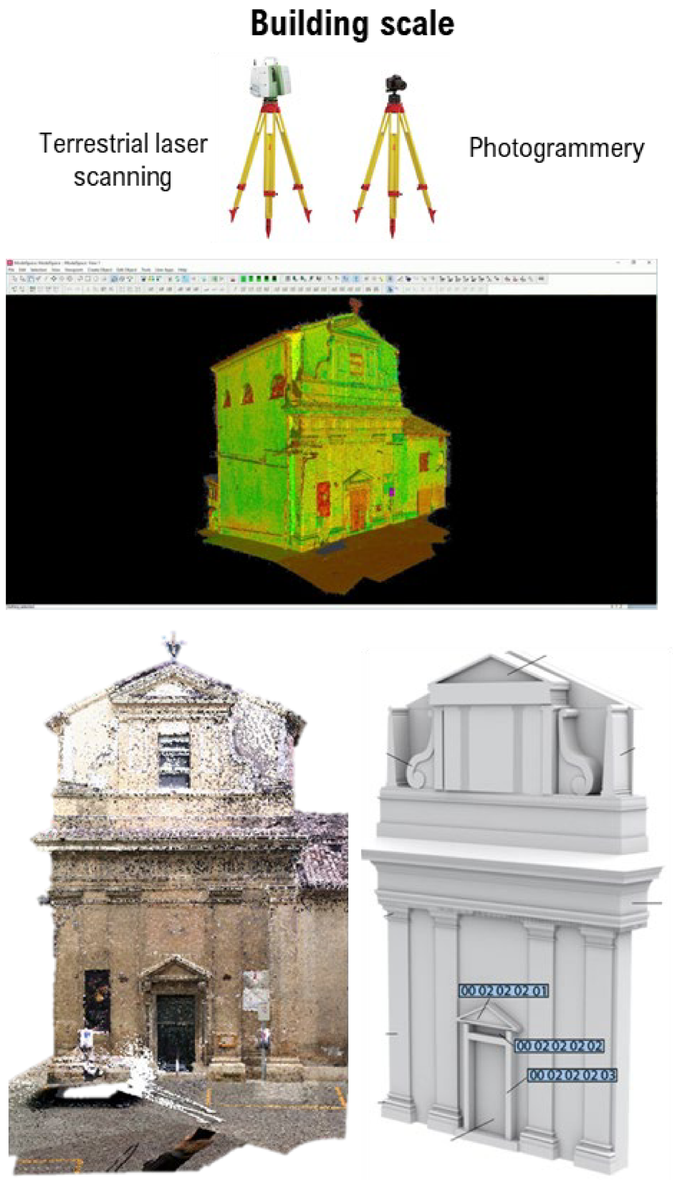
Case study n. 3





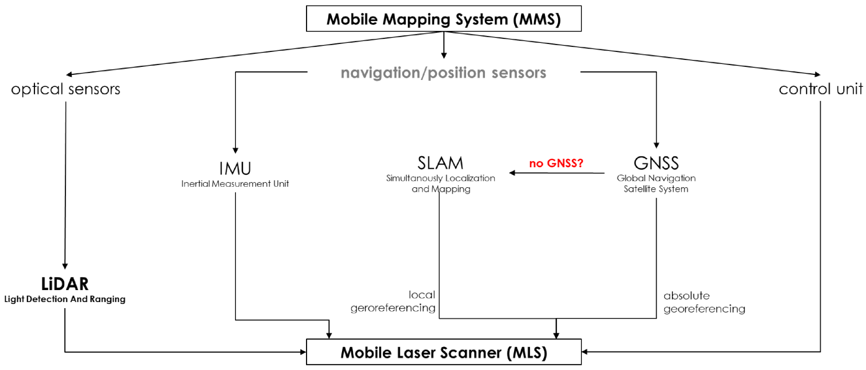
Di Stefano, F., Malinverni, E.S., Pierdicca, R., Fangi, G., Ejupi, S., 2019. HBIM implementation for an ottoman mosque. case of study: Sultan Mehmet Fatih II Mosque in Kosovo. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., 42, 429-436. https://doi.org/10.5194/isprs-archives-XLII-2-W15-429-2019

Case study n. 4



Malinverni, E. S., Mariano, F., Di Stefano, F., Petetta, L., Onori, F., 2019: Modelling in HBIM to document materials decay by a thematic mapping to manage the cultural heritage: the case of “Chiesa della Pietà” in Fermo, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., Vol. XLII-2/W11, pp. 777-784, https://doi.org/10.5194/isprs-archives-XLII-2-W11-777-2019

Case study n. 5



Di Stefano, F., Chiappini, S., Gorreja, A., Balestra, M., & Pierdicca, R. (2021a). Mobile 3D scan LiDAR: a literature review. *Geomatics, Natural Hazards and Risk*, *12*(1), 2387-2429. https://doi.org/10.1080/19475705.2021.1964617

Di Stefano, F., Torresani, A., Farella, E. M., Pierdicca, R., Menna, F., & Remondino, F. (2021b). 3D Surveying of Underground Built Heritage: Opportunities and Challenges of Mobile Technologies. *Sustainability*, *13*(23), 13289. https://doi.org/10.3390/su132313289

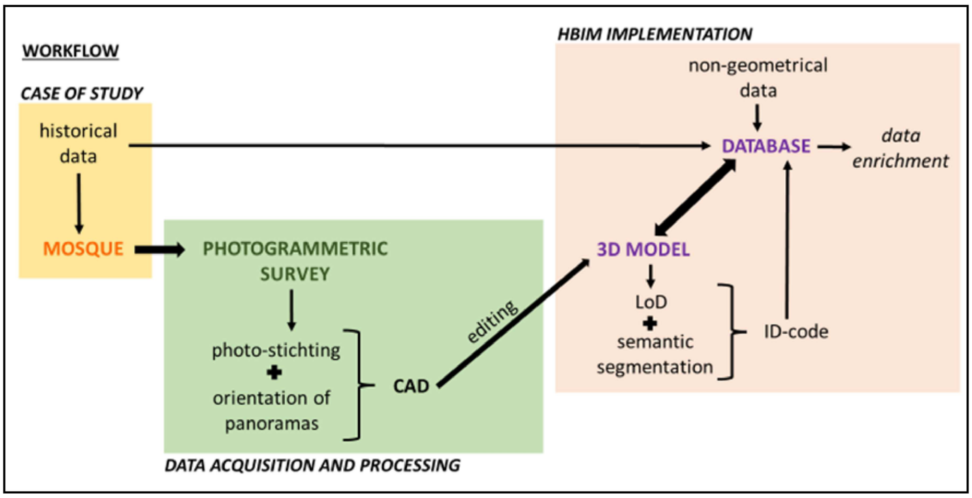
Appendix C.

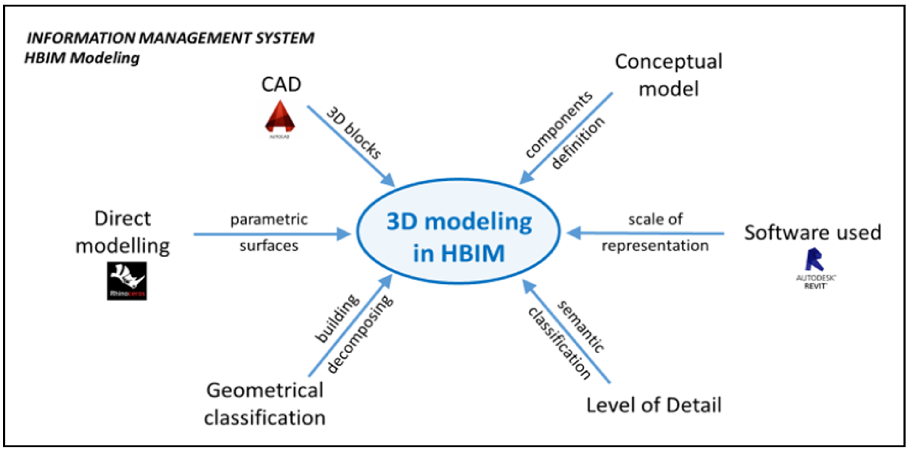
HBIM implementation, case studies

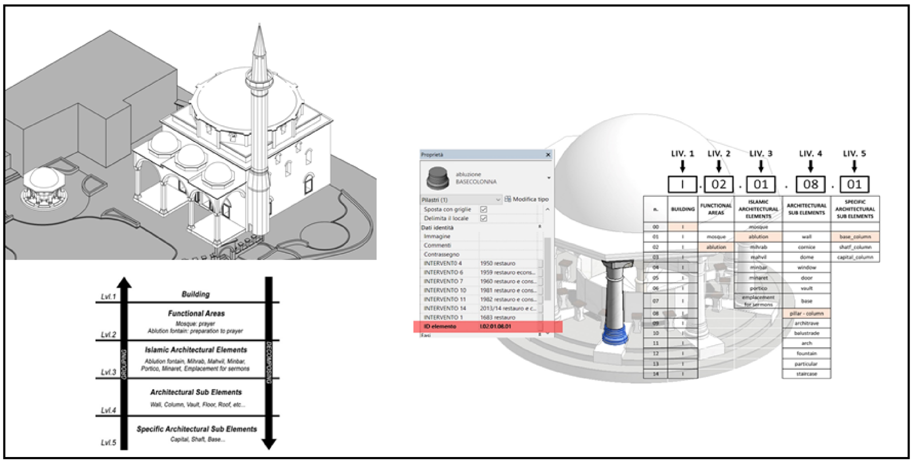
HBIM IMPLEMENTATION FOR AN OTTOMAN MOSQUE.
CASE OF STUDY: SULTAN MEHMET FATIH II MOSQUE IN KOSOVO

Di Stefano, F., Malinverni, E. S., Pierdicca, R., Fangi, G., & Ejupi, S. (2019). HBIM IMPLEMENTATION FOR AN OTTOMAN MOSQUE. CASE OF STUDY: SULTAN MEHMET FATIH II MOSQUE IN KOSOVO. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*. https://doi.org/10.5194/isprs-archives-XLII-2-W15-429-2019

Abstract:
National Strategy For Cultural Heritage 2017-2027 is a Kosovo Government document that aims the enhancement of the system for the protection and preservation of Kosovan **cultural heritage**. Among the listed goals, one can find the promotion of an integrated data management approach towards cooperation platforms that involve advanced technologies and information systems applied to cultural heritage. This research contributes in opening the debate about the use of **HBIM** even for historical architecture, illustrating a methodology of information management promoting the **conservation** and the **valorization** of a Kosovan ottoman mosque. The workflow pipeline started with the close range photogrammetric survey, obtaining first **spherical panoramas** and then the wire-frame processed in a **3D modelling** environment, suitable to implement the HBIM project. Basing on the accuracy of the data acquisition, the availability of information about the building and the related level of knowledge, we proposed a semantic representation of the complex structure integrating in an HBIM collecting in an “ad hoc” **database** the geometrical building components, enriched with attributes as images, materials, decay, interventions, etc., linked to each features. Our approach is an example of how efficient **semantic classification** can be repeated for the analysis and the documentation of other similar ottoman mosque, simplifying the management of construction by a sort of **unique and searchable archive**. The advantage of the interoperability concept allows the data sharing is now stressed by HBIM.







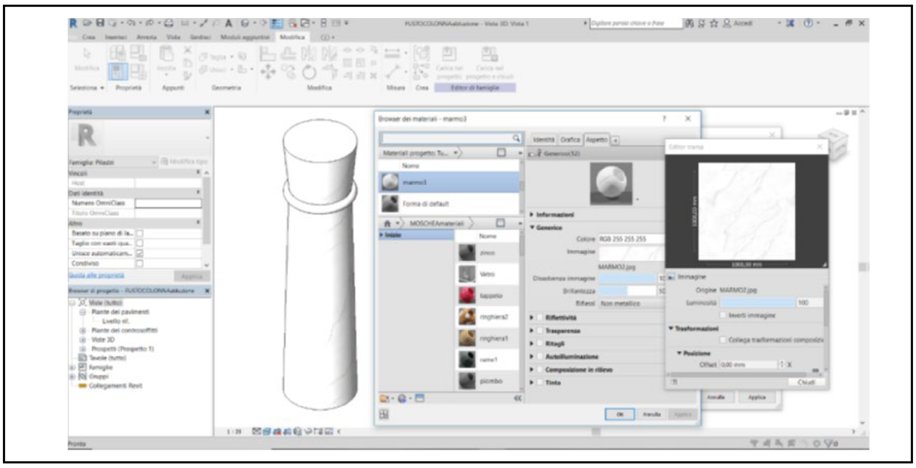
BIM software automatic schema (category-family-type)

Historical data - Interventions

Images

CATEGORIA	FAMIGLIA	TIPO	ID ELEMENTO	INTERVENTO 1	INTERVENT0 4	INTERVENTO 6	INTERVENTO 7	INTERVENTO 10	INTERVENTO 11	INTERVENTO 14	IMMAGINI STORICHE
Attrezzature speciali	abluzione	base	I.02.01.06.00	1683 restauro	1950 restauro	1959 restauro e conservazione	1960 restauro e conservazione	1981 restauro e conservazione	1982 restauro e conservazione	2013/14 restauro conservazione	x
Apparecchi idraulici	abluzione	grata	I.02.01.13.00							2013/14 applicazione	x
Attrezzature speciali	abluzione	fontana1	I.02.01.12.00	1683 restauro	1950 restauro e sostuzione rubinetti	1959 restauro e conservazione	1960 restauro e conservazione	1981 restauro e conservazione	1982 restauro e conservazione	2013/14 restauro conservazione	x
Apparecchi idraulici	abluzione	fontana2	I.02.01.12.00	1683 restauro	1950 restauro	1960 restauro e conservazione	1960 restauro e conservazione	1981 restauro e conservazione	1982 restauro e conservazione	2013/14 restauro conservazione	x
Arredi	abluzione	sgabello	I.02.01.13.00	1683 restauro	1950 sostituzione	1961 restauro e conservazione	1960 restauro e conservazione	1981 restauro e conservazione	1982 restauro e conservazione	2013/14 restauro conservazione	x
Pilastri	abluzione	base_colonna	I.02.01.08.01	1683 restauro	1950 restauro	1962 restauro e conservazione	1960 restauro e conservazione	1981 restauro e conservazione	1982 restauro e conservazione	2013/14 restauro conservazione	x
Pilastri	abluzione	fusto_colonna	I.02.01.08.02	1683 restauro	1950 restauro	1963 restauro e conservazione	1960 restauro e conservazione	1981 restauro e conservazione	1982 restauro e conservazione	2013/14 restauro conservazione	x
Pilastri	abluzione	capitello_colonna	I.02.01.08.03	1683 restauro	1950 sostituzione	1964 restauro e conservazione	1960 restauro e conservazione	1981 restauro e conservazione	1982 restauro e conservazione	2013/14 restauro conservazione	x
Attrezzature speciali	abluzione	architreve	I.02.01.09.00	1683 restauro	1950 sostituzione	1965 restauro e conservazione	1960 restauro e conservazione	1981 restauro e conservazione	1982 restauro e conservazione	2013/14 restauro conservazione	x
Attrezzature speciali	abluzione	cornice	I.02.01.02.00	1683 restauro	1950 sostituzione	1966 restauro e conservazione	1960 restauro e conservazione	1981 restauro e conservazione	1982 restauro e conservazione	2013/14 restauro conservazione	x
Attrezzature speciali	abluzione	cupola	I.02.01.03.00	1683 restauro	1950 sostituzione	1967 restauro e conservazione	1960 restauro e conservazione	1981 restauro e conservazione	1982 restauro e conservazione	2013/14 restauro conservazione	x

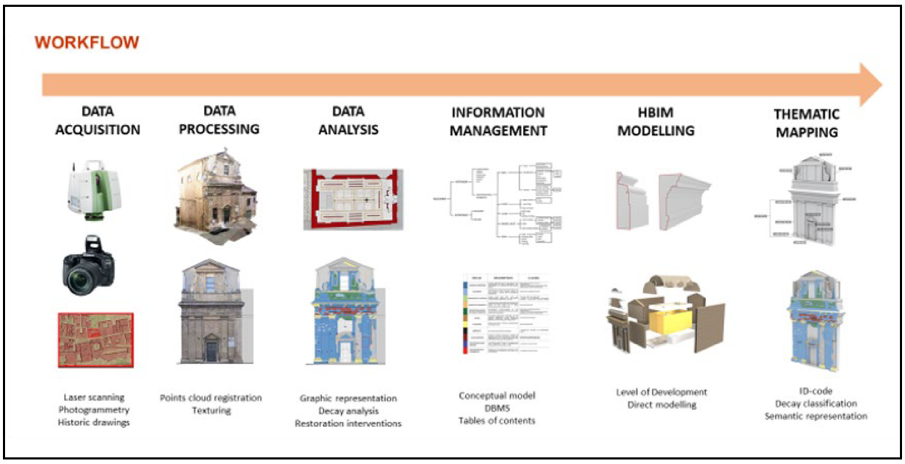
ID-code

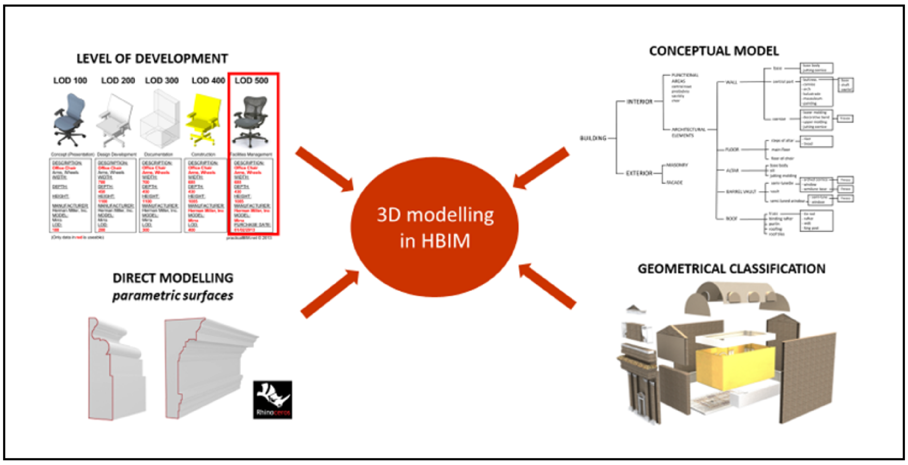


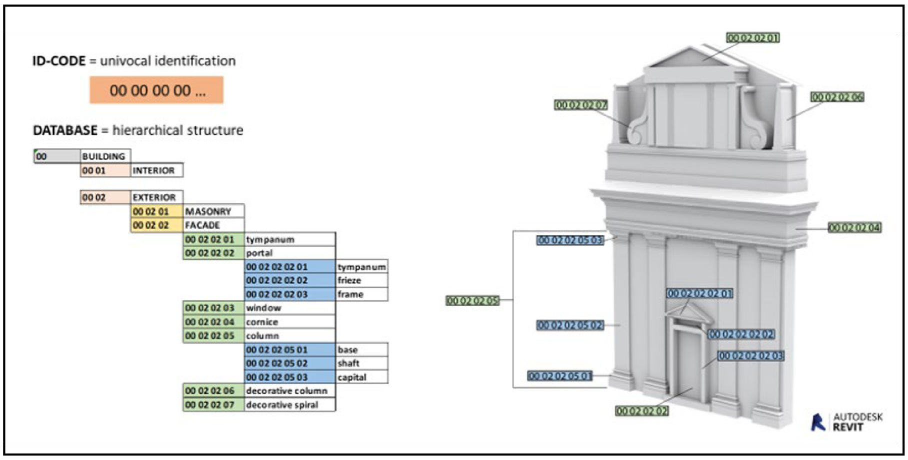
MODELLING IN HBIM TO DOCUMENT MATERIALS DECAY BY A THEMATIC MAPPING TO MANAGE THE CULTURAL HERITAGE: THE CASE OF" CHIESA DELLA PIETÀ" IN FERMO

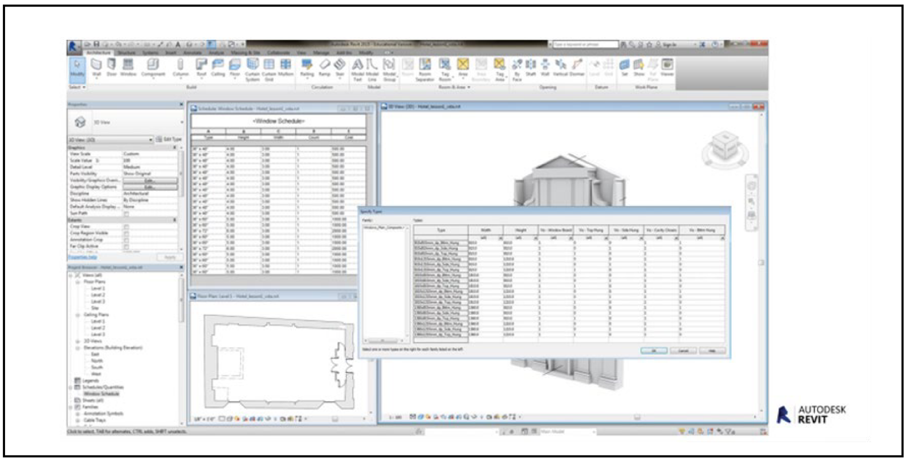
Malinverni, E. S., Mariano, F., Di Stefano, F., Petetta, L., & Onori, F. (2019). MODELLING IN HBIM TO DOCUMENT MATERIALS DECAY BY A THEMATIC MAPPING TO MANAGE THE CULTURAL HERITAGE: THE CASE OF" CHIESA DELLA PIETÀ" IN FERMO. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*. https://doi.org/10.5194/isprs-archives-XLII-2-W11-777-2019

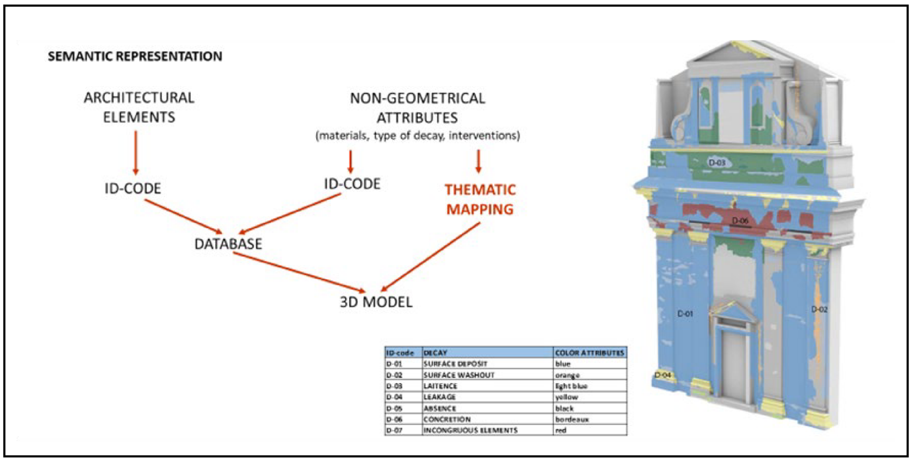
Abstract:
This research starts with the **photogrammetric survey** to document and analyse the existing condition of the church. The data acquisition provides many scans following a network schema and the photographic survey allows to create orthoimages to make more realistic the **3D representation**. Once acquired the geometric and material survey, a series of investigations have been carried out to assess the surface degradation and the material **decay** of the external façades and internal environments. To take under control the decay and to propose a restoration step, we have arranged the 3D model in **HBIM** software with different LOD, according to the BIM Forum Level of Development Specification (2016), suitable to develop a well structured information system. Before the 3D modelling phase, a decomposition of the building is useful to implement a semantic classification of the architectural elements. Basing on a hierarchy of classes and subclasses, the dedicated database organizes the building components assigning an ID-code to the features, putting in evidence materials decay by a **thematic mapping**.




LEVEL OF DEVELOPMENT
LOD 100
LOD 200
LOD 300
LOD 400
LOD 500
CONCEPTUAL MODEL
3D modelling in HBIM
DIRECT MODELLING
parametric surfaces
GEOMETRICAL CLASSIFICATION


ID-CODE = univocal identification
00 00 00 00 ...
DATABASE = hierarchical structure
00 BUILDING
00 01 INTERIOR
00 02 EXTERIOR
00 02 01 MASONRY
00 02 02 FACADE
00 02 02 01 tympanum
00 02 02 02 portal
00 02 02 02 01 tympanum
00 02 02 02 02 frieze
00 02 02 02 03 frame
00 02 02 03 window
00 02 02 04 cornice
00 02 02 05 column
00 02 02 05 01 base
00 02 02 05 02 shaft
00 02 02 05 03 capital
00 02 02 06 decorative column
00 02 02 07 decorative spiral
00 02 02 01
00 02 02 07
00 02 02 06
00 02 02 04
00 02 02 05 03
00 02 02 05
00 02 02 02 01
00 02 02 05 02
00 02 02 02 02
00 02 02 02 03
00 02 02 05 01
00 02 02 02
AUTODESK
REVIT


AUTODESK
REVIT

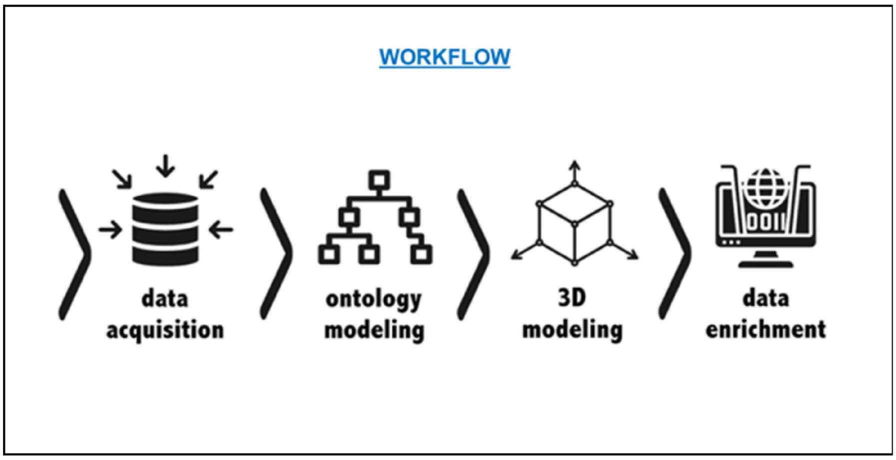


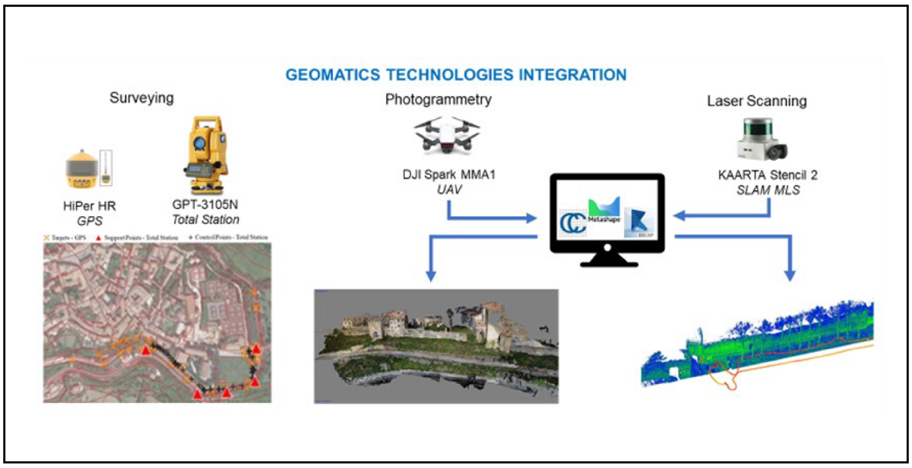
ID-code	DECAY	COLOR ATTRIBUTES
D-01	SURFACE DEPOSIT	blue
D-02	SURFACE WASHOUT	orange
D-03	LAITENCE	light blue
D-04	LEAKAGE	yellow
D-05	ABSENCE	black
D-06	CONCRETION	bordeaux
D-07	INCONGRUOUS ELEMENTS	red

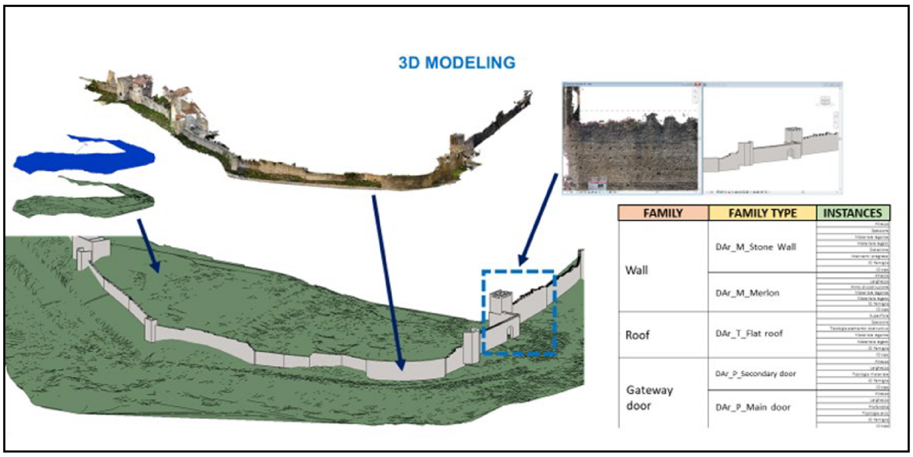
KNOWLEDGE MODELING FOR HERITAGE CONSERVATION PROCESS: FROM SURVEY TO HBIM IMPLEMENTATION

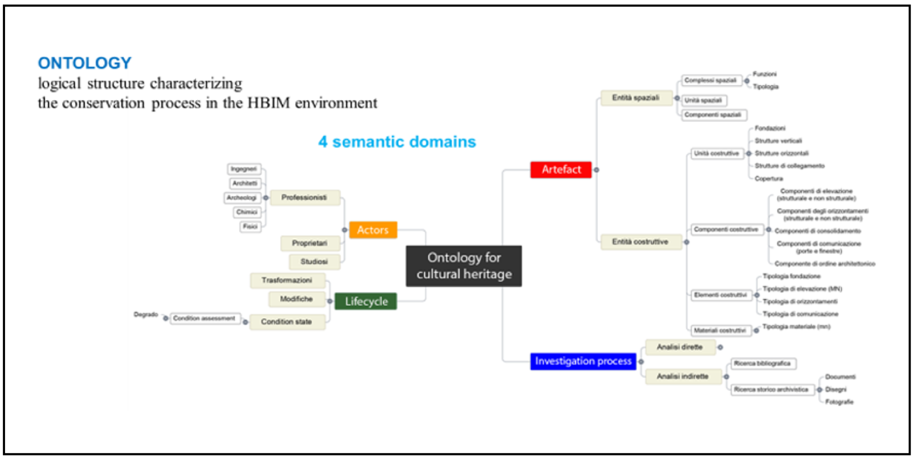
Di Stefano, F., Gorreja, A., Malinverni, E. S., & Mariotti, C. (2020). Knowledge Modeling for Heritage Conservation Process: from Survey to Hbim Implementation. The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 44, 19-26. https://doi.org/10.5194/isprs-archives-XLIV-4-W1-2020-19-2020

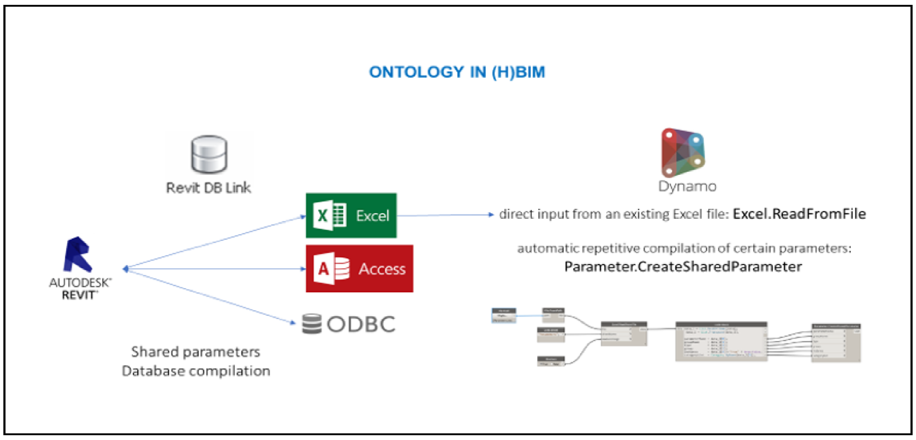
Abstract:
This project aims to develop a strategy for **architectural knowledge modeling** in order to actively support the **built heritage conservation** process by fostering collaboration among stakeholders and interoperability between datasets. The integration of two modeling systems, one **ontology-based** and one in **BIM environment**, seems to be the right way to meet this objective: the former is rather exhaustive to represent the semantic contents of conservation activities, especially non-geometrical data, the latter is absolutely suitable to represent the logic of the construction, above all geometrical-constructive aspects typical of any architectural organism. Thus, this study proposes a side-by-side approach to synchronize these different ways of representing reality by managing the complexity of cultural heritage on the one hand and of technology tools, such as information systems, on the other. The proposed methodology was tested on the city walls of San Ginesio (Macerata, Italy) and included different steps considering the in-use technologies (notably geomatics and information technologies) as key enablers to acquire, hierarchically order, model and enrich the knowledge of that heritage site. The result is a knowledge-led strategy moving from survey to **HBIM implementation**, as a way to enhance representation and management in architectural heritage processes.

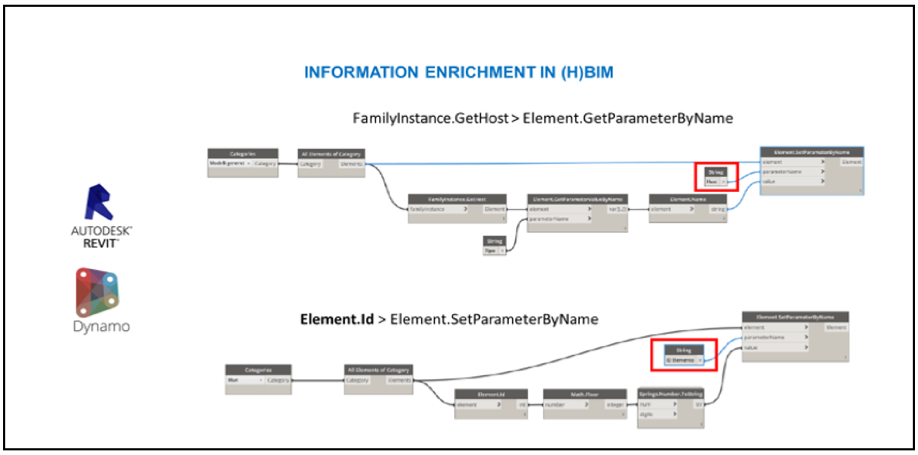


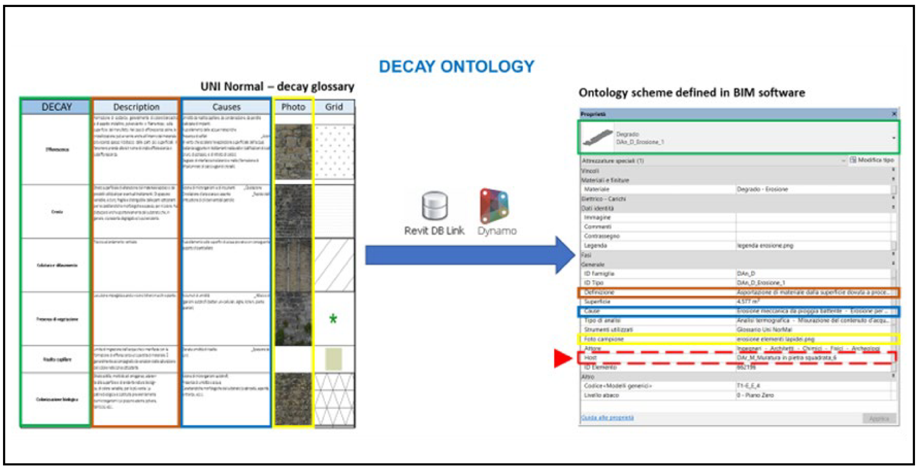

GEOMATICS TECHNOLOGIES INTEGRATION
Surveying
HiPer HR
GPS
GPT-3105N
Total Station
Photogrammetry
DJI Spark MMA1
UAV
Laser Scanning
KAARTA Stencil 2
SLAM MLS
Metashape

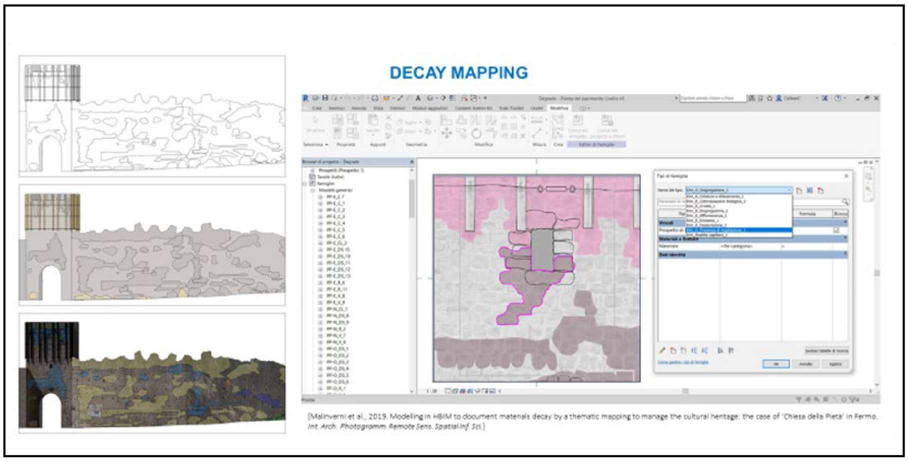

3D MODELING
FAMILY
FAMILY TYPE
INSTANCES
Wall
DAr_M_Stone Wall
DAr_M_Merlon
Roof
DAr_T_Flat roof
Gateway door
DAr_P_Secondary door
DAr_P_Main door

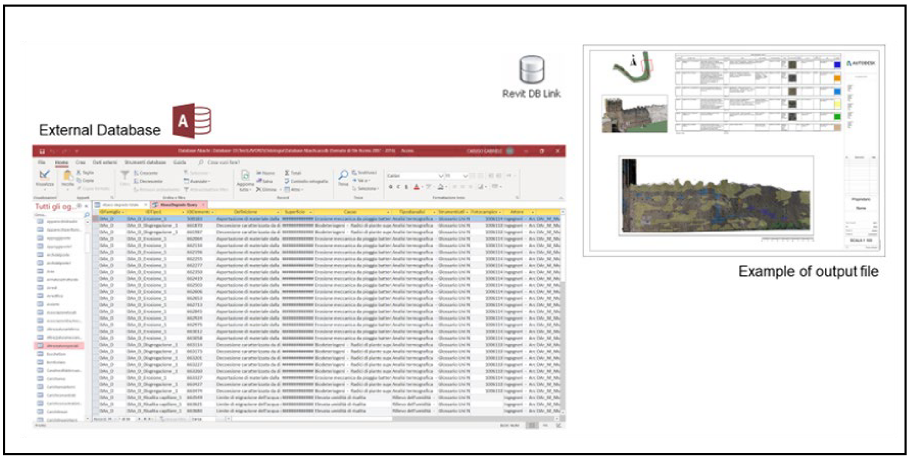

ONTOLOGY
logical structure characterizing
the conservation process in the HBIM environment
4 semantic domains
Ontology for cultural heritage
Actors
Professionisti
Ingegneri
Architetti
Archeologi
Chimici
Fisici
Proprietari
Studiosi
Lifecycle
Trasformazioni
Modifiche
Condition state
Condition assessment
Degrado
Artefact
Entità spaziali
Complessi spaziali
Funzioni
Tipologia
Unità spaziali
Componenti spaziali
Entità costruttive
Unità costruttive
Fondazioni
Strutture verticali
Strutture orizzontali
Strutture di collegamento
Copertura
Componenti costruttive
Componenti di elevazione (strutturale e non strutturale)
Componenti degli orizzontamenti (strutturale e non strutturale)
Componenti di consolidamento
Componenti di comunicazione (porte e finestre)
Componente di ordine architettonico
Elementi costruttivi
Tipologia fondazione
Tipologia di elevazione (MN)
Tipologia di orizzontamenti
Tipologia di comunicazione
Materiali costruttivi
Tipologia materiale (mn)
Investigation process
Analisi dirette
Analisi indirette
Ricerca bibliografica
Ricerca storico archivistica
Documenti
Disegni
Fotografie


ONTOLOGY IN (H)BIM
Revit DB Link
Dynamo
AUTODESK REVIT
Excel
Access
ODBC
direct input from an existing Excel file: Excel.ReadFromFile
automatic repetitive compilation of certain parameters:
Parameter.CreateSharedParameter
Shared parameters
Database compilation


INFORMATION ENRICHMENT IN (H)BIM
FamilyInstance.GetHost > Element.GetParameterByName
AUTODESK REVIT
Dynamo
Element.Id > Element.SetParameterByName


DECAY ONTOLOGY
UNI Normal – decay glossary
DECAY
Description
Causes
Photo
Grid
Revit DB Link
Dynamo
Ontology scheme defined in BIM software


DECAY MAPPING
(Malinverni et al., 2019. Modelling in HBIM to document materials decay by a thematic mapping to manage the cultural heritage: the case of 'Chiesa della Pietà' in Fermo. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.)


Revit DB Link
External Database
Example of output file