Novel digital paradigms to support the Architectural Heritage knowledge process

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Doctor of Philosophy in Environmental and Building Risk and Development

Coordinator: Prof. Michele Mossa

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DICATECh
Department of Civil, Environmental, Building Engineering and Chemistry

Novel digital paradigms to support the Architectural Heritage knowledge process

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POLITECNICO DI BARI

D.R.R.S

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Dottorato di Ricerca in Rischio e Sviluppo ambientale, territoriale ed edilizio

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XXXIV CICLO
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DICATECh
Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e di Chimica

Nuovi paradigmi digitali a supporto del processo di conoscenza del Patrimonio Architettonico

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LIBERATORIA PER L'ARCHIVIAZIONE DELLA TESI DI DOTTORATO

Al Magnifico Rettore
del Politecnico di Bari

Il/la sottoscritto/a MUSICCO ANTONELLA nato/a a TRANI il 11/08/1992
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iscritto al 3° anno di Corso di Dottorato di Ricerca in RISCHIO E SVILUPPO AMBIENTALE E TERRITORIALE ciclo 34 ed essendo stato ammesso a sostenere l'esame finale con la prevista discussione della tesi dal titolo: "Novel digital paradigms to support the Architectural Heritage knowledge process"

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SSD: ICAR/17– DRAWING ICAR/10 –TECHNICAL ARCHITECTURE

Final Dissertation

Novel digital paradigms to support the Architectural Heritage knowledge process

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EXTENDED ABSTRACT *(eng)*

In the field of the documentation process for supporting conservation activities of Architectural Heritage (AH), it is necessary to reach a deep and complete knowledge evaluating the history, physical configuration, condition assessment, and cultural conditions in terms of social, political, and economic aspects, in relation to the building and the environment in which it is located, in order to determine precise protective measures.

However, today, the ambiguity of workflows in the knowledge process, the fragmentation of previous documentation, located in paper and digital archives, and the use of inadequate tools make the conservation process very critical. The risk consists of errors in the assessment of intervention strategies with repercussions on the economic and social system producing the loss of value to the heritage asset.

In accordance with what is stated in the "London Charter" (2009) - which establishes general methodological principles for digital visualization applications in the field of research and communication of AH - undoubtedly the technological contribution can change the way of perceiving the representation of the historic manufacts. Indeed, the introduction of huge digital archives, that can store data deriving from the different types of information, may enrich the 3D models better defining the historical heritage itself.

The development of Computer Vision and digital modelling techniques has enabled increasingly exploiting ICT (Information and Communication Technologies) technologies, and specifically, information systems in the Heritage field. Virtual

repositories allow more effective control over the documentation process permitting the storage of different and heterogeneous data produced on built heritage.
Specifically, Building Information Modeling (BIM) is defined as a complete digital reproduction of an architecture that contains the attributes of digital parametric models. Its introduction into the world of representation has radically changed the meaning of three-dimensional models, proposing them as systems information for architecture. Considering the panorama of AH refers to Historic Building Information Modeling (HBIM) which is a system of representation of built architecture composed of libraries of objects semantically structured and parameterized. HBIM creates new possibilities for sharing different information within a single digital environment and is a way to increase portability and provide data to a wider community of users.
The BIM methodology can be a bridge between archival documentation, architectural survey and digital model, proving to be an effective tool as a semantic data archive, consisting not only of geometrically correct elements but also of alphanumeric and digital attributes (texts, multimedia files, URL links, etc.). The HBIM models are understood as data hubs that in the documentary field, can represent the historical artefacts taking into account the past and the present as a result of constructive transformations, enlargements and changes of use in a wide time span.
HBIM models can be constructed from three-dimensional data derived from digital surveying techniques, such as laser scanner and photogrammetry. The process, called reverse engineering, no longer has the goal of translating geometric survey into two-dimensional plans, elevations and sections, but rather is a starting point for three-dimensional modelling, striving to move from solid to parametric objects, described geometrically and semantically.
Furthermore, from literature emerges that, nowadays, there is no structured and shared digital framework that takes into account the knowledge gathered on the assessment of the state of the buildings, the morpho-metric survey, the report of conservation activities as a whole integrated system. One of the difficulties consists in the use of standardized parametric objects which not fulfil the complexity and

uniqueness of architectural elements (for example vaults, irregular masonry walls, etc.).
The following PhD thesis proposes a methodological workflow that, starting from the digital survey, addresses the issue of modelling and semantic enrichment of HBIM models focusing on the pre-diagnostic analysis of the state of the places, reaching the process of managing data useful for the activities of conservation of historical heritage.
The proposed research connects the aims of two disciplinary areas, architectural survey and representation, and refurbishment by implementing consolidated methodologies with the objective of defining an optimal strategy modelling the fourth dimension (time) of AH in the HBIM environment, to avoid risks of assessment of the state of the places and a coherent future conservation activity. The goal is to achieve complete and flexible management of the large amount of multidisciplinary information processed during the activities of knowledge, survey, analysis and planning of conservation activities.
Therefore, the main objectives of this thesis consist, firstly, in the validation of a consolidated process of representation in BIM that allows to overcome the limitations due to the standardization of parametric objects respecting the specificities of the instances of the historic asset, secondly, in the implementation of semantic segmentation methods through standard (ragion-based, model-based, etc.) and Machine Learning (k-means clustering, random forest, etc.) algorithms to automatically structure and classify 2D and 3D output (orthophoto, UV Map, point cloud, textured mesh, etc.) of digital survey in order to quantify architectural components and the different states of alteration of surface materials essential for prediagnostic activities, and to reduce the time and manual steps of the Scan to BIM process; finally in the integration and the improvement of the semantic level of BIM models by extending the field of representation to several levels of detail, and including the knowledge needed to understand the characteristics of the built heritage that cannot be directly included in its physical components (i.e. history, construction phases, survey data, etc.), through the develop of methods for integrating the

information contained in BIM models through Database Management Systems and 4D simulation.
The validation of the proposed methodology will be carried out on case studies chosen within the Italian Architectural Heritage and starts from the survey and ends with the development of three-dimensional models for the management of historical architecture spendable in areas of different application: accessibility and enhancement, archival and documentary research, conservation and artificial intelligence.

key words: 4D-HBIM (Historic Building Information Modelling), Scan-to-BIM, Machine Learning, Point cloud segmentation, Information management

EXTENDED ABSTRACT *(ita)*

Nell’ ambito del processo di documentazione a supporto delle attività di conservazione dei Beni Architettonici, è necessario raggiungere una conoscenza dettagliata e completa valutandone la storia, la composizione architettonica, lo stato dei luoghi, e le condizioni culturali in termini di aspetti sociali, politici ed economici, in relazione all'edificio e all'ambiente in cui sorge, al fine di determinare misure di tutela coerenti.

Tuttavia, oggi, l'ambiguità dei flussi di lavoro nel processo di conoscenza, la frammentazione della documentazione pregressa, situata in archivi cartacei e digitali e l'uso di strumenti inadeguati rendono il processo di conservazione molto critico. Il rischio consiste in errori nella valutazione delle strategie di intervento con ripercussioni sul sistema economico e sociale che producono la perdita di valore del patrimonio costrutito.

In accordo con quanto stabilito nella "Carta di Londra" (2009) - che individua i principi metodologici generali per le applicazioni di visualizzazione digitale nel campo della ricerca e della comunicazione dei beni culturali - senza dubbio il contributo tecnologico può cambiare il modo di considerare la rappresentazione dei manufatti storici. In effetti, l'introduzione delgi archivi digitali, in grado di memorizzare i dati derivanti dai diversi tipi di informazioni, può arricchire i modelli 3D definendo meglio il patrimonio storico stesso. Lo sviluppo delle tecniche di Computer Vision e di modellazione digitale ha permesso di sfruttare sempre più le tecnologie ICT

(Information and Communication Technologies) e, nello specifico, i sistemi informativi nel settore dell'architettura storica. I repository virtuali consentono un controllo più efficace sul processo di documentazione che consente l'archiviazione di dati diversi ed eterogenei.

Nello specifico, Building Information Modeling (BIM) è definito come una riproduzione digitale completa di un'architettura che contiene gli attributi dei modelli parametrici digitali. La sua introduzione nel mondo della rappresentazione ha cambiato radicalmente il significato dei modelli tridimensionali, proponendoli come sistemi informativi. Considerando l'ambito dei beni culturali architettonici l'approccio è denominato Historic Building Information Modeling (HBIM) con cui è inteso è un sistema di rappresentazione composto da librerie di oggetti semanticamente strutturati e parametrizzati. L'HBIM crea nuove possibilità per la condivisione di informazioni diverse all'interno di un unico ambiente digitale ed è un strumento per fornire dati e aumentarne la portabilità ad una più ampia tipologia di utenti. La metodologia BIM può essere un ponte tra documentazione archivistica, rilievo architettonico e modello digitale, dimostrandosi uno strumento efficace come archivio di dati semantici, costituito non solo da elementi geometricamente corretti, ma anche da attributi alfanumerici e digitali (testi, file mutimediali, collegamenti URL, etc).

I modelli HBIM, intesi come *data hub* nel campo documentario, possono rappresentare i manufatti storici tenendo conto del passato e del presente come risultato di trasformazioni costruttive, ampliamenti e cambi di destinazione d'uso in un ampio arco temporale. Inoltre, possono essere costruiti a partire da dati tridimensionali ricavati da tecniche di rilievo digitali come il laser scanner e la fotogrammetria. Il processo, chiamato *reverse engineering*, non ha più l'obiettivo di tradurre il rilievo geometrico in piante, prospetti e sezioni bidimensionali, ma piuttosto è un punto di partenza per la modellazione tridimensionale, aspirando a passare dalla modellazione solida a oggetti parametrici, descritti geometricamente e semanticamente.

Dalla letteratura emerge che, al giorno d'oggi, non esiste un processo digitale strutturato e condiviso che tenga conto delle conoscenze raccolte sulla valutazione dello stato degli edifici, il rilievo morfo-metrico, e la pianificazione delle attività di conservazione come sistema integrato. Una delle difficoltà consiste nell'uso di oggetti parametrici standardizzati per la modellazione che non soddisfano la complessità e l'unicità degli elementi architettonici (ad esempio volte, pareti in muratura irregolare, ecc.).

Nella seguente tesi di dottorato propone un flusso di lavoro metodologico che, partendo dal rilievo digitale, affronta il tema della modellazione e dell'arricchimento semantico dei modelli HBIM concentrandosi sull'analisi pre-diagnostica dello stato dei luoghi, raggiungendo il processo gestione dei dati utili alle attività di conservazione del patrimonio storico.

La ricerca proposta collega gli obiettivi di due aree disciplinari, il rilievo e la rappresentazione architettonica e il recupero, implementando metodologie consolidate con l'obiettivo di definire una strategia ottimale modellazione della quarta dimensione (tempo) in ambiente HBIM, per evitare rischi di valutazione dello stato dei luoghi. L'obiettivo è quello di ottenere una gestione completa e flessibile della grande quantità di informazioni multidisciplinari elaborate durante le attività di conoscenza, rilievo, analisi e pianificazione delle attività di conservazione.

Pertanto, gli obiettivi principali di questa tesi consistono: in primo luogo, nella validazione di un processo consolidato di rappresentazione in BIM che consenta di superare le limitazioni dovute alla standardizzazione di oggetti parametrici rispettando le specificità delle istanze del patrimonio storico, in secondo luogo, nell'implementazione di metodi di segmentazione semantica attraverso algoritmi tradizionali (region-based, model-based, etc.) e di Machine Learning (k-means clustering, random forest, etc.) per strutturare e classificare automaticamente i prodotti 2D e 3D (ortofoto, mappe UV, nuvole di punti, mesh texturizzate, ecc.) del rilievo digitale al fine di quantificare i componenti architettonici e i diversi stati di alterazione dei materiali superficiali essenziali per le attività pre-diagnostiche, e ridurre i tempi e le fasi manuali del processo Scan-to-BIM; infine nell'integrazione e nel miglioramento del livello semantico dei modelli BIM estendendo il campo di rappresentazione a più livelli di dettaglio e includendo le conoscenze necessarie per

comprendere le caratteristiche del patrimonio costruito che non possono essere direttamente incluse nelle sue componenti fisiche (es. storia, fasi di costruzione, dati di indagine, ecc.), attraverso lo sviluppo di metodi per l'integrazione delle informazioni contenute nei modelli BIM attraverso sistemi di gestione di database e simulazione 4D.
La validazione della metodologia proposta sarà effettuata su casi di studio scelti all'interno del patrimonio architettonico italiano e partirà dal rilievo digitale e si concluderà con lo sviluppo di modelli tridimensionali per la gestione dell'architettura storica spendibili in aree di diversa applicazione: accessibilità e valorizzazione, ricerca archivistica e documentaria, conservazione e intelligenza artificiale.

key words: 4D-HBIM (Historic Building Information Modelling), Scan-to-BIM, Machine Learning, Point cloud segmentation, Information management

INDEX

INTRODUCTION

The digital documentation of Architectural Heritage has assumed a fundamental role for its preservation, enhancement, and protection from institutional neglect or physical-material obsolescence. Complete documentation of the architectural heritage requires a thorough knowledge of its history, physical configuration, condition assessment, and social, political, economic, and cultural conditions, also related to the external environment.

For a complete reconstruction of the condition assessment is necessary a contextual combination of archival and technical information for the rapid recognition of the architectural elements, the transformations, the stratification of the construction phases. In fact, in the case of interventions on historic buildings, due to the fragmentation of the data, the greatest criticalities are found in the evaluation of the existing conditions and in the diagnosis.

Three-dimensional informative models have become an essential tool for investigation and research in the field of Architectural Heritage, indeed, their applications have multiplied enormously over the years. Hence the need to ensure the quality and reliability of 3D models. BIM representations concerning the historic heritage buildings remain poor in terms of semantics and a large area of knowledge, related to relevant characteristics of the artefact, such as its history or its modifications over time, is not adequately represented.

Furthermore, an information model should provide details on the people, times, and places involved, but also on the digital instrumentation, environmental conditions, software, and parameters used at all stages of the documentation process. This requires the use of appropriate procedures to ensure the formal description of all aspects of digitization, from the design and definition of general and specific objectives and perspectives of use up to the publication and dissemination of models. The dissemination of informatics tools could help to build an integrated approach to enable the continuous management of the knowledge system.

In recent years, the use of contactless survey technologies (laser scanner and photogrammetry) represents a common procedure for the investigation of the existing substitution and/or support of the traditional practices because they ensure three-dimensional reconstructions with elevated levels of accuracy and rapidity of acquisition of the data.

These methods result in the use of reverse engineering which is configured as a process of returning the relevant data through the deconstruction of a real object, even in the case of artefacts of considerable complexity, and results in the creation of high-resolution three-dimensional models in the form of point clouds and textured polygonal meshes.

In this context, the current state of the art shows how the techniques of the digital survey allow the acquisition of a large amount of data in such a small interval of time to make it expensive to control them in managerial terms, computational and organizational.

The representation of cultural heritage through 3D data allows to perform different tasks: morphological analysis, degradation mapping or enrichment, and computerization of data are, in fact, just a few examples of possible ways to take advantage of such a rich virtual representation of information.

Therefore, it is important to be able to extract semantic information by developing reliable methods of segmentation and classification, which can give a connotation to the objects represented.

In general, segmentation is understood as the process of grouping data into several homogeneous regions with features in common (geometric, radiometric, etc.) while classification is the passage that attributes these regions a class through a specific name.

Given the large size of the collected data, the complexity and variety of point clouds, which differ, depending on the object detected, by density, distribution of points, RGB values, etc., the use of automatic algorithms is preferable to manual annotation procedures that are long and sometimes inaccurate.

In this context, the state of the art has shown that automatic classification procedures applied above all to the geo-spatial field have been obtained through the development of Artificial Intelligence, to date little implemented in the architectural field.

As anticipated, a further problem, that plagues current documentation methods, is their representation and management. An efficient information management strategy should consider three main concepts: classification, hierarchical relationship organization, semantic enrichment, and process transparency. In this context, the use of digital information systems that exploit three-dimensional representations for the documentation and analysis of the architectural heritage is constantly increasing. In recent years, Building Information Modelling (BIM) is proposed as a new paradigm for the three-dimensional representation and management of the entire life cycle of buildings as it allows a multidisciplinary workflow optimizing the consumption of resources, costs and time. The use of the BIM approach in relation to historic buildings was referred to as HBIM (Historic Building Information Modelling). In the BIM approach, the three-dimensional model is implemented for the purposes of data and information representation and storage, using flexible and customizable tools. Modelling is not limited to the geometric restitution of the factual state, but also includes the computerization of objects through parameters structured in relational databases. The data acquired during the survey, archival research and diagnostic investigation activities can be inserted into the model, in the form of parameters that can be consulted and updated.

Currently, specific procedures of the HBIM approach that help professionals from the survey phase to geometric modelling to computerization and management are not yet defined. Indeed, the use of BIM in historic buildings has highlighted the need for transparent processes that can ensure traceability of the origin of data in order to adequately document digital resources, and repeatability of the operations in order to understand the degree of reliability of the results, and the interoperability of the generated metadata. Transparency of documentation and interpretation processes is necessary for a better understanding of the knowledge embedded in 3D models and their visualizations.

In light of the above, the general objective of the thesis is the validation of an interdisciplinary approach to the creation of 3D models used in Architectural Heritage, maximizing the relationship between survey, 3D modelling, and pre- diagnostics analysis. The aim is to reuse information acquired directly through relevant activities or extracted from extensive research and reuse on several fronts of the multiplicity of data available for improving accessibility, the use, and enhancement of the intrinsic historical and documentary value of cultural heritage to provide a comprehensive and comprehensive knowledge framework.

After an introduction on the topics covered in the thesis project (Section 1), a critical review of the literature about the methodologies and tools useful to integrate and implement the process of building HBIM models was carried out (Section 2). Methodologies related to techniques of digital survey, 3D modelling, 3D segmentation, and information enrichment and management have been deepened to highlight the gaps and introduce new digital paradigms in support of the activities of documentation and preservation of historical buildings developed during the PhD (Section 3).

The methodologies introduced, divided in three sub-section, are configured as part of a unique workflow. Specifically in Sub-section 3.1 has been dedicated to the implementation of Scan to BIM process with a focus on the Quality Assessment and the integration of knowledge in BIM models; In Sub-section 3.2 methodology works on colourimentrical and geometrical segmentation of 3D data deriving from 3D survey; In Sub-section 3.3 4D simulation and information management using Relational Database Management System have been tested. The discussion and results are described at the end of each sub-section in order to highlight lines of further investigations within an extensive framework.

With the prospect of testing the feasibility of the proposed approaches, several selected case studies on Italian built heritage have been chosen. The identified historical buildings are characterized by a masonry construction apparatus, different types of building and different state of conservation and use.

1. INNOVATIVE APPROACHES IN ARCHITECTURAL HERITAGE CONSERVATION PROCESS

1.1. THE ROLE OF DOCUMENTATION

The Architectural Heritage (AH) documentation is a fundamental process in conservation and sustainable management. The activities of valorization of the historical-architectural assets, in order to favour the protection of the territorial identity elements, constitute a complex field which needs multidisciplinary insights and the use of flexible instruments to updates, facilitating the development of projects aimed at monitoring, sustainable recovery or social fruition.

In 2007, Letellier had defined Heritage documentation as "*a continuous process enabling the monitoring, maintenance and understanding needed for conservation by the supply of appropriate and timely information. Documentation is both the product and action of meeting the information needs of heritage management. It makes available a range of tangible and intangible resources, such as metric, narrative, thematic and societal records of cultural heritage*"

So, documentation process is the first and most important step before starting conservation projects and works, configuring as a complex set of stages which include data acquisition, interpretation, and representation of existing condition asset.

In accordance with the contents of Convention for the Protection of the World Cultural and Natural Heritage from UNESCO in 1972, documentation is necessary for transmitting Cultural Heritage (CH) to the next generation, obtaining correct data for future plans, determining the problems of historical building, site or monument, and acquiring of knowledge about the history and constructive evolution of the building (Yilmaz et al., 2007).

ICOMOS (International Council for Monuments and Sites), CIPA (International Committee for Architectural Photogrammetry), ISPRS (International Society for Photogrammetry & Remote Sensing), ICOM (International Council for Museums), ICCROM (International Centre for the Conservation and Restoration of Monuments) and UIA (International Union of Architects) are just a few of the organizations involved in conservation task of CH.

So, the analysis of a historical artefact starts from the mapping of archival sources and necessarily takes into account the phase of survey and representation. The architectural survey is understood as an accurate methodology of analysis, observation, and interpretation which underlies a process of selective analytical abstraction and synthesis (Pellegri, 2015). The aim is the choice of the sign and the hierarchical order of the elements to be represented, according to the place and purpose of the representation. Therefore, the drawing that, not only is intended as a sign of graphic restitution, but also as a testimony of lost architecture and especially the culture of the period in which it is developed and read, a form of representation and testimony of current and historical entities (Brusaporci et al., 2012).

In addition to the survey and representation, the description and analysis of AH is carried out using a wide and diverse number of resources such as documentary sources (text, graphics, voice) and analytical data (from sample analysis, data from various sensors, cartographic data from different radiation images, etc.). The generation and the data process are conventional according to the domain of competence (architecture, mechanics, computer science, etc.) and all include the entire historical, archaeological and constructive information necessary to understand the structure of the heritage and its evolution over time. Despite their complementarity, analytical data sources are often separated from each other (Messaoudi et al., 2018).

In the field of documentation for conservation processes, it is necessary to reach a deep and complete knowledge of cultural property evaluating the current condition assessment, the structural performance, and so on, in order to determine problems in the building's system, decays in materials (Remondino et al., 2010)(Valero et al., 2018).

1.2. THE RISKS OF CONSERVATION PROCESS

Types of risks to Cultural Heritage vary from sudden and catastrophic events (such as major earthquakes, floods, fires, and armed conflict) to gradual and cumulative processes (such as chemical, physical, or biological degradation). Sometimes the risk does not involve any type of material damage to the heritage asset, but rather the loss of information about it, or the inability to access heritage items.

Furthermore, today, the ambiguity of workflows in documentation process, the fragmentation of previous documentation, located in paper and digital archives, the use of inadequate tools makes very critical. The risk consists of errors in the assessment of intervention strategies with repercussions on the economic and social system producing the loss of value to the heritage asset.

The ICOMOS Charter (2003) - *Principles for the analysis, conservation and structural restoration of architectural heritage* - guides the knowledge phase establishing the objectives of surveys and diagnosis such as the complete understanding of the structural behaviour and the qualification of the building materials. In the charter are also illustrated the risks of an erroneous conservation activity generated on the basis of insufficient documentation such as the risks of a wrong conservation activity generated on the basis of incorrect documentation are illustrated such as the errors in the evaluation of the historic asset, design and/or procedural mistakes, low compatibility and durability of materials, a worst structural behaviour, the devaluation of the authenticity of the original asset, the condensation and mold growth risk after energy retrofitting, the higher energy consumption than predicted values, the underestimation of the risk for health and safety and so on.

In the last years, the concept of risk management was introduced as the process by which risk is measured or estimated and then strategies are developed to govern it (Angelosanti et al., 2022). In 2009 all general concepts related to risk management were formalized in the standard ISO 31000:2009 and then evolved giving light to the latest version published in May 2018.

In 2016, the ICCROM developed a guide to risk management where the main steps defined by the standard as well as concepts and tools have been applied to the sector of Cultural Heritage. In the guide rick management process has been divided in six stages (context, identify, analyse, evaluate, treat, monitor) and the ten 'agents' of deterioration and loss (Fig. 1), the six 'layers' of enclosure (region, site, building, room, fitting, support) and the three 'types' of risk occurrence have been identified (rare events, common events, cumulative processes).

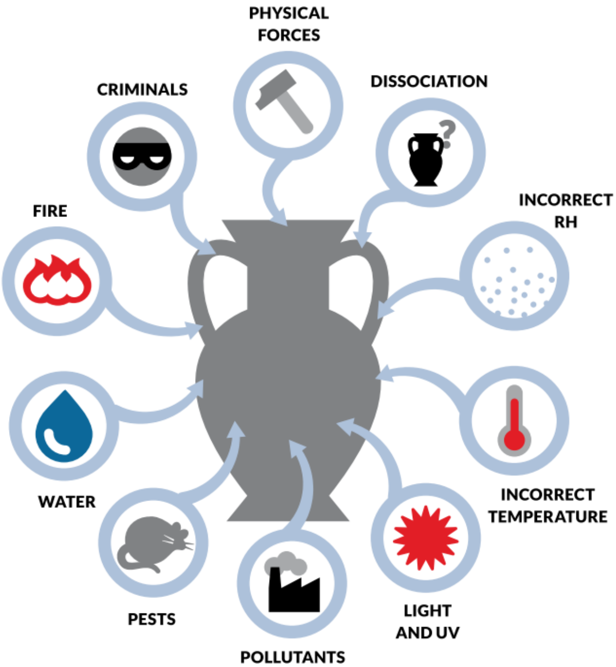


Fig. 1 Ten agents of deterioration and loss in heritage asset - Source (ICCROM, 2016)

In this context, the concept of documentation for conservation has produced many reflections on the use of digital tools and their intrinsic democratization of the information acquired, making more information accessible to a wide range of users (Vacca et al., 2018).

In accordance with what is stated in the "London Charter"[1] (2009) (Brusaporci & Trizio, 2014b) - which establishes general methodological principles for digital visualization applications in the field of research and communication of CH - undoubtedly the technological contribution can change the way of perceiving the representation of the past, especially from a quantitative point of view. Indeed, the introduction of huge digital archives, that store an exponential number of data and images deriving from the different types of information, may enrich the 3D models better defining the historical heritage itself.

1.3. BIM MODELS FROM 3D DATA

The development of Computer Vision[2] and digital modelling techniques has enabled increasingly exploiting ICT (Information and Communication Technologies) technologies, and in particular, information systems in the Heritage field. Virtual repositories allow more effective control over the documentation process permitting the storage of different and heterogeneous data produced on built heritage. The available information produced in the context of AH studies can be directly integrated in three-dimensional (3D) representation (Giovannini, 2017).

This allows several tasks to be achieved, including the mapping of materials (Malinverni et al., 2017), degradation states of buildings (Chiabrando et al., 2017) (Musicco et al., 2021), and frescoed or decorated surfaces (Mongelli et al., 2018)(Bolognesi & Fiorillo, 2019), morphological and historical analyses (Brumana et al., 2014)(De Luca, 2014) and constructive evolution (Rodríguez-Gonzálvez et al.,

[1] "The London Charter for the Computer-based Visualisation of Cultural Heritage was conceived, in 2006, as a means of ensuring the methodological rigour of computer-based visualization as a means of researching and communicating Cultural Heritage [...]. In 2006, Beacham, Denard and Niccolucci published a concise account of the origins and rationale of the London Charter, concentrating on the issue of intellectual transparency" from: http://www.londoncharter.org/introduction.html, consulted in dicember 2021.

[2] Computer Vision is a mathematical technique for recovering the three-dimensional shape and appearance of objects in imagery (Szeliski, 2010).

2017)(Mammoli et al., 2021) allowing multi- temporal and multi-layered management of the available information.
For the construction of virtual repositories, reality-based survey techniques, such as photogrammetry and laser scanning, enable the quick acquisition of reliable digital replicas in the form of point clouds (Di Giulio et al., 2017). Thus, once the digital replica of the existing architecture is created, the representation can be enriched with knowledge-related information.
In this regard, Historic/Heritage Building Information Modeling (HBIM)(Murphy et al., 2009) can be considered a powerful tool to gather contents useful to experts in the domain of historical-documentary knowledge. The BIM methodology may be a bridge between archive documentation, architectural survey, and the digital model, proving to be an effective tool as a semantically oriented data repository, consisting not only of geometry, but also of alphanumeric attributes (Parisi et al., 2019). The HBIM models, intended as a data hub, in the documentary field, represent the architectures taking into account the past and present as a result of changes, extensions, and different classifications of use over time(Bruno et al., 2019b).
Collect and organize hierarchically the information of physical transformation of the artefact, automate the processes of construction and graphicization of its evolutionary phases, and manage the heterogeneous data resulting from analysis become objectives to be achieved to enrich and renew the consolidated methodology of investigation of the AH (Bruno, 2017) (Yang et al., 2020).
The process of digitally capturing a physical space or site as laser scan data, which feeds into the initial creation, development and maintenance of a BIM model, is called Scan to BIM (Wang et al., 2019). However, point clouds are raw data that do not contain semantic information. Indeed, the reconstruction of enriched information models starting from 3D unstructured data derived from surveys is still a largely manual, time-consuming and error-prone process (Pocobelli et al., 2018a).
The application of Machine Learning (ML) techniques to semantically label 3D heritage data by identification of relevant geometric, radiometric and intensity features(Grilli & Remondino, 2019)(Fiorucci et al., 2020), and the use of the

annotated data to streamline the construction of Heritage-Building Information Modeling (H-BIM) systems(Croce et al., 2021b)(Moyano et al., 2021), where purely geometric information derived from surveying is associated with semantic descriptors on heritage documentation and management, can improve the current Scan to BIM workflow.

1.4. REFURBISHMENT ORIENTED HBIM SYSTEM

Currently, the management of data deriving from different domains is an emerging topic, indeed, there is an increasing demand for mixing and merging collections of datasets for their reuse in larger contexts.

Building Information Modelling (BIM) methodology is a possible platform for the representation and the sharing of information for historical architecture. The 3D model is designed as an information hub in which it is possible to connect different databases (Sub-Sec.2.4.1) to the geometric representation through DataBase Management System (DBMS)(Bruno, 2017)(Bruno et al., 2019a).

Moreover, in the field of AH, it may be possible to carry out applications on semantic interpretation of architectural geometries (Moyano et al., 2021),automatic generation of 3D models (López et al., 2018) historical and morphological evolution (Rodríguez-González et al., 2017), structural (Crespi et al., 2015)(Abbate et al., 2020)(Currà et al., 2021) and retrofitting analysis (Khodeir, 2016)(Shi et al., 2016), mapping of degradation (Bruno et al., 2020)(Croce et al., 2021a), semantic information enrichment (Giovannini et al., 2019)(Simeone & Cursi, 2017), diagnostic purposes (De Fino et al., 2017), and constant updating of data (Afsari et al., 2017).

Hence, in the refurbishment building process, the model could provide details on people, times and places, equipment, environmental conditions, software, etc. allowing a collaborative digital approach which from the survey through the morphological and informative digital modelling allows the involvement of different skills for specific analyses.

In addition to being an information repository, many authors describe the BIM model as a tool whose most important characteristic is interoperability, indeed, different professionals are usually involved in a building project, and through BIM’s flexibility,

they are able to access all information they may need (Arayici, 2007)(Lee Worrell, 2015)(Di Mascio & Wang, 2013)(Sammartano & Spano, 2016).
However, as evidenced by the review of Sidani et al.(2021), not all corporations are able to implement and use BIM effectively. Consequentially, supportive tools, such as Virtual Reality, to assist BIM in achieving its full potential in the interoperability field, are in high demand, Rysanek et al., (2017) propose Virtual Reality platforms integrated in BIM environment for navigating physical environments, created with equirectangular images, labelled with data or text widgets for conservation activities on existing buildings. In the same direction, VERBuM project (Virtual Enhanced Reality For Building Modelling) designs and develops a digital environment for Virtual Reality and Augmented Reality to allow the immediate consultation and effective use of information, even in immersive mode, for supporting BIM interoperability.(Bruno et al., 2022).
The interoperability is also guaranteed through the traceability and accessibility of data through shared vocabularies. For this reason, methods have been developed in other researches with the aim of semantically enriching BIM models and at the same time ensuring a structuring of the data contained in them through the integration of BIM models with a knowledge base created through the information ontologies (Nafis et al., 2019)(Bonduel et al., 2019) (Simeone et al., 2019). Along the most widespread ontologies in the field of CH there are the CIDOC Conceptual Reference Model (CRM) to enable information integration for cultural heritage data and their correlation with library and archive information (Doerr et al., 2016) and MONDIS to link documentation about damaged historical structures, and also about how the diagnosis was made and what possible interventions might be made (Cacciotti et al., 2013).
Furthermore, from the reviews of (Pocobelli et al., 2018b)(Yang et al., 2020)(Radanovic et al., 2020) nowdays, there is no structured and shared digital framework that takes into account the knowledge gathered on the assessment of the state of the buildings, the morpho-metric survey as a whole, the maintenance of conservation activities as an integrated system (Hu et al., 2021). If the declaration of tools, use, modeling process, etc., is an essential aspect for the transparency of each

digital visualization, this assumes an even more marked value in the case of BIM which still fails to fully meet the specific needs of AH (Simeone & Cursi, 2017)
One of the difficulties consists in the use of standardized parametric objects which not fulfill the complexity and uniqueness of architectural elements (for example vaults, irregular masonry walls, etc.). In most cases, it is required the adoption of specific solutions. Murphy et al., (2009), in one of their first experiments, use laser scanning to produce a BIM model. Architectural elements are modelled using a range of different software, from point clouds editors to meshing tools. Baik et al. (2017) proposed the Jeddah HBIM whit the purpose of producing a parametric smart object library (linked to graphics, tables and metadata) that can be used both for buildings in Jeddah (specific materials, common material degradations, local construction techniques) and for heritage buildings in general. JHBIM study practically demonstrates that BIM technology is possible for heritage buildings. However, constructing parametric digital libraries still remains a manual and time-consuming task.
In some applications, for speeding up the Scan-to-BIM process the connection of Articial Intelligence (AI) methods have been implemented for facilitating the automatic identification of historical architectural elements or decay pattern in point clouds (Valero et al., 2018)(Bruno et al., 2019b)(Morbidoni et al., 2020)(Croce et al., 2021a).

1.5. OBJECTIVES OF THE THESIS

From the consideration illustrated in above paragraphs emerge two main consequences which deeply affect conservation activities through BIM:

- Heritage Building Information Models are not suitable for achieving the representation of specificity and uniqueness of artefacts also including semantic data;
- There is not a structured and shared digital framework that takes into account collected knowledge on building state assessment from survey to intervention

and maintenance, allowing the conservation activities as an integrated system.

This doctoral thesis proposes a methodological workflow which, starting from the digital survey, addresses the theme of semantic enrichment of HBIM models focusing on the analysis of decay assessment of materials, and reaches the process of conservation and management of that heritage.
The proposed research connects the aims of two disciplinary areas, architectural survey and refurbishment, and implements established methodologies with the aim of defining an optimal strategy modelling the fourth dimension (time) of AH in HBIM environment, for its interpretation in the present and for its consistent future conservation. The aim is to obtain a complete and flexible management of the large amount of multidisciplinary areas elaborated during the activities of knowledge, survey, analysis, and conservation planning.
Therefore, the objectives of the following related research work are:

- Validate a consolidated process of representation in BIM that allows to overcome the limitations due to the standardization of parametric objects respecting the specificities of the instances of the historic asset testing different modelling methodologies;
- Implement semantic segmentation methods through standard and Machine Learning algorithms to automate some steps of the classification process of 2D and 3D reconstruction (orthophotos, UV maps, point clouds, meshes, etc.) resulting from the digital survey primarily to identify and quantify architectural components and different states of conservation of surface materials and secondly to reduce the time and manual steps of the Scan to BIM process.
- Integrate and improve the semantic level of BIM models by extending the field of representation to documental information to include the knowledge needed to understand the characteristics of the built heritage that cannot be directly included in its physical components, such as history, construction phases,

survey data, etc., developing methods for integrating the information contained in BIM models through Database Management Systems and 4D simulation.

The stated objectives will be developed through the methodology described in the following paragraphs. For the development of the research, various architectural scenarios have been taken into consideration, in order to offer a reliable methodology which can be replicated and deployed in various heritage cases.

2. LITERATURE REVIEW METHODOLOGY

To allow the introduction of the proposed methodologies for integrating digital documentation and conservation process of Architectural Heritage, firstly is necessary to define an overview about existing methods and techniques which will be used. The topics of the digital 3D survey, 3D semantic data extraction, parametric 3D modelling and BIM semantic enrichment in relation with thesis objectives (Sub-Sec. 1.5) will be dealt with in the following paragraphs.

2.1 BASIC PRINCIPLES OF 3D DIGITAL SURVEYING TO SUPPORT BIM REPRESENTATION

One of the most important task in documentation process is the survey of heritage buildings. The metric survey has the purpose of constructing a discrete model of the artefact by detecting the position in space of some points of the object considered significant.

Position, size, shape, and identity of the components of a historic building and/or site are fundamental aspects to understand in a project related to the conservation of Architectural Heritage (AH). The information provides a detailed framework for the assessment of the site's significance, a basis for further conservation analysis. For example, knowing the size and shape of a barrow located in a historic landscape can help archaeologists identify its significance; a stone by stone Computer-Aided Design (CAD) drawing of a cathedral elevation provides valuable information for an architect to quantify the conservation effort; or, by repeating surveys, a section of a masonry wall can be monitored for deformation, which will assist the conservator in determining the appropriate protection. Traditionally presented as drawings and latterly in two-dimensional (2D) CAD form, the information is increasingly being delivered as 3D data for further analysis, modelling, and visualization (Boardman, 2011). Indeed, the development of three-dimensional (3D) surveying and representation systems promoted the birth of new forms of documenting, disseminating and analysing cultural heritage objects in digital environments.

Reality-based acquisition systems provide reliable 3D reconstructions of the object of study. Laser scanning and photogrammetry are widely applied methodologies (Russo & Manferdini, 2014)(Palomba et al., 2019) for capturing the basic 3D data to be used as input for the creation and development of digital models (Rocha et al., 2020). Therefore, it is important that the digital survey generates an optimal product that is the basis for the next stage of the conservation process.

In this thesis digital survey is integrated in the generation of HBIM models trough Scan to BIM process which will be that will be deepened in Sub-Sec 2.3.

In Balzani & Maietti (2017b) a Data Acquisition Protocol is structured, for elaborating HBIM models. It is divided in eight main stages with specific requirements and related activity indicators: 1. major project; 2. health and safety; 3. resolution requirements; 4. registration procedures; 5. control network; 6. quality control; 7. control and verification of data; 8. data saving and archiving. Each stage must be understood as a set of questions to which the technician or operator responsible for carrying out the survey must answer in order to obtain the data useful for the purposes of the survey. Four categories of assessment of the relief have also been defined to understand the ratio among effectiveness, usability and reliability of survey (Di Giulio et al., 2019).

In general, when approaching a digital survey, the aspects explained below should be considered. First of all, the quality of the survey outputs should be programmed as a level of reliability of the survey in relation to its purpose. Furthermore, time should be considered as the degree of usability of the acquired data and the cost can be evaluated as the potential effectiveness of the survey (guaranteeing a level of proficiency in terms of an increasingly smaller scale of representation).

In essence, the quality of a survey could be thought of as the ability to conform to standards and ensure long-term support. For this reason, the key features of a reliable survey are:

- the ability to constantly update a survey database during daily use for ordinary purposes, enriching it with new information or minimal changes;
- the integration of the survey by carrying out the updating the data collected, adding a new part of a building or site, previously not included in the survey, or performing a more accurate analysis of the parts of the model that already exist;
- technological obsolescence: since the hardware and software for data management are evolving extremely rapidly, the application of strategies to avoid technological obsolescence has become a key feature to ensure the reliability of the survey over time.

While the acquisition of 3D survey data is a well-established practice, recent studies have explored the subsequent phase, which involves the processing and elaboration of raw data obtained from the survey. In fact, starting from in the representation phase, it is required to decode and organise the raw information obtained from digital survey in order to represent the morphological complexity of heritage buildings understanding the shape and geometry of the elements to be represented as well as their mutual relationships for building complete and intelligible representations (Gonizzi Barsanti et al., 2017b). Only through this phase, which requires a logical and operational process of segmenting and classifying the raw data, an accurate and complete 3D model can be reconstructed and used as a support for the documentation and analysis (Oreni et al., 2017). Once the model has been reconstructed in a 3D environment, the geometric elements can be associated with semantic data, i.e. information about the historical asset.

2.1.1 3D RECORDING TECHNOLOGIES AND DATA PROCESSING IN SCAN-TO-BIM PROCESS

Architectural Heritage (AH) is undeniable documents of world history. Its thorough study is an obligation of our era to mankind's past and future. Conservation of heritage artefacts is a major issue for modern societies, both from economic and cultural viewpoints.

The introduction in the last decades of 3D optical instruments for the 3D digitization of objects and sites has undoubtedly changed the concept of heritage conservation and preservation. Significant is their use in architectural fields such as civil engineering (Jiang et al., 2008)(Lubowiecka et al., 2009)(Lovas & Barsi, 2012), architecture (Gomes et al., 2014), (Aicardi et al., 2018),(El-Din Fawzy, 2019), and archaeology (Adami et al., 2019)(Verdoscia et al., 2021a).

Before undertaking any intervention, it is necessay to reach a deep and complete knowledge of historic manufacts, the existing situation before the restoration in order to determine problems in the building's structural system, decays in materials, deformations, distortions, and interventions, evaluation of damage, the analysis of the fissures, determining anomalies besides the history of construction. Lots of research studies connected highlighted the utility of 3D digital survey in:

- determining of historical and archaeological value of the building (Remondino, 2011)(Verdoscia et al., 2020a),
- detect morphologica characteristics of architectural components (Grilli & Remondino, 2019)(Sub-Sec. 2.2.1)
- defining and obtaining measured drawing and 3D reconstruction of the building (Balzani & Maietti, 2017b) (Antón et al., 2018);
- determining deformation, evaluation of damage, analysis of the decay, deformation, and crack (Prasanna et al., 2012) (Valença et al., 2013)(Grilli & Remondino, 2019)(Bienvenido-Huertas et al., 2019)(Galantucci et al., 2018) (Sub-Sec. 2.2.1);
- controlling the situation of the building in the lifecycle such as before and after restoration (Russo & Guidi, 2011) (Verdoscia et al., 2020b);

In Scan-to-BIM process the first step is the acquisition of complex geometries as point clouds via range-based technique as laser scanning (LiDAR - Light Detection and Ranging) or image-based technique as photogrammetry/video-grammetry in terrestrial and aerial configurations respectively, for territorial and/or detail scale acquisitions. Both are able to provide the generation of 3D or 2D results in terms of geometric and radiometric accuracy with additional texture information (such as orthophotos, dense point clouds, discrete highly precise measures).
In particular, the main output of digital survey is the point cloud (Fig. 2) which is a collection of points converted from range and angular measurements into a common Cartesian (x,y,z) coordinate system that defines the surfaces of the subject in great detail.

Fig. 2 Example of point cloud of the portal of the inner courtyard of Palmieri Palace, Monopoli (Italy)

This is the raw data of the survey, and for each point, there is usually information on the intensity of the reflection. The colour of the surface at each point can be added to the coordinate and intensity information by interrogating the imagery from the on-board camera. This is normally done at the processing stage; the colour can also be appended from external photography. More sophisticated instruments, predominantly airborne, can provide information on the range of reflections of a laser pulse and are known as full waveform scanners (Han et al., 2017).

In the field of historical and architectural heritage, a detailed survey obtained by 3D recording tools is now essential, which allows to obtain a digital copy of the existing buildings with high metric precision. However, for some contexts the cost and reduced portability of LiDAR technology have favoured the use of the photogrammetric technique (Templin & Popielarczyk, 2020). For each method has advantages and disadvantages, the most appropriate techniques need to be chosen according to documentation requirements and the unique specifications of the study site.

Three are the main differences between range-based and image-based techniques. Firstly, in range-based systems the point cloud is the directly result of the acquisition, while image-based techniques require two-dimensional images that can generate a three-dimensional point cloud by exploiting vision techniques and photogrammetric principles. Furthermore, the point cloud generated by range-based systems is a metrically correct model consistent with reality; the one generated by photogrammetry needs to be scaled using at least two known measure. Finally, the measurement error of the models derived from range-based techniques is only related to the acquisition tools. In the models derived from image-based techniques, however, the error is given by the contribution of several factors such as, for example, the grip distance, the characteristics of the camera and the algorithms used to generate the cloud from the 2D images.

The 3D laser scanning belongs to the category of Active Reality Capture methods for acquiring discrete data, while photogrammetry is a Passive image-based alternative. According to survey objectives, the remote sensing is performed with equipment installed on space probes, satellites, and aircraft, Remotely Piloted Vehicles (RPVs) or Unmanned Aerial Vehicles (UAVs), cameras, smartphones (Shults, 2017).

In the las years, the use of remote sensing was reduced in favour of conventional aerial platforms because of the widespread diffusion of UAVs applications, firstly applied in the military sector and then for civilian purposes (Vacanas et al., 2016). The devices installed on UAVs ensure the acquisition of inaccessible spaces because of the height (i.e. roofs) or restricted dimensions (Bakirman et al., 2020). Moreover, mobile scanning systems have begun to acquire their own value because wearable lasers are particularly flexible and suitable for detection operations in demanding environments such as quarries, caves, uneven terrain, tunnels, tunnels and wherever it is not possible using traditional instrument (Nespeca, 2018). However, the use of terrestrial laser scanner or photogrammetric devices would not acquire parts of the building due to their short distance or presence of objects impeding the view. The critical factors described have been resolved combining LiDAR and photogrammetry ensuring a higher level of quality and detail of the data obtained (Battini & Sorge, 2016)(Liang et al., 2018).

An advantage would be to integrate TLS outputs with those of UAV cameras which have a higher planar data acquisition rate in areas that are not easily accessible, such as the roof of a building, compared to terrestrial laser scanning. Documenting the shape of entire buildings, including the roof covering, exclusively through terrestrial laser scanning is rather difficult. In particular, acquiring data in locations where the scanner cannot be positioned is prohibitive (Palomba et al., 2019). Furthermore, the 3D reconstruction deriving from photogrammetric reconstructions have a better texture quality and allow for geometric accuracy, so they can be integrated with a laser scanner acquisition to optimize the results obtained for morphologically complex architectural elements. Actually, the integration of multiple techniques speeds up and optimizes survey acquisitions and produces multiscale and multi-functional data, increasing the available products.(Galantucci et al., 2018).

In recent years, some research lines have been studying the possibility of implementing the Scan-to-BIM process by pushing the use of point clouds beyond the current limits of use: in the documentation of architectural heritage the greatest challenge is to generate workflows able to provide semantic information relating to conservation or restoration purposes to be included in the information models (Quattrini et al., 2015)(Bienvenido-Huertas et al., 2019)(Di Stefano et al., 2019)(Verdoscia et al., 2020b).

The following research fits into this trend using digital survey techniques to support the data semantic extraction and 3D modelling in Scan-to-BIM process.

Since the first applications of BIM, such as the work of Arayici, et al. (2007)and Murphy et al. (2009), the 3D model of an existing building is usually created by fitting manually parametric elements to point clouds acquired by surveying techniques (Sec. 2.3). Since then many studies have been carried out to introduce a certain degree of automatism into the modelling process (Bruno et al., 2018)(Lòpez et al., 2018)(Radanovic et al., 2020)(Fig. 3).

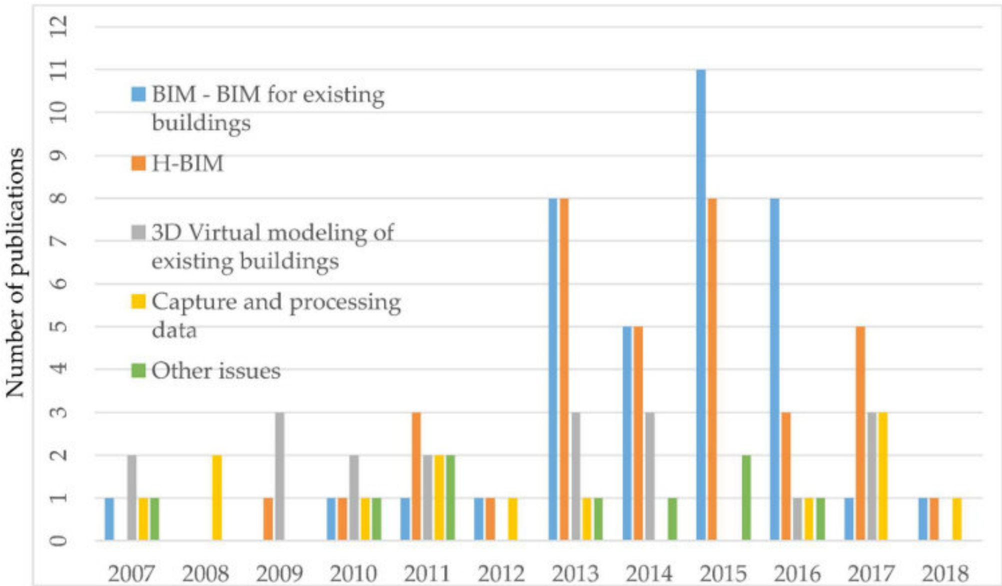


Fig. 3 Trend in parametric modelling from acquired point clouds in HBIM methodology (Source: Lòpez F et al., 2018)

Projects as INCEPTION (Balzani & Maietti, 2017b) are focusing on the 3D data capturing and modelling of heritage buildings and sites, through digital representation of the shape, appearance and conservation condition, in addition to a set of semantic information able to enrich research and deployment applications in order to guide the

process of digitization of cultural heritage and innovation strategies to the three-dimensional modelling.
Nowadays, there are no regulations or specific guidelines which illustrate the best practices for the digital acquisition process for Scan-to-BIM process. To the best of the author's knowledge, the only guideline that deals with laser scanning and photogrammetric data acquisition for BIM implementation is the GSA BIM Guides Series 03 (2009) where are summarized pros & cons, suggested examples of applications and guidelines are given for instruments use, reduction of errors and data processing. Nevertheless, as it dates back to 2009, this document is no longer exhaustive up-to-date, due to the many improvements occurred in these fields.
So the general workflow is concerned, from the analysis of literature (Biswas et al., 2015)(Castagnetti et al., 2017) (López et al., 2018)(Badenko et al., 2019) (Rocha et al., 2020)(Moyano et al., 2021); the most agreed upon and consolidated process is summarized in Fig. 4

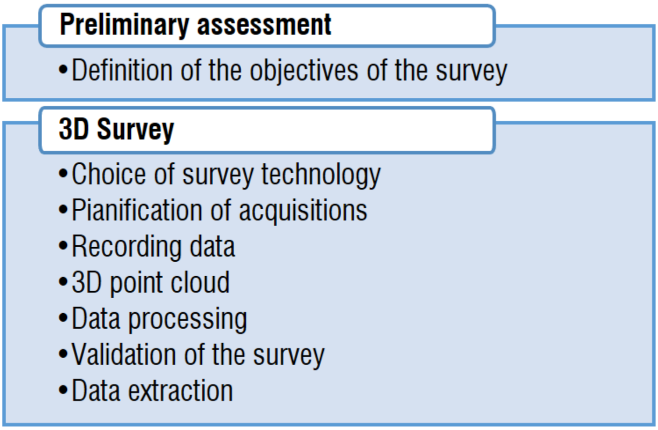


Fig. 4 3D digital survey workflow

About Scan-to-BIM modelling phase we will discuss in the Sub-Sec. 2.3, instead, in this section the methodological aspects of acquisition and processing of the point clouds will be detailed, which will be used as a reference for the subsequent phase of the Scan to BIM process illustrated in this thesis.

2.1.2 DIGITAL SURVEY THROUGH LASER SCANNER

Laser scanners are instruments that collect 3D spatial coordinates automatically for a considerable number of points in a very short time (Polewski et al., 2016).They are also called LiDAR systems due to the use electromagnetic waves to measure both objects or/and entire portions of territory. The term LiDAR is commonly used for aerial, sometimes terrestrial surveying (Battini, 2012). Laser scanners cover a variety of tools that operate on different principles, in different environments, and with different levels of precision and accuracy.

The data acquired in the form of point clouds are collected thanks to the use of the instrument mounted on a tripod or in flight. More recently, handheld systems allow for data collection while on the move.

Many definitions attributed to this technology, Grussenmeyer et al. (2016) defined laser scanning as active, fast and automatic acquisition technique for measuring without any contact. In Boehler et al.(2001) laser scanner is considered as a device that collects 3D coordinates of a given region of an object's surface automatically, in a systematic pattern at a high rate and achieving the results in near real time.

From these definitions it emerges that two main aspects are important: firstly, the concept of active due to laser scanners emit and receive their own electromagnetic radiation rather than relying on reflected ambient or artificial light as in passive technique as photogrammetry; secondly that are no-contact technology useful in unsafety environment condition for the operator and preserve artefacts from risk of damage during the survey.

The laser scanner technology usually has a single point precision of between ± 2 and ± 50 mm. In the review of Mukupa et al. (2017) is shown how the point clouds derived from laser acquisition have been effective in assessing the changes in the form of an object surface. Moreover, laser-scanning systems allow the measurement in very short periods of time of large numbers of data points (Riveiro, Belén et al., 2013).

Due to the laser scanner relying on a signal reflected back from the object surface to the receiving unit, the strength of the returning signal is influenced (among other facts such as distance, atmospheric conditions, incidence angle) by the reflective abilities of the surface. White surfaces will produce good reflections whereas reflection is poor from black surfaces. The effects of coloured surfaces depend on the spectral characteristics of the laser (green, red, near infrared). Shiny surfaces usually are not easy to record. It has been observed that surfaces of different reflectivity result in systematic errors in range. For some materials these errors may reach amounts several times larger than the standard. For objects consisting of different materials or differently painted or coated surfaces, one has always to expect serious errors. These can only be avoided if the object is temporarily coated with a unique material which, of course, is not applicable in most cases. If the effect has to be examined and evaluated, one may use plane white targets and apply the material in question to the centre part of the target (Boehler et al., 2003).

Laser scanning system can be divided into three main sub-sections: Triangulation scanners, Pulse (Time of Flight- ToF) and Phase comparison scanners(Boardman, 2011). The first typology is used for the relief of small-medium-sized objects (for example archaeological finds), on the other hand, the other two are more used on a building scale. In ToF scanners a pulse of laser light is emitted and the time it takes for the return flight is measured. The range is calculated from a simple formula involving the speed of light. High accuracies are achieved by pulse scanners, typically 2–6 mm even at longer distances, with, generally, less noise than other types. This is sufficient for most cultural heritage applications, and 1mm accuracies can be reached at closer ranges. Phase-comparison scanners, while offering similar accuracies as pulse systems, calculate the range to the target differently because they base them measurement on the phase differences between the emitted and returning signals rather than directly on the ToF. Phase-comparison systems have traditionally had much higher rates of data capture (greater than a million points per second) as a result of the emission of a continuous wave. These high-density point clouds produce very detailed scans for cultural heritage (Vatan et al., 2009).

2.1.3 PRINCIPLES OF PHOTOGRAMMETRY

In the last years, the use of images for measuring 3D features have a wide success in many application fields, including Cultural Heritage documentation and analysis. The Close Range Photogrammetry (CRP) offers the possibility of a cheap acquisition, fast and automatic processing and high accuracies in the results capturing points, lines and surface curvature in an image or to detect object boundaries(Goda et al., 2019).

CRP uses a contactless measuring method and it starts from the knowledge of the camera parameters (focal length and principal point) and then moves to the extraction of homologous points for starting the activities of 3D reconstruction of physical model which occur by means of Structure from Motion (StM) algorithms in the process of reverse engineering (Aicardi et al., 2018).

The photogrammetry technique is based on the concept of the central projection which is a geometric procedure that transforms a 3D entity into a 2D reality. To obtain this assumption occur that an object, a projection centre, and a projection plane, oriented in any way with respect to the projected object, are connected through a series of straight lines (or projecting rays) intersecting the projection plane, and generating the image points. For this condition, in a frame, the object point P, the projection centre O, and the image point P' have to be on the same straight line or rather the collinearity conditions representing the alignment between the points in the image and in the object system (Huang et al., 2018). The mathematical representation of this condition can be expressed in the following way:

$$\frac{\xi - \xi_0}{c} = \frac{X' - X'_0}{Z'_0 - Z'}$$

$$\frac{\eta - \eta_0}{c} = \frac{Y' - Y'_0}{Z'_0 - Z'}$$

- ξ, η, ζ represent the image system ($\zeta = 0$ for the image points and $\zeta = c$ for the projection centre)
- *X, Y, Z* represent the object system.

The coordinates X', Y', Z' of the point P and the coordinates X'_0, Y'_0, Z'_0 of the projection centre may be processed in the system X, Y, Z by the spatial rotation matrix R:

$$\begin{pmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{pmatrix} = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix} \cdot \begin{pmatrix} X' - X'_0 \\ Y' - Y'_0 \\ Z' - Z'_0 \end{pmatrix}$$

Therefore, if the matrix above is multiply for the matrix RT = R−1, and replaced in the equations, explicating the image coordinates, the relationship between the image coordinates and the ground ones is obtained. These are called collinearity equations:

$$\xi = \xi_0 - c\frac{r_{11}(X - X_0) + r_{21}(Y - Y_0) + r_{31}(Z - Z_0)}{r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)}$$

$$\eta + \eta_0 - c\frac{r_{12}(X - X_0) + r_{22}(Y - Y_0) + r_{32}(Z - Z_0)}{r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)}$$

So, the physical meaning of the collinearity equations consists in the concept that each point is projected into a unique image point, if it is not occluded by other object points (Fig. 5).

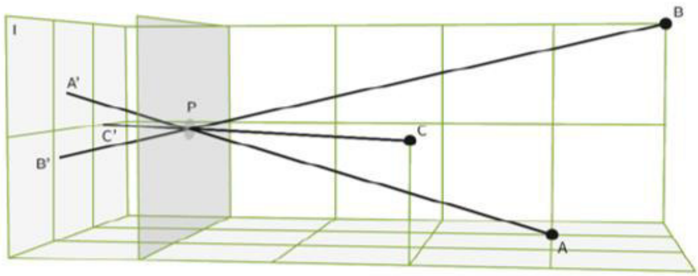


Fig. 5 Collinearity condition (Source; Historic England, 2017)

Another principle to consider for the geo-spatial reconstruction of an object, and therefore to know its coordinates, is the use of at least one pair of images that provide a stereoscopic rendering. Any part of the subject that is not shown in at least two images cannot be reconstructed.

However, in real cameras there are always geometric distortions, which means that the points of the image are slightly out of position with respect to the idealized central projection. These deviations from the ideal must be quantified, mathematically

described and compensated. In most digital cameras you can assume the flatness of the sensor. The calibration of the cameras is important when the photographs are used with for 3D reconstructions with metric purpose: it allows, in fact, to calculate the internal calibration parameters of the camera and the distortions that the lenses cause on the image.
Therefore, the three-dimensional spatial coordinates of each point of the object can be derived from the images, based on the reciprocal position of the cameras. This process is generally carried out by specific software (Agisoft Metashape©, Photomodeler, Pix4d, etc.) that through Structure from Motion algorithms (SfM) perform an automatic calibration of the cameras using, in the case of digital images, the metadata contained in the source files and the three-dimensional reconstruction of the 3D object.
Therefore, for obtaining an accurate 3D colour model it is necessary to contemplate different kinds of processing tools or acquisition procedures based on the kind of object to be surveyed evaluating the geometry, the texture, the distance, the complexity of its shape, and so on.
Indeed, for a given point in one image, its correspondences on other images may not exist due to occlusion. Moreover, it is possible to have more than one match, due, for example, to repetitive texture patterns or even no matches, according to image noise or lack of textures; semi-transparent object surfaces could also give similar problems.
For these reasons, as in LiDAR survey, also for CRP it is important to evaluate a survey strategy considering all boundary conditions that may affect the quality of the 3D model: lighting, inaccessibility of some place/parts, camera settings, necessity of target (for low-textured objects), weather conditions, etc.
The processing time to build point clouds depends on the considered amount of points. The measurement errors, that can occur with photogrammetry, due to its function algorithm of image matching that is sensible to object movements, decrease by employing strict acquisition plans, professional equipment and accurate programs for photo-modelling.

2.2 INNOVATIVE SEGMENTATION APPROACHES IN HERITAGE FIELD

Segmentation is one of the most important methods for the automated discretization of survey raw data because it allows the labelling of pixels or points with similar features into homogeneous regions. The features constitute a characteristic property or set of properties which are measurable and differentiable.

Therefore, the concept behind segmentation is to enrich the representation of an image/point cloud/mesh into something more meaningful and easier to analyse. Many of its applications have been developed in fields such as medicine (Ying et al., 2015), industry (Su et al., 2016) or geomatics (Hossain & Chen, 2019), etc.

In the past, semantic segmentation concerned 2D images where features refer to visual properties such as size, color, shape, scale patterns, etc. (Chen & Pavlidis, 1980)(Sonka et al., 2008)(Yuheng & Hao, 2017)(Jeevitha et al., 2020).

Due to some limitations related to occlusions, illumination, posture and other problems, the researchers began to deal with 3D data (point cloud or meshes)(Vosselman & Dijkman, 2001)(Gonizzi Barsanti et al., 2017a)(Marzoog et al., 2020). This change also occurred thanks to the growing diffusion of photogrammetry and laser scanning surveys (Sapkota, 2008). They typically result from specific geometric characteristic (Surface, normal, gradient, curvature, etc.) of the global or local 3D structure (Ho & Chuang, 2012)(Araùjo et al., 2019).

In AH, the understanding of 3D scenes is essential, as it can have many applications such as the identification of similar architectural elements in large dataset, the analysis of the state of conservation of materials (Xu et al., 2020), semiautomatic detection and classification of degradation (Sánchez & Quirós, 2017), non-invasive diagnostic techniques (Zhou et al., 2016)(Galantucci et al., 2018), the subdivision of the point clouds in its structural parts preliminary for Scan-to-BIM processes (Wang et al., 2015a) (Valero et al., 2018), etc.

Nguyen and Le (Nguyen & Le, 2013) classified segmentation methodologies in five classes according to geometrical derivatives: edge-based, region-based, attributes-based, model-based and graph-based methods. However, in recent years, the researches for semantic segmentation of point clouds in AH have made a significant progress thanks to the application of Artificial Intelligence (AI) methods such as Machine Learning and/or Deep Learning (Grilli et al., 2017)(Matrone et al., 2020). In addition, Ahmed et al., (2019) had classified 3D data for segmentation into Euclidean and Non-Euclidean. While Xie et al., (2020) individuated two types of methodologies: 3D point cloud semantic segmentation that associates points with semantic labels and point cloud segmentation.

Specifically, these methodologies have been often used and developed for detecting building components within 3D point clouds (Fig. 6). Region based methods were used from Lerma & Biosca (2005) to automatically extract all the planar surfaces of an ancient building and filter out non-relevant points with region growing algorithm, instead, from Poux et al. (2020) to analyse indoor scene. Furthermore, Hackel et al. (2016) describe a method based on edge detection to automatically detect contours of outdoor scenes

In other works, a combination of segmentation algorithms has been used. Spina et al., (2011) and Valero et al., (2018) elaborated a pipeline able to partition raw point clouds to identify stone blocks in masonry walls. Dimitrov and Golparvar-Fard, (2015) propose a multi-scale feature detection implementing region growing method based on geometrical continuities while Teruggi et al., (2020) developed a multi-level and multi-resolution approach based on machine learning and geometric features (planarity, linearity, anisantropy, surface variation, etc.) to improve the learning process and optimize 3D classification results through a hierarchical concept. Also Hamid-lakzaeian implement a distinctive 3D feature segmentation method for multi planar building façades practicable and scalable with respect to building types and architectural complexities (Hamid-lakzaeian, 2020).

Grilli et al., (2019) introduced two segmentation methods, one on 2D data (“texture-based” approach) and one directly on the 3D data (“geometry-based” approach) with Machine Learning (ML) strategies for restoration and documentation purposes, providing metric information e.g. of damaged areas to be restored.

In most of the literature available segmentation processes are performed for annotation and restoration purposes. In the NUBES project, it was elaborated a system for the storage and the spatial referencing of iconographic sources on the 3D space and for their segmentation into semantic layers allowing the map of data in real time such as annotations concerning stone degradation, dating and material (Stefani et al., 2013).

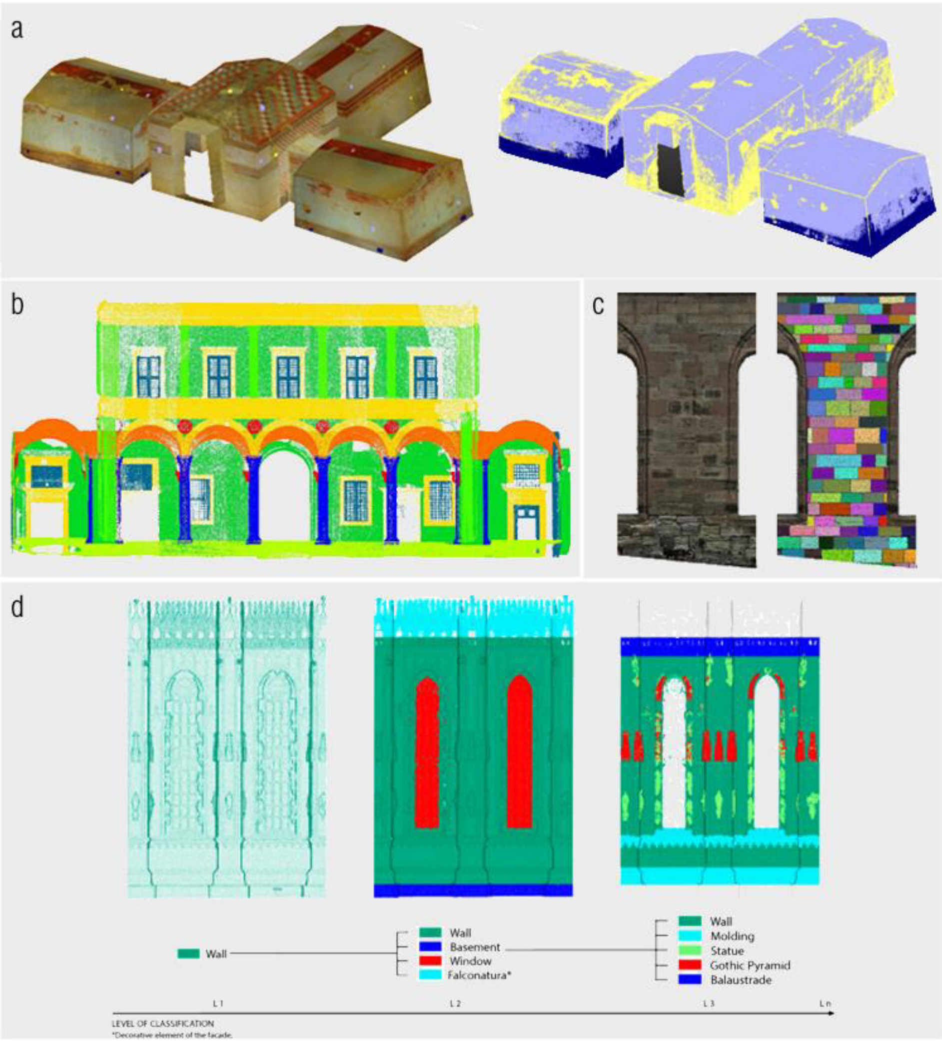


Fig. 6 a) Texturized-based method results (Grilli et al. 2019), b) Deep Learning based semantic segmentation (Morbidoni et al.2020), c) Segmented ashlar units (Valero et al.,2018), d) Classification levels for a decorated wall (Terruggi et al., 2020).

Other applications have been developed for speeding up the Scan-to-BIM process. For example, (Morbidoni et al., (2020) and Croce et al., (2021) facilitate the automatic identification of historical architectural elements implementing semantic segmentation and classification of point clouds using Deep Learning and Machine Learning.

The inclusion of geometric segmentation methods within a complete refurbishment framework for managing decay detection has been actualized with the HBIM approach. For example, in (Bruno et al., 2019b) a virtual representation of damages has been combined with a timeline about transformations and previous interventions. In (Valero et al., 2018) reality capture, data processing and HBIM have been employed for structuring a monitoring strategy of the decay evolution in historic buildings.

However, in some cases, geometrical segmentation methods lead to over-segment complex architectures, because they cannot separate architectural elements belonging to the same plane (i.e. wall and door). In some research works, colour-based segmentation, based on colorimetric difference measurement for the identification of objects with the same direction of normal vector but different colours, addresses this gap. In (Zhan et al., 2009) colour information has been used to improve the geometric pipeline, for the identification of objects with the same normal directions but different colours. On the other hand, colour-based segmentation has been performed mostly on 2D images (Vorobel et al., 2021) (Malinverni et al., 2017), or in a few cases on 3D data (Valero et al., 2019) (Galantucci et al., 2020), for the detection of decay patterns recognizable for their predominant colours or their chromatic differences.

The use of colour-based segmentation allows the labelling of damp spots, thanks to the colour variation caused by moisture phenomena on materials (Lerones et al., 2016).

From this it emerges that the use of segmentation on 3D models would represent a cost-effective and non-invasive method of analyzing the condition assessment of Architecture Heritage. There is a rich literature about segmentation methods for geometrical purposes, but only a few references refer to automatic segmentation strategies for the identification of chromatic evidences which usually characterize architectural elements on 3D data. Therefore, a segmentation pipeline may be improved, in order to automatically partition a raw point cloud into meaningful subsets of points, based on the colour attribute.

2.2.1 SEMANTIC DATA EXTRACTION FROM POINT CLOUD

The development of reality based surveying techniques analysed in Sub-Sec. 2.1.1 for documenting cultural heritages is important in terms of architectural conservation practices, history of art and architecture, archaeology and architectural researches.

The necessity to implement procedures for analysis, management, visualization and using the data acquired through the digital survey is a consequence of the enormous amount of data which acquisition techniques are currently able to provide. In this section, an overview of segmentation methods for the extraction of semantic information from point clouds starting from geometric and colour characteristics will be carried out focusing on methods directly used in this thesis.

2.2.2 COLOUR SPACES FOR SEGMENTATION

Human eyes can perceive and understand the objects in a bi-dimensional or three-dimensional representation (images, orthophotos, point cloud, etc.). In order to design a digital process that can understand like a human, it requires appropriate algorithm and massive training starting from information like colour (Hema & Kannan, 2019).

A colour model is an abstract mathematical model describing the way colours can be represented as tuples of numbers, typically as three or four values or colour components. When the colour model is associated with an accurate description of how the components are to be inferred and the conditions are viewed, the set of resulting colours is called “colour space.” Colour space can also describe the ways in which human colour vision can be modelled.

Colour information of bi-dimensional or three-dimensional data (images, orthophotos, point cloud, etc.) are usually expressed in RGB (Red, Green, and Blue) which is an additive colour model where the primitive colours red, green and blue are combined together in various ways to reproduce a broad array of colours (Sonka et al., 2008). In fact, as pointed out in (Zhan et al., 2009), in RGB space, the metric distance does not correspond to the colorimetric distance between colours. The lighting and shading factors influence the colour perception, producing a mismatch between proximity in RGB space and perceptive colour closeness. Then, the spatial proximity, corresponding to the geometric distance between colour-values, is not coherent with the perceptive similarity among colours (Sonka et al., 2014) (Gonzalez and Woods, 2018).

For this reason, for segmentation application on 2D and 3D data it is necessary to consider other colour-spaces such as HSV, YCbCr, YIQ, YUV, where the human perception is taken into account and the geometric distance and the perceptive similarity are related (Burdescu et al., 2009) (García-Lamont et al., 2016). RGB data may be converted into any other colour space using any transformative functions.

Different colour spaces have been examined for the purpose of identifying the most accurate one:

a. HSV (Hue Saturation Value);
b. YCbCr (luma component, blue and red difference chroma components);
c. YIQ (luma component, in-phase, quadrature);
d. YUV (luma component, blue projection, red projection).

In these colour-spaces, unlike the RGB, the perceptive similarity is more proximate to the Euclidean distance between colour triplets, because they take human perception into account. They are defined by mathematical coordinate transformations from an associated RGB colour space (Chai and Bouzerdoum, 2000) (Gonzalez and Woods, 2018).

The HSV colour space is fundamentally different from the widely known RGB colour space since it separates out the Intensity (luminance) from the colour information (chromaticity)(Sural et al., 2002). In HSV, Hue corresponds to the colour’s position on a colour wheel and is related to the colour transitions from red to orange, yellow, green, cyan, blue, magenta, and finally back to red. Saturation ranges from unsaturated (shades of grey) to fully saturated (no white component). While Value coincides with brightness (García-Lamont et al., 2016) (Fig. 7).

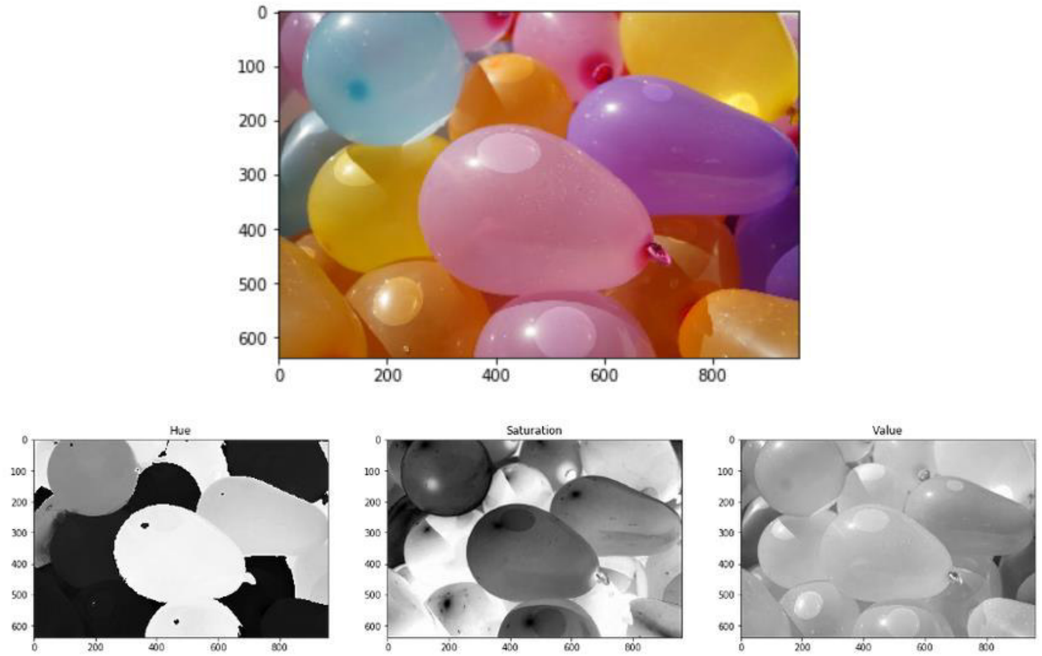


Fig. 7 On the Top, original image, on the bottom different HSV channels (Source: https://medium.com)

YCbCr, YIQ and YUV belong to the family of luminance/chrominance colour spaces, which allow to consider reduced bandwidth for chrominance components. YUV is defined through a luminance component (Y) and two chrominance components (UV), representing the deviations of blue and red from the luminance component. YIQ is analogous to YUV, but it is meant for the analogic television signal.

On the contrary, in YCbCr is a colour space used as a part of the colour image pipeline in video and digital photography systems. As in others colour spaces, Y is the luma component (the brightness in an image) and Cb and Cr are the blue-difference and red-difference chroma components. The chrominance components correspond to the deviations of blue and red from the luminance expressed in the greyscale (Gonzalez and Woods, 2018). YCbCr colour space is defined by a mathematical coordinate transformation from an associated RGB colour space (Chai & Bouzerdoum, 2000).

2.2.3 AN OVERVIEW ABOUT SEGMENTATION METHODS

Point cloud segmentation can be achieved through a plurality of methods, diversified according to the data grouping criteria, on the basis of some properties or features (like geometry, colour, size, shape, scale patterns, etc.). The choice of the segmentation method, such as the level of segmentation e.g., are strictly related to the objective of the analysis and the kind of problem the research is addressing. In fact, the process can be considered satisfactory when the object of interest is correctly isolated (Sonka et al., 2008).

The main approaches could be classified into several categories: standard ones, based on the principles of discontinuity (edge-based methods) or similarity (region growing) (Nguyen & Le, 2013); model-fitting methods, performed by mathematical models (RANSAC, Hough Transform, etc.)(Schnabel et al., 2007); and machine learning applications, AI algorithms, which make predictions on empirical training data (k-means clustering, hierarchical clustering, etc.) (Zhang, 2006) (Sonka et al., 2014) (Nguyen and Le, 2013).

In following sections, the methodologies that have been suggested for 3D segmentation process are shown.

2.2.4 STANDARD SEGMENTATION METHODS

2.2.4.1 Region-based methods

Region-based methods use similarity criterion for segmenting. They avail neighbourhood point to combine nearby points that have similar properties to obtain isolated regions and consequently find dissimilarity among the different regions. In addition, region-based methods can be further divided into two categories: seeded and unseeded (Yuheng & Hao, 2017):

- Seeded region methods are considered a bottom-up approach because they include two steps: identification of seed points and growing them based on predefined criteria such as proximity of neighbour points or planarity of a surface.

- Unseeded region methods are a top-down approach since they start from a unique region, from which all points are subdivided into smaller regions, according to certain features. How to subdivide unseeded regions is very difficult and requires a prior knowledge (e.g. number of regions, object models, etc.).

In 3D, these methods divide the point cloud or mesh into regions based on points (seeded points) with similar characteristics such as geometrical features, chromatic values, etc.

The algorithm was introduced by Besl et al. (1988) and several variation are presented in literature. Initially, Tovari et al. improved a method for separating object points from ground points in sets of airborne laser scanner data (Tóvári & Pfeifer, 2005); Pu and Vosselman (2006) adopted a planar surface growing algorithm for segmenting TLS data. Ning et al., (2009) proposed a method founded on two stages: "Rough segmentation" was first adopted for classification of objects, and further "detailed segmentation" was implemented for object components.

Vo et al., (2015) introduced an octree-based region growing method to classify points of urban environments and adopted a coarse-to-fine concept to improve the efficiency of the classification.

James et al., (2017) developed an intuitive method of enhancing the selection of required features of a triangular mesh during the segmentation process (Fig. 8).

In some works, region-based methods were implemented for constructing more efficient grow criterion to allow the automatic measure of the discontinuity geometric properties from the point cloud (Chen et al., 2016)(Cao et al., 2017) (Ge et al., 2018).

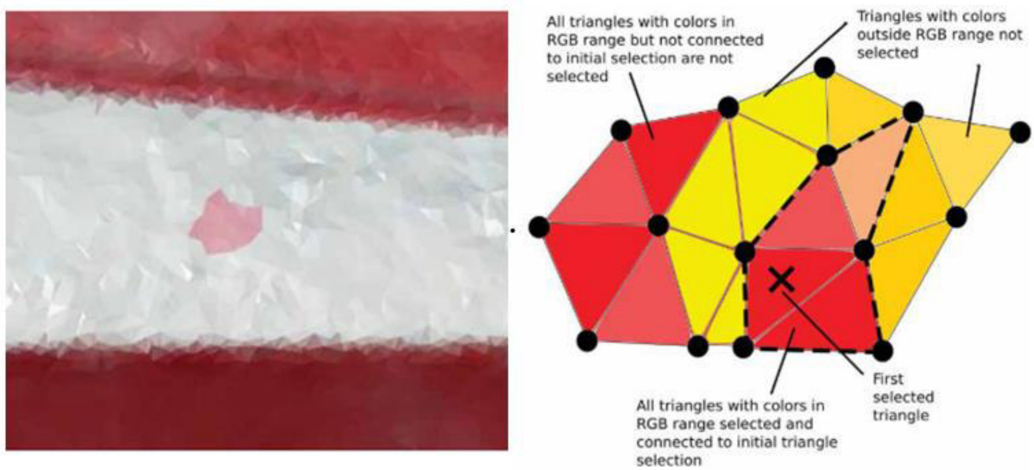


Fig. 8 a) The triangle selection (pink triangles) as an initial input of the colour segmentation algorithm. b) Only triangles connected to other triangles in the RGB range are selected from the initial selection (James et al.2017).

A collection of region based algorithms is available in the Point Cloud Library (Rusu & Cousins, 2011).

In general, the region based methods are more robust to noise because of the using of global information. Nevertheless, these methods are sensitive to (i) the individuation of initial seed points - inaccurate selection of seed points can affect the segmentation process and cause under- or over-segmentation results - and (ii) inaccurate estimations of the normals and curvatures of points near region boundaries.

2.2.4.2 Model-based algorithms

Model-based algorithms are based on the assumption that objects can be decomposed into geometric primitives like planes, cylinders, and spheres, etc. Primitive shapes are fitted onto point cloud data, and the points that conform to the mathematical representation of the primitive shape are labelled as one segment.

The early model-based methods, Hough Transform (HT) (Duda & Hart, 1972) and Random Sample Consensus (RANSAC) (Fischler & Bolles, 1981), are widely employed and have been proven to successfully extract 2D and 3D elements.

The 2D HT, concerned with the identification of lines in the image, has been extended to 3D HT in Vosselman & Dijkman (2001) where it was used for the extraction of the roof faces and the generation of 3D building models by combining the extracted roof faces with the ground plans. Later, its principle has been extended to the extraction of other 3D geometric forms like cylinders (Rabbani & Heuvel, 2005).
The RANSAC is firstly introduced by Fischler and Bolles for 2D detection, then it has been proven by Schnabel et al. (2007) to detect basic shapes, for example cones, spheres, cylinders, planes from 3D point clouds as well.
The RANSAC is a global iterative method that robustly finds model parameters from a set of data points and it is used for segmenting both mesh and point cloud. It works constructing candidate shape primitives (planes, cylinders, spheres, etc.), in correspondence of randomly selected minimal sets from the point data (Fig. 9).

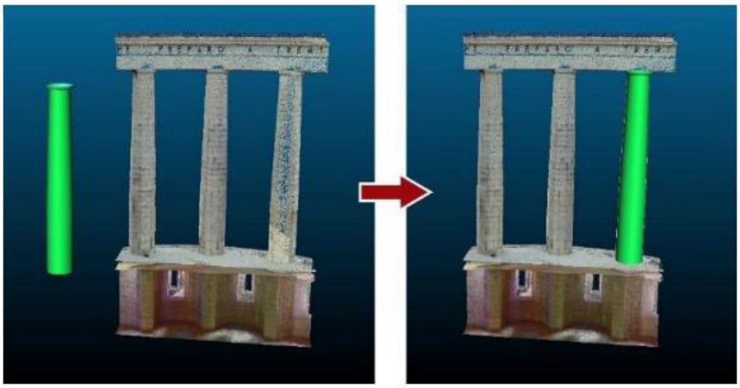


Fig. 9 Segmentation of 3D point cloud by model based algorithm (Grilli et al., 2017)

These sets are constituted by the smallest number of points required to uniquely define a geometric primitive. The primitives are verified for all points in the dataset, to understand how many points they can approximate.
The procedure is recursive, and it stops with the extraction of the shape approximating the major number of points. The limit of acceptance is related to a pre-determined probability that there is no better candidate for the considered set of points. The remaining data are tested against a new primitive, following the same scheme.

In (Tarsha-kurdi et al., 2008) RANSAC and HT are compared for automatically detect roof planes from point cloud laser data and the conclusion was that RANSAC is more efficient due to it can process a large amount of input data in negligible time. On the other hand, 3D HT is slower and more sensitive to the segmentation parameters values.

Zeineldin & El-fishawy (2017) gave a review study of the most recent RANSAC enhancements techniques. In addition, the work covers the solving techniques for the speed, accuracy and optimality problems.

Several extensions are available within the Point Cloud Library i) MLESAC (Maximum Likelihood Estimation SAmple and Consensus) ii) MSAC (M-estimator SAmple and Consensus), iii) PROSAC (Progressive Sample and Consensus)(Grilli et al., 2017).

Model-based methods are fast and robust with outliers. Their efficiency for the 3D detection of primitives has been tested, producing an efficient shape descriptor with insight over the geometrical properties of a point cloud sample. Due to it isn't able to recognize complex shapes or to ensure fully automated implementations, the use of the richness of surface geometry through local descriptors provide a better solution (Poux et al., 2016). However, in the architectural field, details cannot always be easily traceable into recognisable primitive shapes. Thus if some entities can be characterized by geometric properties, others are more readily distinguished by their colour content (Barnea & Filin, 2013).

2.2.5 MACHINE LEARNING FOR 3D DATA SEGMENTATION

Machine learning (ML) was introduced for the first time from Samuel (1959) and it is a data analysis method that automates the construction of analytical models. It is a branch of Artificial Intelligence –including Deep Learning, Neural Network, etc.- and it is based on the idea that systems can learn from data, identify patterns on their own and make decisions with minimal human intervention. It embraces some segmentation algorithms such as hierarchical clustering, K-means or mean shift.

ML algorithms build a model based on sample data, known as training data, in order to make predictions or decisions. Training data are the characteristics features - such

as relations between observed variables- in the given training set that can powerfully/sufficiently help us build an accurate predictive model.
Therefore, the basic problem of ML consists to find the clustering method, namely to find homogeneous groups of data points in a given data set. Each of these groups is called a cluster and can be defined as a region in which there are some similarities and differences from the others. The class labelling procedure is usually achieved following three different approaches (Alloghani et al., 2020):

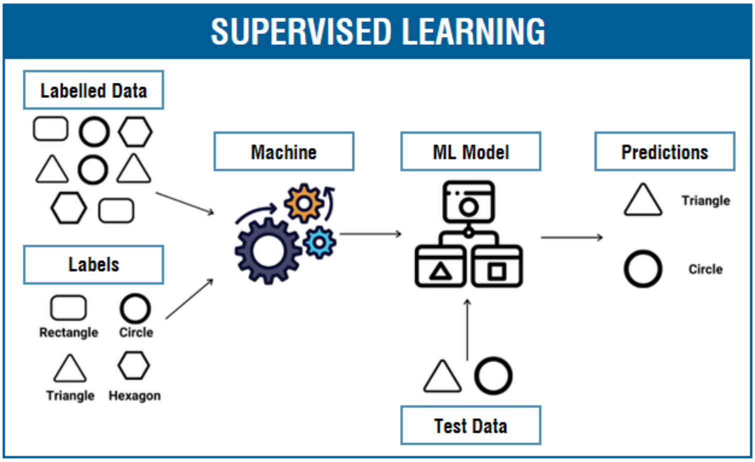


Fig. 10 Supervised learning approach workflow

- Supervised learning approach: its application consists in the use labelled data, i.e. a data set that has been classified, to infer a learning algorithm. The data set is the basis for predicting the classification of other unlabelled data through the use of machine learning algorithms (Fig. 10). Two important techniques in supervised learning are the Regression and Classification. Regression techniques is used in predicting, forecasting, and finding relationships between quantitative data. A regression problem is when the output variable is a real value, such as “dollars” or “weight”. Classification Techniques focused on predicting a qualitative response by analysing data and recognizing patterns. (Talabis et al., 2015). A classification problem is when the output variable is a category, such as “red” or “blue” or “disease” and “no disease”. Some popular examples of supervised machine learning algorithms are: Linear regression for regression problems, Random forest for classification and regression problems (Sub-Sec. 2.2.5.1), Support vector machines for classification problems.

- Unsupervised learning algorithms: the model automatically partitions data into groups using the method chosen from the user. Previous annotations aren't necessary. For this reason, the outcomes might not be aligned with the objectives of segmentation (Fig. 11). Unsupervised learning problems can be further grouped into Clustering and Association problems. The goal of Clustering problem is to discover the inherent groupings in the data. The Association learning problem is used where the aim is to discover rules that describe large portions of your data. The most used unsupervised approach, for its simplicity of implementation and convergence speed, is clustering. Common clustering algorithms are hierarchical, k-means, and Gaussian mixture models. Some of them will be addressed in the following sections (2.2.5.2, 2.2.5.3)

- Semi-supervised learning approach: this approach sits in between both supervised and unsupervised learning. It is used when there is a large amount of input data and only some of the data is labelled (Bergamasco et al., 2011). Many real world machine learning problems fall into this area. This is because it can be expensive or time-consuming to label data as it may require access to domain experts. Whereas unlabelled data is cheap and easy to collect and store. Generally, unsupervised learning techniques is applied to discover and learn the structure in the input variables while supervised learning techniques to make best guess predictions for the unlabelled data, feed that data back into the supervised learning algorithm as training data and use the model to make predictions on new unseen data.

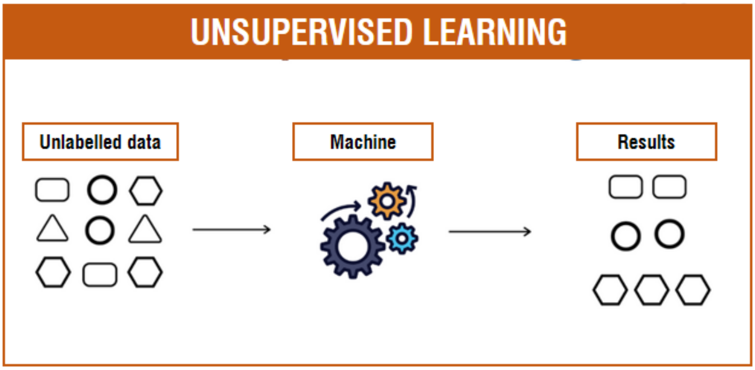


Fig. 11 Unsupervised Machine learning approach workflow

From descriptions above emerges that applying ML approaches data are not only segmented but also classified.

As previously mentioned (Sub-Sec. 2.1.1), in recent years, ML methods have been used in literature for semantic segmentation purpose in Cultural Heritage (Grilli et al., 2017)(Xie et al., 2020)(Fiorucci et al., 2020).

2.2.5.1 Decision trees and Random Forest

Decision Tree is one of the most widely used and practical method for supervised learning, in fact, it is used for both classification and regression. Decision Tree Analysis is a general, predictive modelling tool that has applications spanning a number of different areas. In general, decision trees are constructed via an algorithmic approach that identifies ways to split a data set based on different conditions. The goal is to create a model that predicts the value of a target variable by learning simple decision rules inferred from the data features.

A decision tree consists of three components: decision nodes, leaf nodes, and a root node. A decision tree algorithm divides a training dataset into branches, which further segregate into other branches. This sequence continues until a leaf node is attained. The leaf node cannot be segregated further. The nodes in the decision tree represent attributes that are used for predicting the outcome. Decision nodes provide a link to the leaves. The following diagram shows the three types of nodes in a decision tree (Fig. 12).

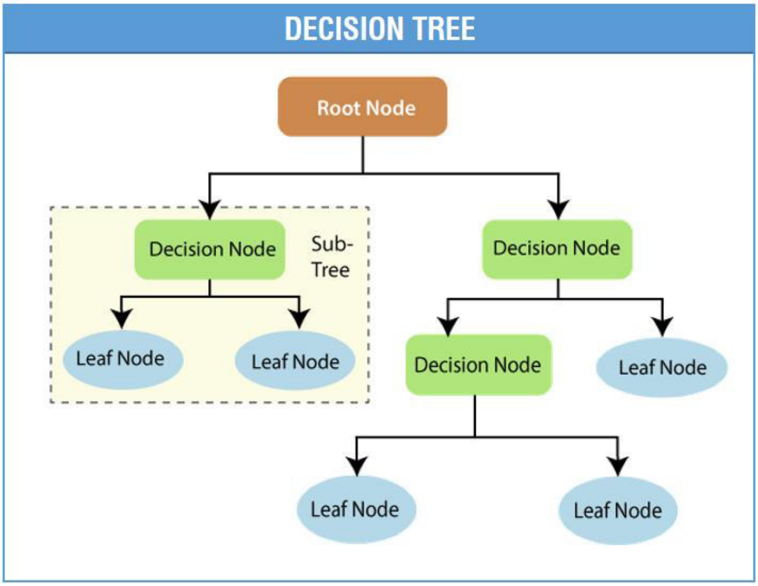


Fig. 12 The workflow of the Decision Tree algorithm

The widespread use of decision trees is due to their simplicity to understand and interpret. Trees can be visualised and requires little data preparation. Therefore, it is able to handle both numerical and categorical data permitting the validation of a model using statistical tests. It performs well even if its assumptions are somewhat violated by the true model from which the data were generated.

The disadvantages of decision trees include the overfitting, therefore mechanisms such as pruning, setting the minimum number of samples required at a leaf node or setting the maximum depth of the tree are necessary to avoid this problem. Moreover, decision trees can be unstable, so it can not guarantee to return the globally optimal decision tree, consequently it is recommended to balance the dataset prior to fitting.

The classical decision tree algorithms have been around for decades and modern variations like Random Forest (RF) (Breiman, 2001) are among the most powerful techniques available.

A RF algorithm consists of many decision trees. The ‘forest’ generated by the random forest algorithm is trained through bagging or bootstrap aggregating to avoid the overfitting problems:

- Bootstrap: Random subsets of the considered features when splitting nodes;
- Bagging: Random sampling of training data points when building trees. Bagging is an ensemble meta-algorithm that improves the accuracy of machine learning algorithms.

The main difference between the decision tree algorithm and the RF algorithm is that establishing root nodes and segregating nodes is done randomly in the latter. The random forest employs the bagging method to generate the required prediction.

Bagging involves using different samples of data (training data) rather than just one sample. A training dataset comprises observations and features that are used for making predictions. The decision trees produce different outputs, depending on the training data fed to the random forest algorithm. These outputs will be ranked, and the highest will be selected as the final output.

Instead of having a single decision tree, the RF will have many decision trees. The outcome chosen by most decision trees will be the final choice. The training data is fed to train various decision trees. This dataset consists of observations and features that will be selected randomly during the splitting of nodes.

For these reasons RF can handle large datasets efficiently and it provides a higher level of accuracy in predicting outcomes over the decision tree algorithm.

RF has become popular within the remote sensing community due to the accuracy of its classifications (Belgiu & Dra˘gut, 2016). The RF classifier has been successfully used to map urban buildings (Belgiu et al., 2014), to improve urban object classification from airborne LiDAR data (Chehata et al., 2009)(Niemeyer et al., 2014), and also for image objects delineated by segmentation (Li et al., 2015). A few studies have also explored the use of random forests in the classification of Unmanned Aerial Vehicle (UAV) data (Ma et al., 2015). In (Grilli & Remondino, 2019) RF has been used with a set of selected image features to produce pixel-based segmentations for heritage constructions. According to Weinmann (2016) RF can be considered as one of the most suitable classifiers for point cloud analysis.

2.2.5.2 K-means clustering

The K-means clustering is the simplest unsupervised learning algorithm and it was introduced in 1967 in (Macqueen, 1967). It is an incremental approach, data-partitioning algorithm, to classify a data set, into a fixed number of clusters (k), defined by their centroids (Fig. 13).

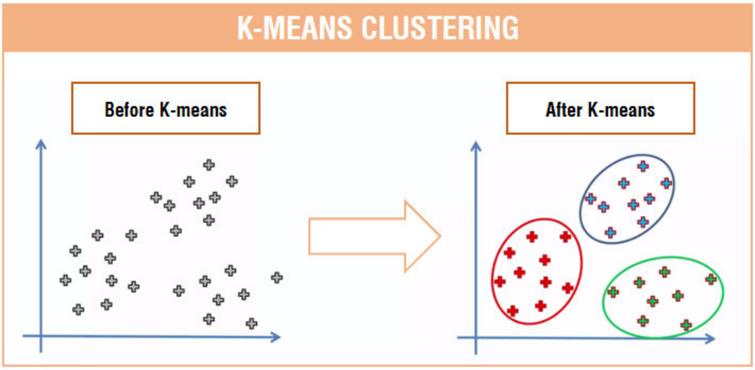


Fig. 13 K-means workflow

It is an exclusive method because each of the "n" observations are assigned to only one of the k clusters. The algorithm starts randomly choosing "k" initial cluster centres (centroid) and computes the distances between each point and each centroid. In every iteration of the procedure the centroids vary their position, in order to minimize the total within cluster variance (the average distance of the observations in a single cluster from the cluster mean) (Hastie et al., 2008).

The clustering centres of K-means are different from the seed points of region growing (Sub-Sec. 2.2.4.1). In K-means, every point should be compared to every cluster centre in each iteration step, and the cluster centres change when absorbing a new point. The process of K-means is "clustering" rather than "growing."

The K-means clustering is relatively simple to implement and it is useful for scaling large data sets guarantying every time convergence. The disadvantage consists in the difficulty to predict "K" value, and it has trouble clustering data where clusters are of varying sizes and density.

For its simplicity, K-means is applied in different fields i.e. in marketing to characterize and discover customer segments for marketing purposes (Hung et al., 2019), in biology for genetic purposes (Lu et al., 2004), in urbanism to extract suggestions on planning the healthy city (Zhou et al., 2019) or in earthquake studies for learning the earthquake-affected areas and to determine the dangerous zones (Novianti et al., 2017), in multimedia content for structuring data on the base of categories of object represented (Obeso et al., 2016)

In the field of AH, the data set is represented from 3D point clouds and the grouping is done by minimizing the sum of squares of distances between points and the corresponding cluster centroid (Grilli et al., 2017). It was relied for point clouds by various researchers (Shi et al., 2011)(Shahzad et al., 2012)(Zhu & Shahzad, 2014)(Wang et al., 2015b).

2.2.5.3 Hierarchical clustering

The Hierarchical clustering organizes data on its own, in hierarchical representations like cluster trees or dendrograms. Each level of the dendrogram collects groups of data with similar characteristics, and it results from the combination of the clusters at the lower level. Therefore, the whole structure consists in an ordered sequence, which allows the user to define the pruning of the dendrogram, on the basis of the specific application.

There are two main kinds of strategies for hierarchical clustering (Fig. 14):

- Agglomerative approaches start with every observation in its own cluster, and, at each level, pairs of clusters are merged into one, moving up the hierarchy recursively. The choice of the pairs is made, according to the smallest dissimilarity between clusters.
- Divisive approaches begin at the top of the hierarchy, grouping all the observation into a single cluster. They proceed splitting groups of data with the largest dissimilarity between clusters.

The hierarchical clustering guarantees an ease of handling of any forms of similarity or distance in data-set and consequently, applicability to any attributes types. However, for very large datasets, it can be computationally expensive and slow. In point cloud segmentation works, it was used for classification of LIDAR data (Chehata et al., 2008), for progressive compression of point clouds in respect of a prefixed level of detail (Fan et al., 2013), for fast plane extraction (Feng et al., 2014), for outdoor scenes (Xu et al., 2016) etc.

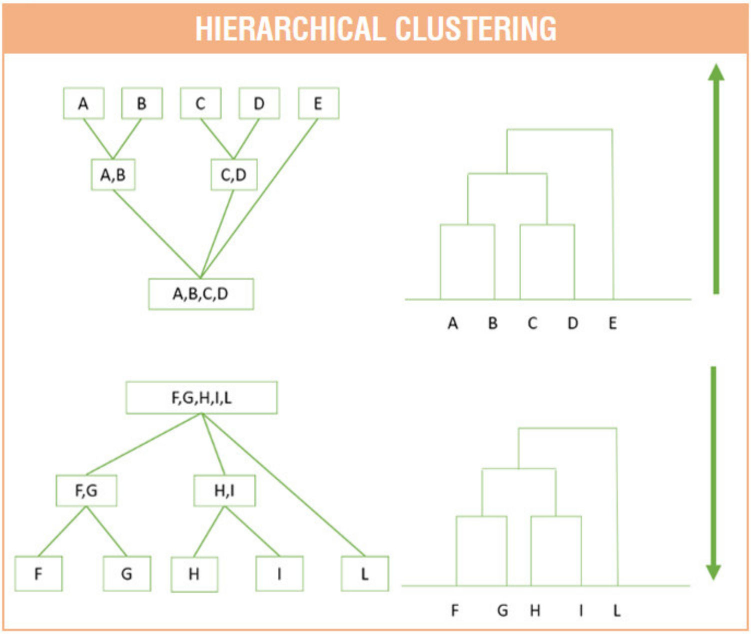


Fig. 14 Agglomerative Hierarchical Clustering (on the top), Divisive Hierarchical Clustering (below)

2.2.6 VALIDATION TEST

In the field of Machine Learning and specifically for classification problems it is important to validate the results obtained. Generally, the confusion matrix, also known as error matrix, is used. It is a specific table layout that allows visualization of the performance of a supervised or unsupervised algorithm. In the matrix, rows represent the instances in an actual class while columns represent the instances in a predicted class, or vice versa (Powers, 2014). In Table 1, four different combinations of predicted and actual values are shown.

A True Positive (TP) and True Negative (TN) are outcomes where the model correctly predicts the respectively positive or negative class. A False Positive (FP) is an outcome where the model incorrectly predicts the positive class. Similarity, a False Negative (FN) is an outcome where the model incorrectly predicts the negative class.
In Machine Learning applied to point cloud for segmentation, actual classes are represented by ground truth obtained, for example, using manual segmentation. Performance metrics of an algorithm are accuracy, precision, recall, and F1 score, which are calculated on the basis of the above-stated TP, TN, FP, and FN.

		Actual classes	
		True	**False**
Predicted classes	**Positive**	True Positive (TP)	False Positive (FP)
	Negative	True Negative (TN)	False Positive (FP)

Table 1 Confusion Matrix

Accuracy (1) is represented as the ratio of correctly classified data (TP+TN) to the total (TP+TN+FP+FN).

$$Accuracy = \frac{\mathrm{TP} + \mathrm{TN}}{(\mathrm{TP} + \mathrm{TN} + \mathrm{FP} + \mathrm{FN})}$$

(1)

Precision (2) (also called positive predictive value) is the ratio of correctly predicted positive observations(TP) to the total predicted positive observations (TP+FP).

$$Precision = \frac{\mathrm{TP}}{(\mathrm{TP} + \mathrm{FP})}$$

(2)

Recall (3) is the ratio of correctly predicted positive observations(TP) to the all observations in actual class (TP+FN).

$$Recall = \frac{\text{TP}}{(\text{TP} + \text{FN})}$$

(3)

F1 Score (4) is the weighted average of Precision and Recall.

$$F1\ Score = \frac{2 * (\text{Recall} * \text{Precision})}{(\text{Recall} + \text{Precision})}$$

(4)

Therefore, this score takes both false positives and false negatives into account. Intuitively it is not as easy to understand as accuracy, but F1 is usually more useful than accuracy, especially if classes have an uneven distribution.

In literature, Confusion Matrix permits the validation of classification and segmentation process in different works such as in (Sánchez & Quirós, 2017), (Valero et al., 2018),(Grilli et al., 2019), (Morbidoni et al., 2020).

2.3 BIM MODELING METHODS

In the field of new constructions, Building Information Modeling (BIM) is currently used to integrate a three-dimensional model and digital data of various fields with properties collected into an external file or database with a specific format. therefore, these platforms allow project designers, project managers, construction units, owners, and clients to view the design through a three-dimensional visual model and to obtain relevant digital data of the project.

In recent times, the HBIM (Historic Building Information Modeling) gives a very interesting research perspective. The main requirement in using BIM for representation and survey of historical architecture is the quality of the model and its reliability regarding the geometry. A second condition involves the addition of a comprehensive database of historical notes regarding each component about materials and changes during the time. (Quattrini et al., 2015).

The semantic organization is central in BIM environment. The parametric modelling technique is able to establish a relation among geometric and morphological characteristics of constructive elements and their attributes, permitting a geometric reconstruction enriched with multiple shared data (Eastman et al., 2011). The data collection of all significant aspects in 3D content may allow to HBIM become the best way to manage the process from survey to restoration (Oreni et al., 2017). The advantage of creating parametric objects on digital BIM platforms is that the resulting products are dynamic objects that can be transformed instantaneously (Barazzetti, 2016).

The reliability of 3D virtual reconstruction of the architectural heritage is the logical step towards the realization of "as is" BIM models for conservation and management purposes. "As-built" or "as-is" BIM refers to BIM of existing buildings where the model reflects the real conditions of the construction (Tang et al., 2010).

To develop a reliable HBIM model, one of the challenges is to convert the point cloud data obtained from the 3D digital survey techniques (Sec 2.1.1) into a three-dimensional information model as accurately as possible.

In particular, the major challenge of heritage BIM is the process of creating a parametric building information model from a point cloud. The first problem is that BIM software libraries do not contain complex elements found on heritage buildings, such as mouldings or ornaments, because BIM is originally optimised for the design of modern buildings The second problem is that nowadays platforms for HBIM no exist (Logothetis et al., 2015). Autodesk Revit, Graphisoft ArchiCAD are the most used BIM software for AH purposes (Radanovic et al., 2020). The third problem is that the BIM is volumetric while point clouds only represent the external shape, so information such as materials, construction procedures, wall thickness, the composition of assembly, but also installations are lacking. This means that the reconstruction should be made by an expert who is familiar with the building.

The modelling phase of heritage BIM from point cloud is called Scan-to-BIM if the metric reference used is a point cloud. In literature three methods of modelling are individuated for obtain parametric objects.

a) Firstly, the conversion of point cloud in mesh or solid objects to avoid the limitations of regular parametric models and increase the geometric accuracy and visual fidelity of parametric heritage models for complex and irregular elements (i.e. vaults). Several authors have proposed the conversion of point cloud in mesh or solid objects. Macher et al., (2017) proposed to process point clouds into meshes only for complex surfaces and high level of detail. Banfi et al., (2017), Rodríguez-Moreno et al., (2016), Abbate et al., (2020) use NURBS (Non-Uniform Rational Basis-Spline) surfaces fitting with boundaries points of clouds. through software tools (generative tools), external to BIM platforms. This method is efficient when irregular and complex surfaces may be modelled (i.e. vaults) with flexibility. This is possible due to the use of in-teroperable and open source formats (such as *.dwg, *.dwx, *.sat, ACIS files).

b) The second method consist in importing point clouds in BIM parametric tools, in order to trace reference lines from the point clouds and modelling (Lòpez et al., 2018) adapting system families. In BIM software system families are the definition and the collection of all the elements that we can insert in a project. These may be modified according to project or representation needs. However, the process is predominantly manual and it can be developed in two approaches. The first approach consists of adapting architectural components already included in BIM software as system families to the reverse-engineered model (point clouds or polygonal surface meshes) as a guide(Oreni et al., 2014)(Yang et al., 2016)(Verdoscia et al., 2019). The second geometric modelling approach uses 2D cross-sections and/or plant derived from CAD or extracted from 3D data. In Herráeza et al., (2014) is shown how it is easy to determine 3D thicknesses the of a vault calculating the difference between the scans the interior vaults and the roof of the church. This approach is less computationally intensive than the surface-fitting approach, but it can lead to errors due to the components do not follow their real geometries(Kushwaha et al., 2020).

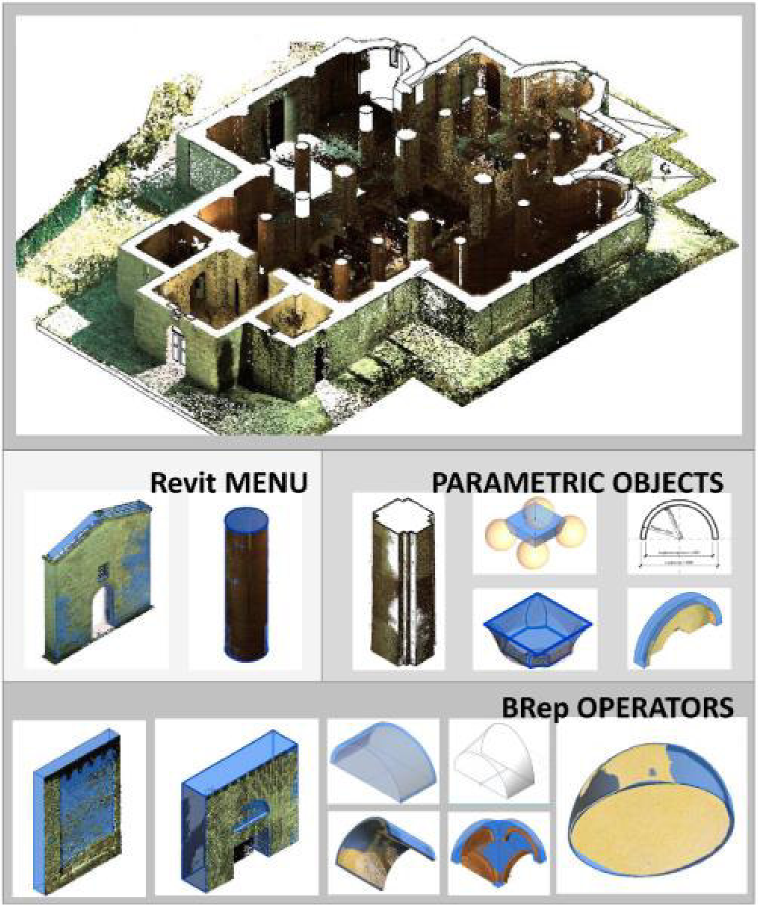


Fig. 15 HBIM from point cloud in Revit software. Building methods of architectural shape (Source: (Quattrini et al., 2015)

In other works the procedure was made semi-automatic through the creation of libraries such as in Fai & Sydor, (2013),Oreni et al., (2014), José López et al., (2017), Baik et al., (2017). Automation consists in the fact that library objects can be used quickly within the model. However, two problems arise from their use. The entire built heritage is characterized by a geometric and morphological heterogeneity difficult to generalize through adaptable standard elements. Subsequently, the creation of libraries remains a still manual process. To overcome this problem in Yang et al., (2018) Giovannini (2017) Visual Programming Language (VPL) software (i.e. Dynamo Studio

Autodesk®,, Geometric Descriptor Language – GDL or Grasshopper® by Graphisoft) connected to BIM software have been used for the construction of algorithms for generate *ad hoc* geometric primitives for the building condition.

c) The third method consists in the automated conversion of point clouds into parametric objects. In fact, currently, in literature, many researchers are developing methods for the automation some steps of the modelling phase of heritage buildings from the point clouds (Wang et al., 2019). The implementation consists of creating algorithms to generate model surfaces directly from point clouds, following procedural rules and constraints to extract features of different architectural elements and create parametric objects (Radanovic et al., 2020). Through boundary detection algorithms Wang et al., (2015a) had created an automatism for building geometries in BIM environment. These algorithms are generally integrated in software such as the Leica Geosystems CloudWorx, the As-Built for Autodesk®, and the Scan-to-BIM® by IMAGINit for Revit, or EdgeWise® ClearEdge3D, Pointsense, and Leica CloudWorx, that currently works only with laser scanned data, etc. Although they show excellent progress for the automation reconstruction of as-built BIM from point clouds, those works only deal with planar walls and floors and some other regular structures (i.e., rectangular openings and cylinder columns).

In the BIM context, sometimes is necessary the source-based modelling when the model is carried out from existing documentary sources (drawings, photos, etc.) using existent libraries or developing new parametric families to elaborate the BIM model. This kind of modelling is used for parts of the building that are inaccessible or destroyed (Apollonio, 2018).

In this thesis realty based and source based representation method will be adopted, in particular for the first a) and b) will be used for representing historic building.

According with topics descripted above, the sector studies propose different methodologies to modelling historical assets, but despite this, it is clear that some issues need further investigation: the accuracy and reliability of the survey, the adherence of the model to reality, the management of time and historical data, etc.(Barba et al., 2020) as we can see in following sections.

2.3.1 QUALITY ASSESSMENT FOR 3D RECONSTRUCTIONS ACCURACY

Generating three-dimensional (3D) as-is Building Information Models (BIMs), representative of the existing conditions of buildings, from point cloud data collected by laser scanner or photogrammetry techniques, or a combination of both, is becoming common practice (Sub-Sec. 1.3). However, the generation of such models currently is mostly performed manually, and errors can be introduced during data collection, pre-processing, and modeling (Garagnani & Manferdini, 2013). Inadvertent errors can happen in any step of this process, affecting the quality of the final product.

The complexity and heterogeneity of the building elements of historic buildings require to conduct a Quality Assessment (QA) of as-is BIMs to verify the completeness and accuracy of the model. Generally, the goal of QA is to design a procedure for an objective evaluation of the geometric accuracy of 3D models.

The definition geometric accuracy is used in this thesis to indicate the degree to which the model replicates the geometric state of the building in reality (Historic England, 2017). In literature, the accuracy is considered only one aspect of the geometric quality of a 3D model, and other aspects that have to should also be taken into account when comparing the model to a reference are completeness and correctness (Tran et al., 2019).

Nowadays, no exist guidelines of methods specifically for the Scan-to-BIM process in Heritage contest.

In GSA BIM guide for 3D Imaging (United States General Services Administration (GSA), 2009) are mentioned some ranges of tolerance for as-built deliverables such as a plan documents, point clouds and surface models, but no for BIM products . Moreover, two methods for checking the correctness of the BIM are proposed such as the visual checking method and the comparison between the model and the point cloud that is considered as optional. The Common BIM requirements 2012 –series 2 (COBIM) (Oy & Rajala, 2012) guideline highlight the necessity to integrate BIM in heritage process. In the guide are suggested accuracy levels for some BIM elements: corner points (10 mm), surfaces (25 mm), old irregular structures (50 mm) and historical details (5 mm). However, the guide does not mention a definition of BIM accuracy and methods for checking the accuracy of the model.

The British PAS 1192:2 (BSI, 2013) specification introduces the concept of checking the as is/as built model using point clouds which should be delivered together with the BIM to allow the users of the model to control the accuracy. Also in the BIM survey specification and reference guide of Plowman Craven (Plowman Craven, 2015), the use of point cloud for controlling the as-built or as-is BIM is proposed. In the text are defined three tolerance levels for vertical and horizontal deviations: low-level (60 mm), mid-level (30 mm), and high-level (15 mm) tolerance.

In the Metric Survey Specifications for Cultural Heritage (Andrews et al., 2015), a Level of Detail classification depending on a range of tolerance for heritage artifacts is suggested for BIM objects.

As we can see in the following section (Sub-Sec. 2.3.2), the "Level Of Accuracy (LOA) Specification Version 2.0"(USIBD, 2016), not only indicates a clear definition of 'measured accuracy' (reality vs. point cloud) and 'represented accuracy' (point cloud vs. model), it also defines LOA classes for "standard" and "heritage' building" (described in following Sub-section).

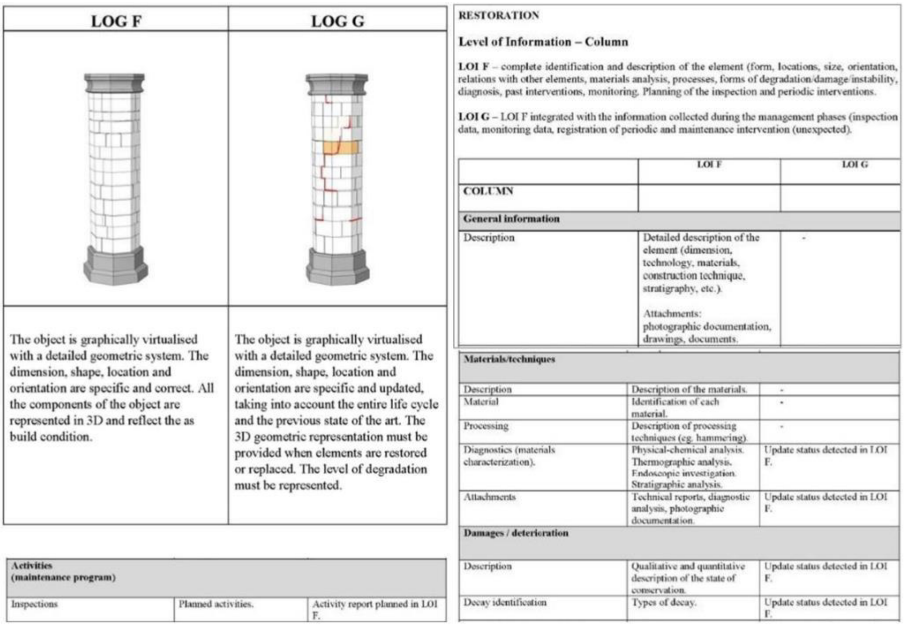
2.3.2 RELIABILITY IN ARCHITECTURAL HBIM MODELING

To take advantage of the full functionality of the BIM it would be necessary to connect to the geometric representation also informative completeness. The management of graphical and non-graphical information begins with the definition of the level of details, a concept with different definitions and specifications.

In USA, the Level of Development (LOD) consists of the content of objects in BIM, corresponding to the stages in the design and construction process (AIA, 2013)(BIMForum, 2018)(BIMForum, 2018), and organized by CSI Uniformat 2010. In UK, the PAS 1192-2, 2013(BSI, 2013)defines the Level of Definition, as Level of Detail (LoD) and Level of Information (LoI). the LOD of a digital object is considered as a result of the combination of the Level of Geometry (LOG) and the Level of Information (LOI).

The classification of LoDs, according to the UNI legislation, goes from grade A to G of completeness and graphic exemplification of the object.

The LoD refers to graphical elements, the LoI refers to the description of non-graphical information. In Italy, the concepts regain the English specifications introducing LOD for restoration activities (LOD F and G)(UNI/CT033-GL05 2017)Fig. 16.



LOG F	LOG G
The object is graphically virtualised with a detailed geometric system. The dimension, shape, location and orientation are specific and correct. All the components of the object are represented in 3D and reflect the as build condition.	The object is graphically virtualised with a detailed geometric system. The dimension, shape, location and orientation are specific and updated, taking into account the entire life cycle and the previous state of the art. The 3D geometric representation must be provided when elements are restored or replaced. The level of degradation must be represented.

Activities (maintenance program)		
Inspections	Planned activities.	Activity report planned in LOI F.

RESTORATION

Level of Information – Column

LOI F – complete identification and description of the element (form, locations, size, orientation, relations with other elements, materials analysis, processes, forms of degradation/damage/instability, diagnosis, past interventions, monitoring. Planning of the inspection and periodic interventions.

LOI G – LOI F integrated with the information collected during the management phases (inspection data, monitoring data, registration of periodic and maintenance intervention (unexpected).

	LOI F	LOI G
COLUMN		
General information		
Description	Detailed description of the element (dimension, technology, materials, construction technique, stratigraphy, etc.). Attachments: photographic documentation, drawings, documents.	-
Materials/techniques		
Description	Description of the materials.	-
Material	Identification of each material.	-
Processing	Description of processing techniques (eg. hammering).	-
Diagnostics (materials characterization).	Physical-chemical analysis. Thermographic analysis. Endoscopic investigation. Stratigraphic analysis.	Update status detected in LOI F.
Attachments	Technical reports, diagnostic analysis, photographic documentation.	Update status detected in LOI F.
Damages / deterioration		
Description	Qualitative and quantitative description of the state of conservation.	Update status detected in LOI F.
Decay identification	Types of decay.	Update status detected in LOI F.

Fig. 16 UNI 11337-3-2017 draft of the proposed LoG-LoI (‘F and G’). Source: (Brumana et al., 2017)

In addition to the LOD, especially as regards the documentation of existing buildings, particular importance is taken by the accuracy of the model compared to the existing. In this regard, in recent years in the literature have been investigated other levels of knowledge of BIM models for Heritage: some interesting studies (Bianchini &

Nicastro, 2018) have defined the Level of Reliability (LOR) and the Level of Evolution (LOE) and their methodological criteria. The restitution of the acquired data happens following processes of reconstruction for digital objects and observing strategies that are set on the knowledge and the critical interpretation of the operator.

In reference to these concepts it is possible to affirm that the reliability of the information represented, and therefore the LOR, is not only linked to the properties of the instruments and to the measurement approaches, but also and above all to the critical data processing process, the way they are managed. LOR is defined as the overall process consistency level that can define any digital object. With regard to reliability in relation to geometric characteristics, some research (Chiabrando et al., 2017) (Garozzo et al., 2019) have investigated the Level of Accuracy of the BIM model with respect to the point clouds from which the Graphic Detail was generated and defined, according to the level of precision related to the metric survey. Further reflections on the accuracy in terms of overall precision, were conducted with the work of Campi et al., (2017) which demonstrates how it is possible to obtain an optimal 3D model for the knowledge of the architectural heritage despite the lack of convergent protocols to achieve the precision required for modeling and representation.

2.3.2.1 Geometric accuracy evaluation methods

In this section existing methods for verifying geometrical accuracy of BIM model will be introduced to obtain a qualitative and/or quantitative comparison of the reconstructed model in the form of a BIM model, mesh, segmented point cloud (Radanovic et al., 2020).

The simplest is the visual inspection method which consists of a visual comparison by overlapping a 3D model to its point cloud. It does not require much computation, but it is subjective and cannot provide a quantitative evaluation.

The physical measurement method compares a set of measurements taken on the real building and their virtual correspondence in the BIM reconstruction (Anil et al., 2011). The values compared are then statistically analysed to obtain a confidence value. The advantage consists in avoiding the errors caused by scaling the point clouds. However, it also has some limitations since it is not possible to make an overall coverage of all the possible measuring (such for ceiling heights, complex morphologies), and directly identify the sources of error, because the limited number of measurements cannot provide sufficient information to distinguish them in the point clouds or in the 3D model. Furthermore, it is a time-consuming process that requires the collection of a large number of measurements.

In Anil et al., (2013), (Quattrini et al., 2015), Surface Deviation Analysis (SDA) is proposed to evaluate geometric accuracy of BIM model of existing modern building. Bitelli et al., (2017) and (Verdoscia et al., 2021b) showed the application of SDA applied to an HBIM model of an ancient irregular building.

This is a method born in the manufacturing contest and it is able to evaluate the geometric accuracy and localise modelling errors and their relevance in reference to a model adopted as a ground truth.

In the architectural domain, the comparison is generally carried out between a 3D model and a reference point cloud. A fundamental assumption is that the model and the reference point cloud should geometrically match in terms of tolerance. In fact, the deviation analysis dependents on the used mathematical model, the density of the point clouds and the order of comparison. Results of the analysis can be graphical and numerical. (Bonduel et al., 2017).

Carrying out a SDA requires three main steps. The first consists in the computation of the deviations of the point cloud from the BIM model, in order to find errors. To estimate the correspondences between the points and the BIM, it is possible to use direct or indirect methods based on mathematical models: i) the calculation of the minimum Euclidean distance to associate data-points with the objects that are in their close proximity; ii). projecting points on tree-dimensional surfaces; iii) tracing rays on the surfaces to find correspondences, or eliminating the matches by certain metrics (e.g., normal direction). In this thesis the minimum Euclidean distance has been used. One problem in its application consists in the fact that some points, such as those corresponding to furniture, may have no correspondence in the 3D model because they are not relevant to heritage reconstruction and are intentionally not modelled. The problem can be solved using a threshold to limit distraction caused by irrelevant points. The selection of the threshold depends on several factors, including scene complexity, data noise level, types of error being analysed, and accuracy requirements of the as-is model.

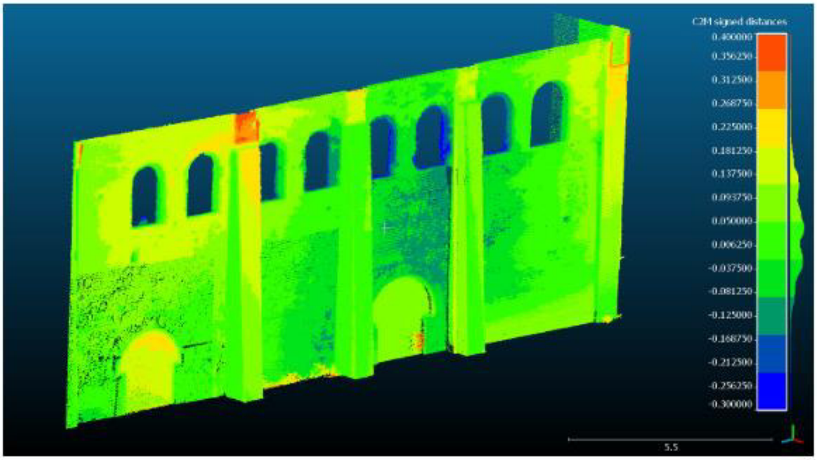


Fig. 17 Deviation Analysis applied to ancient building (Source00: Bitelli et al 2017)

The second step is visualising the correspondences through a colour-coded deviation map which is made by colouring each surface according to the different distances. The different errors result in deviation patterns, which can be analysed, so as to identify their sources, their type, and their relevance within the point-cloud data or those derived from the as-is BIMs. In Anil et al. (2011) are explained several colouring methods that can be used such as continuous vs. binary colouring, colouring points vs. colouring surfaces, signed vs. unsigned deviation maps, to support the maps' understanding. The choice of visualization method depends on the goals and requirements of the Quality Assessment process. To explicit with an example the first and the second steps, considering a wall, if the maximum deviation of the wall surface due to no-planarity is 5 cm, the threshold value shall be set at 5 cm. For lower threshold values, the exact size and position of the larger error cannot be identified because all regions with deviations above the threshold value are coloured with the same colour. Smaller thresholds are more effective for visualizing detailed deviations, such as local geometrical errors. Larger thresholds are more effective for visualizing modelling errors influencing the global geometries of larger components in the facilities. A data set can be analysed using a series of thresholds to identify different types of errors.

Finally, the third step consists in analysing the deviation maps to identify the deviation patterns (Fig. 18). This step is generally performed manually and requires a visually professional inspection of the deviation maps for identifying potential problems, and verifying the source, type, and magnitude of the errors. This step may be supported with additional information sources, such as site photographs, field notes, etc. of the building. Additionally, the professional may use other QA methods, such as the physical measurement method, in parallel with the deviation analysis method for a more effective QA.

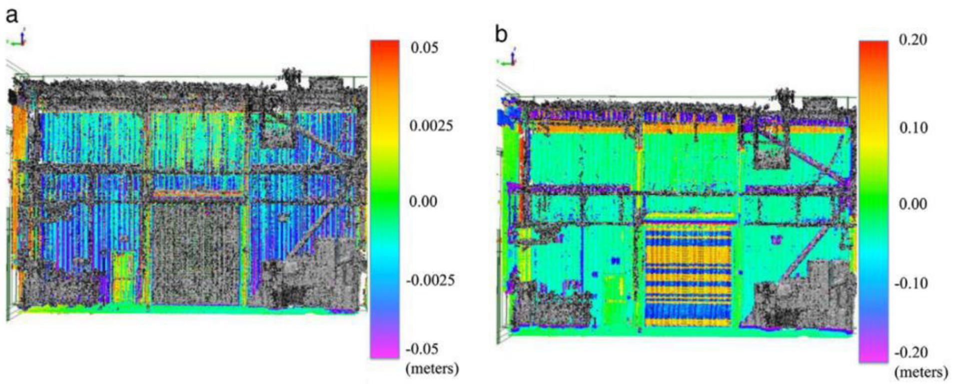


Fig. 18 Deviation maps with two different maximum deviation values. (a) at the 5 cm scale (b) At the 20 cm scale (Source Anil et al., 2013)

In BIM environment the geometric accuracy of the model may be expressed in Level of Accuracy (LOA). In "Level Of Accuracy (LOA) Specification Version 2.0"(USIBD, 2016), the US Institute of Building Documentation clarified the LOA in documenting the existing building and classified at a confidence level of 95 percent as expressed in the Table 2. The USIBD's LOA is structured in five increments of ten beginning with LOA10 and extending thru LOA50.

Level	Upper range	Lower range
LOA10	User defined	5cm
LOA20	5cm	15 mm
LOA30	15 mm	5 mm
LOA40	5 mm	1 mm
LOA50	1 mm	0

Table 2 Level of Accuracy (USIBD, 2016)

The abovementioned LOA may be comparable with the precision required for architectural restitution scales in restoration and refurbishment and other BIM standards about LOD. The level of accuracy accepted is a maximum of 3 cm of more than 60% of processed points (Quattrini et al., 2015).

Generally, the accuracy via deviation analysis can be assessed by the open-source software tools Cloud Compare[3] (Girardeau-Montaut, 2020), using the point clouds as reference (Quattrini et al., 2015) (Rodríguez-Moreno et al., 2016), or MeshLab (Cignoni et al., 2008) to measure differences between two meshes. Alternatively, As-Built™ for Autodesk Revit® allows the comparison between 3D model and point cloud.

Afterwards, the results of the deviation analysis can be represented in multiple ways: graphical with the use of 2D or 3D color maps or numerical (e.g. % of points within a certain LOA range).

Many of the available semi-automatic scan-to-BIM plugins can calculate and visualize deviations graphically, but they all use different methodologies and lack the ability to give a precise numerical indication of the accuracy per BIM object.

The HBIM model must be modelled with the Level of Development (LOD) 500 (AIA 2013) (corresponding to the Italian LOG F, with a geometric Level of Detail 500 (or the Italian LOG F). The specific provisions of the Italian UNI 11337-3-2017 introduces the LOD G for a detailed description of all the architectural components for refurbishment and restoration. Thus, the uniqueness and the state of the art of the

[3] CloudCompare: https://www.danielgm.net/cc (Accessed on February 08, 2022)

building are taken into consideration documenting materials and decay, and the updating of the interventions. Likewise, the consistent Level of Information (LoI) G is defined, with the aim of updating it during the building life cycle management and maintenance (Brumana et al. 2017).

2.4 SEMANTIC ENRICHMENT IN HBIM

Thanks to the structure of the BIM models based on relational databases (Relational Database Management System-RDBMS) it is possible not only to consult the data contained in them, but also the import and export of the same. Therefore, as described above (Sub-Sec. 1.4) it is necessary a semantic organization of data to take this advantage also in Architectural Heritage.

In literature, there are not many references on semantic data and on the enrichment of the HBIM model. Indeed, the question of documenting historical data in a 3D digital environment (i.e. photographs, archival documents and plans, original drawings, sketches, texts, etc.) or survey products (i.e. point clouds, orthophotos, etc.) is ignored or not investigated. Furthermore, there are no established guidelines or procedures that specify which data must be collected, how to process and organize them, or what information must be associated to an HBIM model. In most cases, these documents are generally stored in paper archives, so it is necessary for their conversion in digital format and organization (Fai et al., 2011).

As a result of the considerations of Volk et al., 2014, further developments of the methodology were initiated for knowledge management, not only in terms of collation of documentation and graphic and technical elaborations. A recent orientation of research aims to analyze data and information, in different formats, through increasingly automated procedures integrating Artificial Intelligence (AI) for the computation of alphanumeric data (Bienvenido-Huertas et al., 2019) and raster (Image processing)(Llamas et al., 2017)(Dang & Shim, 2018) to complement the documentation and storage process.

At the same time, research projects are being implemented to prepare data for advanced applications of the BIM approach during the semantic enrichment phase, using machine learning and logical inference to compile and compare the attributes inherent in the classification of the intended use of rooms in a residential building (Bloch & Sacks, 2018).

In order to concretize the integrated and computational management of the information, it is necessary to understand which tools and methods have at its disposal the BIM approach and the subsequent evaluation of the information systems listed below:

- Relational databases exported/imported with open source middleware such as ODBC (Open Database Connectivity) or proprietary interfaces, such as GDL in Archicad® or MDL in Bentley® (Eastman et al., 2011);
- Customizable and flexible applications developed through scripts (add-ins, also called add-ons or plug-ins), through using software libraries of a programming language as the Apis (Application Program Interface) or Visual Programming Language - VPL (supported for example. by Dynamo Studio Autodesk®,, Geometric Descriptor Language – GDL or Grasshopper® by Graphisoft) (Negendahl, 2015)(Bruno, 2017);
- Customizable cloud platforms, capable of connecting the three-dimensional model to relational databases of static attributes and Real-time Monitoring Sensors(Eastman, 2016), (Chien et al., 2017).

In literature, two different approaches in the organization of data are stated. The first is based on the only use of relational database (Sub-Sec. 2.4.1), instead, the second on the integration of database with ontological-scheme (Sub-Sec. 2.4.2) as we see in following sections. To hear the differences between the two approaches is necessary understand that using an ontology means adopting a conceptual schema-oriented approach, describing a specific domain, while using a relational database, means addressing the problem with a data-oriented approach.

2.4.1 RELATIONAL DATABASE FOR SHARING KNOWLEDGE IN HBIM

A BIM model can function as a web database that documents the inherent attributes of the parametric architectural objects. The BIM repository is a server system or a

database that collects the entire set of objects data, useful to facilitate information management. Indeed, BIM tools are software programs (more or less interoperable) where databases support the organisation and the collection of information, which is disconnected and sometimes unavailable, and reported in separate sources. Indeed, in BIM, semantic data are arranged or in the integrated database, by entering parameters, or associating external databases.
Database design phase addresses three main classes of problems (Bruno, 2017):

- identification of information and documents required and consequent data acquisition;
- data organization into a relational database;
- interoperability with the database and usability.

In Architectural Heritage (AH) environment, the documentation consists, first of all, of historical and photographic memories, archival documents and prior drawings, and secondly, of the products of architectural survey (point cloud, semantic data extracted, etc.), the analysis of materials/construction technique, analytical and typological studies about building conditions. In addition to generic problem of usability and accessibility of data, there are often problems of semantics and organization. In fact, the data are different in structure, format, content, and type. Their organization in a rigid structure, such as the relational tables of a database that is the basis and the core of information systems, is complicated also due to the fact that every architectural component in a historical building can present specificity that make the organization even more complex (Bruno et al., 2019a).
Furthermore, as we have discussed in Sub-Sec.1.3, in AH, there aren't unique and standardized procedures to build an information system, therefore it is more useful to trace guidelines and reference methodologies, which should be flexible and adaptable to specific requirements.
Another aspect is the multi-temporality of information which can be used for diachronic analyses(Rodríguez-Gonzalez et al., 2019), indeed the conservation process consists of continuous activities that requires constant updating of

information, the comparison with previous conditions and the continuous collection and processing of different data. Moreover, the multi-scale aspect has to be taken into account (Dou et al., 2020).

Thus, a semantic classification of the building is required not only for modelling purposes but also for the semantic data enrichment.

The Levels of Development (LOD) indicate the level of detail and reliability of both the geometric model and the associated information, in the Cultural Heritage field, this aspect does not find the correspondence. The UNI 11337 that, as pointed out in Sub-Sec 2.3.2, introduces specific LODs for restoration, but does not specify in detail the required information and semantic content.

On the contrary, in literature (Bruno, 2015)(Brusaporci & Maiezza, 2016), the historical nature of the investigation is taken into account detailing the structuring of historical databases or historical information systems.

Examples of information systems implemented at the architectural scale have been developed in the NUBES project (De Luca et al., 2017) or 3D IMPACT project (De Fino et al., 2020) which represent integrated frameworks, based on web technologies, able to manage and connect data about Cultural Heritage building, in order to describe, analyse and document the assets. 3D buildings representation takes into account shape, dimension, conservation state, hypothetical transformations in time, virtual tours, and for collecting and associating heterogeneous information.

In the field of managing information through external database in HBIM, Pauwels et al., (2008) developed an approach similar to BIM, namely Architectural Information Modelling (AIM) which describes more theoretical and historical building knowledge instead of the explicit and component-based descriptions inside BIM.

Fassi et al., (2015) have used a database for archiving and management of historical data implementing a web-based system. The database hosts the 3D models (in different format and level of detail), information and files (such as photo, video, documents, dwg, etc.) associated with the objects, maintenance and restoration activities with their relative information and files. It gives solution to problems of managing of big, high resolution and heterogeneous 3D models, ensuring data and information sharing. Quattrini et al., (2017), Simeone & Cursi, (2017), (Fiorani, 2017) have modelled an ontology with the main information needs for the building and a methodology that, using the BIM existing platforms and semantic-web technologies, make the user able to explore the 3D model and the associated semantic data. Mandelli et al., (2017) and Bruno et al., (2019a) have used connection of HBIM models to external relational database to diagnostic purposes.

From these works emerges that, relational databases allow both consultation of data and import and export by means of protocols connecting databases to an external data source (using ODBC - Open Database Connectivity drivers) or proprietary interfaces of modelling software. The management of the model data can take place through the use of spreadsheets (realized in Excel, Access, etc.), or using plug-ins of BIM software (Ideate-BIM Link, WhiteFeet Tools, Codeblocks, etc.), whose advantage is the ability to maintain the correlation between three-dimensional objects and information.

In both cases, it is possible to use database query languages such as SQL (Structured Query Language) which consist of standardized programming tools. The methods based on the use of relational databases are easy to use by users, even less experienced, because it is based on the processing of spreadsheets managed through scripts, predefined and easily available, to extract, compare, modify and integrate the data contained in it. In addition, the use of relational databases allows rapid communication of information that is easily accessible. So, implementing structured methodologies based on the connection of 3D models and relational database may support the documentation process.

2.4.2 ONTOLOGY-BASED REPRESENTATION FOR HBIM

In addition to geometric accuracy, a further aspect to be considered in the field of information technologies is the accuracy of information. The creation of archives, survey tools, and data collection requires a combination of technical and professional skills. This need is even more of primary importance in the world of Architecture Heritage due to together with the traditional methods of transmission of knowledge, there is a coding process based on the interpretation of documents (Nisheva-Pavlova

et al., 2008). As described in the previous in Sub-Sec.1.4, the collection, the organization, and the integration of data in a unique graphic-lexical structure, together with the semantic construction of the digital model meant not only as of the three-dimensional structure but as a cognitive system, are the core of the BIM system (Simeone et al., 2014).
The implementation of data collection processes and the development of semantically enriched 3D models is an effective way to improve the dialogue between ICT technologies, different cultural heritage experts, users, and different disciplines, both social and technical. The semantic structuring of the elements that constitute the model is a subjective and interpretative ontological action (Colucci et al., 2021). Therefore, in the commonly procedure based on the integration of data through parameters or associating of an external relational database, commonly tied to the element in a 1:1 relationship, the relational complexity is lost, for this reason, often the use of a database is not enough.
The presence of ontologies and the ability to reason on the knowledge that they allow us to represent, allow you to emulate the human logic based on the cognition of the cause in a determined reality. In the BIM environment, the critical operation of discretization in the transition from numerical models to geometric ones requires that the modeller proceeds from the continuum of reality to digital by making an interpretative step and exploring a hierarchical domain in which digital objects find their place.
In the cultural heritage context, International Committee for Documentation Conceptual Reference Model (CIDOC CRM)[4] is the main ontological reference model (Doerr, 2003), which became a standard since 9/12/2006: ISO 21127:2006. CIDOC/CRM provides definitions and a formal structure to describe the implicit and explicit concepts and relationships used in cultural heritage documentation by providing a common semantic framework on which any information can be mapped. CRM is configured as an ontology whose primary role is to serve as a support for the mediation of information on cultural heritage, necessary basis to transform today's

[4] CIDOC-CRM:https://cidoc-crm.org (Accessed on February 08,2022)

disparate and localized sources of information into a coherent and valuable global resource. Within CIDOC-CRM, different models have been developed to widen the representation field such as CRMdig which encodes metadata about the steps and methods of production ("provenance") of digitization products and synthetic digital representations such as 2D, 3D or even animated Models created by various technologies (Doerr et al., 2016), CRMsci (Doerr et al., 2015) for integrating metadata about scientific observation, measurements and processed data in descriptive and empirical sciences, or CRMba (Ronzino, 2015) to support buildings archaeology documentation.

Some projects on ontology for architectural heritage are ARMOS (Architecture Metadata Object Schema), a project for cataloguing architectural heritage. (Agathos & Kapidakis, 2019) or MONDIS which is an example of ontological framework for supporting documentation about damaged historical structures, for taking into account the diagnosis and possible interventions (Cacciotti et al., 2013).

In literature, some researchers have developed ontology-schema to describe acquisition and annotation of 3D digital survey process such as in (Drap et al., 2017), (Messaoudi et al., 2018), (Croce et al., 2021b), (Homburg et al., 2021). In other works the attention has been focused on structuring preliminary collected data (Nafis et al., 2019), (Giovannini et al., 2019)

Recently, some research works are implementing methods for allowing the possibility of developing a connection between a BIM environment with an appropriate, semantically enriched and flexible representation of information, starting from international standards, vocabularies, and ontologies (CityGML-Geography Markup Language, CIDOC-CRM, Industry Foundation Classes-IFC, Getty Art and Architecture Thesaurus) (Yang et al., 2020).

Previtali et al., (2020) and Colucci et al., (2021) have established a framework based on ontology-scheme for generating a parametric, structured model from point clouds. Dezen-Kempter et al., (2018) have developed an ontology-based strategy to defining the non-geometrical data necessary for obtaining a representation with two LOD (200 and 400). (Parisi et al., 2019)

In Cursi et al., (2017) and Simeone et al., (2019), authors have focused on the development of a BIM semantic-enrichment approach that integrates BIM and a knowledge base developed through information ontologies as a way to enhance knowledge representation and management in built heritage processes

An ontology or a complete conceptualization that is able to formalize semantically historical buildings does not exist in ICT. Although, in recent decades, many standards, vocabularies and some ontologies to represent the built domain and architecture have been developed and adopted internationally, none of these can define spatially entirely architectural elements of historical buildings and their relationships with the informative/documentary aspect that provides a complete picture of the condition assessment.

As we have stated, the use of ontologies in AH is becoming increasingly widespread. Indeed, this formalism is particularly suitable for heterogeneous data and offers concepts and tools to manage incompleteness, updates and revisions of the involved knowledge. Therefore, the way ontologies are structured is far from a traditional relational database, and managing them can be difficult for a person without a solid background in computer science. In addition, even if many research papers are published in the field of ontology for cultural heritage, the use of ontologies is not yet a common or widespread tool for managing documentation process.

Although, in recent decades, many standards, vocabularies and some ontologies to represent the domain of the historical built have been developed and adopted internationally, none of these defines the relationship between the element represented and the related documentary sources to facilitate the process of analysis of the conservation status to facilitate management, consultation and traceability of the data entered in the three-dimensional model and repeatability of the operations of construction of the morpho-geometric representation.

2.5 4D-HBIM: TIME DIMENSION FOR DOCUMENTING HISTORIC BUILDING OVER TIME

The Architectural Heritage is constantly subjected to enhancement and protection activities which require a multidisciplinary knowledge and the use of flexible instruments for the management of the information and the analysis of data acquired during the survey. In traditional practices, the information acquired are collected as paper or digital documents that are often difficult to consult and manage, especially if there is the necessity of comparing data about different chronological periods. These circumstances can cause the risk of misunderstanding the actual building conditions and pathologies' causes, as a result of the implementation of incompatible actions.

In the BIM environment, the 3D collaborative models are the evolution of 2D drawings for documentation. Furthermore, the possibility to add in the models the time schedule allows the virtual construction and space-conflict identification (clash detection) (4D). The 5D models integrates a 3D model with time, quantity take-off, and cost estimates for owners, project engineers, and managers. The last two dimensions are the sustainability of the entire building's lifecycle project consists of the 6D, and the use of all the precedent models support the facility management, maintenance, and operation (7D)(Acampa et al., 2020). The continuous evolution of the BIM "philosophy" has sparked a debate on the three "new dimensions of BIM" (which are not, to date, included in UNI 11337): the 8D dimension for adding information relating to safety in the design and execution of the work to the geometric model of the building. the 9D for lean construction, and 10D for industrialized construction(Rodrigues et al., 2018).

The knowledge of building evolution over time is essential for evaluating the current condition and defining strategies of maintenance and intervention (Yilmaz et al., 2007)(Binda & Cardani, 2015).Traditionally, the temporal analysis is the result of a reconstruction carried out on heterogeneous documentary sources such as drawing and reports (mostly paper-based sources).

The aim of obtaining semantically enriched information models is justified by the need to develop spatio-temporal databases capable of conveying and clearly showing how the building evolved over the time.

Nowadays, the integration of digital survey techniques (aerial and terrestrial laser scanner, photogrammetry, etc.) in the 3D reconstruction process in form of polygonal mesh or parametric objects (Chiabrando et al., 2018)(El-Din Fawzy, 2019), can consent the visualization of the constructive evolution of the historical artefact through the introduction of the time factor for better understanding the building conditions.

The temporal simulations may be considered non-invasive methodologies for analysing and monitoring historical sites and buildings (Doulamis et al., 2018), and are of immediate use because they can be viewed immediately from any device (Fritsch & Klein, 2018).

In literature, the time factor or fourth dimension (4D) and its addition to three-dimensional representations let record the historian's interpretation of documentary sources (Charbonneau et al., 2018), understand the development and transformations suffered by the manufact over time (Rodríguez-Gonzálvez et al., 2017), analyse their condition after the exposure to a natural event (earthquakes, erosion, etc.) (Fieber et al., 2017), enable stratigraphic analysis (Mammoli et al., 2021) and verify the adequacy of future recovery interventions. Furthermore, the 4D reconstructions permit the virtual access to urban spaces or partially destroyed historical artefacts (Rodríguez-Gonzálvez, 2019)(Hejmanowska & Mikrut, 2017), also through the connection to Virtual Reality for an immersive use of the model generated by technicians and users (Kersten et al., 2017)(Lee et al., 2019).

In the field of heritage buildings, the challenge represented by four-dimensional modelling requires additional adjustments and modifications for the integration of the knowledge about the environment and condition assessment of artefacts with the aim of accessibility, management, and global visualization.

The connection to Relational Databases enables information systems such as GIS (Geographic Information System) and BIM (Building Information Modelling) to integrate semantic data and represent the real world from different input like integrated surveys supporting the documentation process and consequently the decision-making and the problem solving actions (Rodríguez-Gonzálvez et al., 2017) (Vacca et al., 2018). GIS tools are used on urban scale (terrain, land parcels and outdoor data), instead, BIM tools on building scale (walls, doors, decoration) (Templin et al., 2019).

Furthermore, the hierarchization of architectural elements of BIM modelling facilitates the control and navigation operations of 3D models.

In literature and practice, within the HBIM model, the approach for documenting the transformations over time has been supported by assigning a constructive phase to the parametric objects (Rodríguez-Moreno et al., 2016). However, this approach limits the manual selection and the visualization of one constructive phase per time and, also, the extraction of independent descriptive tables does not help to assess decay and settlements caused by transformations (Fig. 19).

The modelling of a 4D-HBIM can offer several benefits: on the one hand, it enriches the knowledge phase of the conservation process and helps to affirm the authenticity and material of historic buildings. On the other hand, it supports and improves management strategies, which have been given increasing attention in recent years, as demonstrated by UNESCO's commitment to world heritage sites(Brusaporci & Trizio, 2014a).

Having analysed the evolution of heritage buildings over time from documentary sources, the state of conservation and the constructive and functional evolution of a historic building, the research objective is to develop a 4D modelling protocol to optimize data organization so information is easier to access and modify through the tools linked to the HBIM approach(Bruno et al., 2019b)(Verdoscia et al., 2020b)

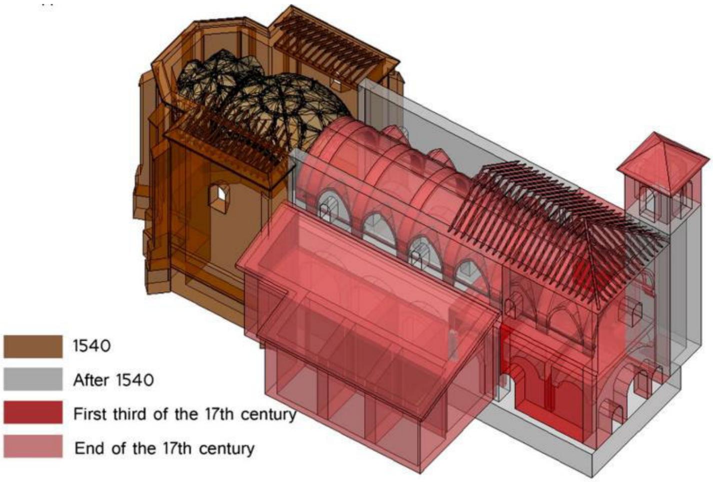


Fig. 19 Visualization constructive evolution of an ancient building in BIM model (Source: Rodríguez-Moreno et al., 2016)

The analysis of the existing research about HBIM and 4D reconstruction reveals the absence of an operative method with the aims of collecting, classifying, managing and sharing information and data relating to construction phases, transformations and interventions over time, and recording the state of previous and current decay phenomena of an existing building, benefiting from the 4D Information Management. The computational nature of the Historical Building Information Modelling (HBIM) approach has demonstrated flexibility in managing heterogeneous data sets on geometries and structural element properties, multiple construction technologies (walls, vault system, roof, etc.), and the decorative layers (frescoes, stuccoes, and frames) that contribute to the explanation of the construction sequences and technologies adopted and the current decay conditions.

3. METHODOLOGICAL PREMISES

Before explaining in more detail the methodological aspects and the applications in the chosen case studies, it is considered appropriate to briefly report, what were the fundamental premises for the research carried out.

As emerged from the state of the art presented in the previous section 2, with the concept of BIM means a process that concerns the development, analysis and management of a building from the creation of a 3D model. In the field of historic buildings, the HBIM model allows the incorporation and management of information, configuring itself as a useful repository in various areas of application of heritage conservation activities. The process of realizing an HBIM starts from the real object, that is, from the artefact and arrives at the model, that is to an abstraction of reality.

Therefore, the Heritage-BIM not only introduces the concept of three-dimensional parametric modelling in the historical context, but also proposes itself as an innovative process for the documentation, management, planning and maintenance of historical architectures. The advantages of this methodology consist in a greater control of the complexity of the specificities of the architecture thanks to the introduction of the informative data connected to the digital model as parameters. As reported in Sub-Sec. 1.4, positive results have been obtained in the evaluation of conservation interventions, structural analysis, performance, morphological, historical, etc. and finally in the greater accessibility of buildings through the integration of interactive 3D representations for cultural and educational purposes and uses. However, for the complexity and heterogeneity of historical contests, the application HBIM suggests the necessity of different approaches which consider the mandatory requirements and the limitations related to the methodology. The gaps encountered from the state of the art highlight the need for the following aspects:

- Integrate and enhance the semantic level of BIM extending the domain of representation to Cultural Heritage through the creation of libraries that enclose reusable digital objects or implementing methods to extract geometric data from the raw digital survey for speeding up and automatize the modelling process and obtain most accurate results. The virtual reconstruction procedure of the CH is not simple: the objects to model are made up of components with heterogeneous, complex and irregular morphologies. It is therefore essential to start from technical approaches, such as point clouds, to model the different virtual parametric components and obtain a BIM as a built model of the architectural heritage analysed.

- Include the knowledge necessary for understanding the existing asset of the building which cannot be directly included in its physical components such as the history of construction, construction phases, survey data, e.g.;

- Implement semantic segmentation methods able to structure and automatically classify the 3D survey data firstly identifying and quantifying architectural components and different states of conservation essential for monitoring or restoration purposes and sub sequentially for reducing time and manual stages of Scan to BIM process.

Currently, the Scan to BIM process (from digital data acquisition to the three-dimensional model HBIM) is consolidated and consists of a sequence of operational phases in the process for the realization of models for asset management historical architectural (Fig. 20).
However, from literature emerges the necessity of structuring consolidates and shared guidelines and procedures for the Scan-to-BIM process allowing the consultation and use of information, within the Scan-to-BIM process in the "vertical" direction, compared to the different methodological phases, and "horizontal"

compared to the different sources and data that identify each phase and architectural element.

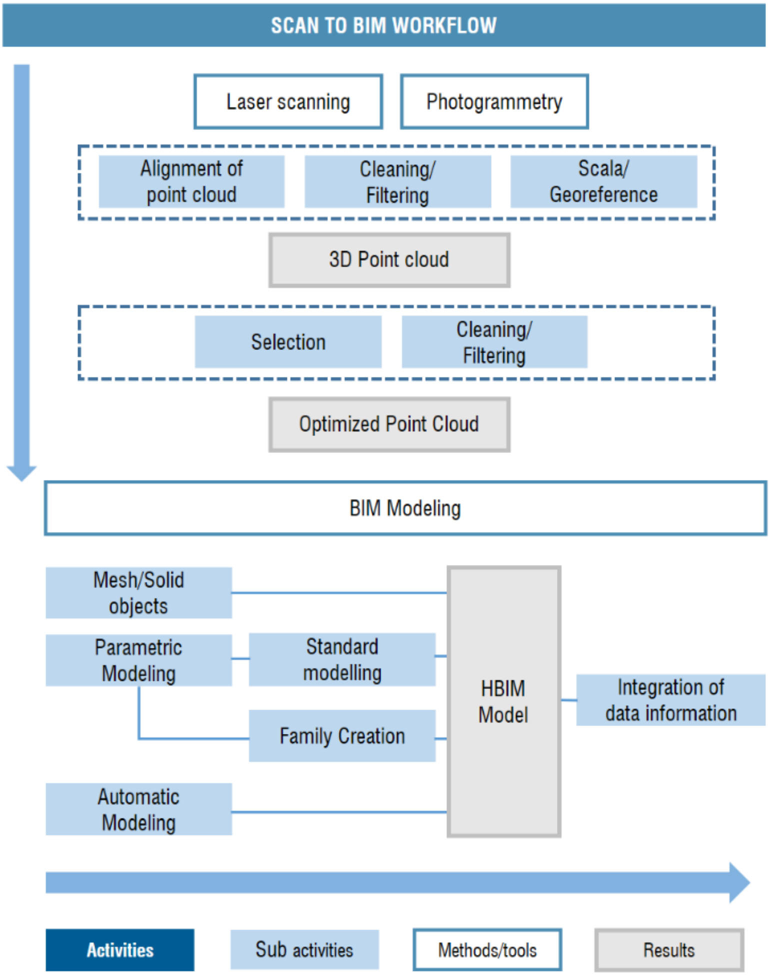


Fig. 20 Scan to BIM workflow

Focusing on the Scan-to-BIM process and previously summarised gaps in literature the proposed methodology enriches the illustrated workflow in Fig. 20, through the addition of implemented activities, described below, to permit the overcoming of cited limitations.

Indeed, in the proposed methodology great importance is given to the informative enrichment of the 3D models. In particular, methods (discussed in Sub-Sec. 3.1, 3.2, and 3.3) that include the parametric modelling at different levels; the automatic segmentation of 3D point clouds to optimize modelling times and to extract semantic data; and the procedures to add, manage and consulting documentation data through Relational Database Management System with a focus on the time factor (4D), will be carried out, exceeding the limits of the allowed static representation of current software authoring BIM. The proposed workflow is divided into six stages (Fig. 21):

A. Preliminary Knowledge and Data Collection;
B. 3D survey;
C. Data processing and filtering;
D. Semantic data extraction;
E. 3D modelling and information enrichment;
F. Data management and 4D simulation.

A. Preliminary knowledge and Information Collection:

The first stage consists in a preliminary evaluation of the manufact starting from its history and condition assessment. Previously the elaboration of a 3D model, a significant amount of documentation of different research fields (architecture, archaeology, history of arte, conservation, e.g.) have to be collect. First of all, the preliminary documentation consists of historical and photographic memories, archival documents and prior drawings. Secondly, a raw survey, a preliminary analysis of materials/construction techniques and, analytical and typological studies about building assessment have to be carried out for evaluating the condition assessment. Indeed, the understanding of the constructive evolution begins from the study of historical texts and project documents, stored in the archives.

Therefore, the data capture and the selection of devices and techniques start on the basis of information obtained from the documentation, and from the inspection of the space/place where the digitization will be performed. The information about size, accessibility, site condition, material, and texture can be very relevant for selecting the appropriate scanning method or to retrospectively judge if the object has been scanned with an appropriate scanning method in phase (C).

Furthermore, the information collected at this stage will be used for support the modelling phase (E) and, Data management and 4D simulation (F). Furthermore, the digitalization of the documentation collected in this phase may permit the addition of the extracted data to the 3D model in the informatization process (E).
Finally, the information gathered during this step are relevant for detailed planning of more systematic investigations for conservation process.

B. 3D survey:

The second phase is the 3D survey campaign that can be completed or using traditional direct survey (triangulation, total station, e.g.) or using different digital device such as laser scanner and or cameras for aerial or terrestrial photogrammetry, or a combination of survey techniques (Sub-Sec. 2.1). For ensuring the transparency and repeatability of survey activities and the quality of the data captured, it is necessary to add survey information to the 3D model (operators, digital device chosen, device settings, location of scanning position). In this research, the architectural survey will be carry out using non-contact surface techniques (as explained in Sub-Sec. 3.1,3.2, 3.3) such as Terrestrial laser scanner (TLS) (Sub-Sec. 2.1.1) and aerial and terrestrial photogrammetry (Sub-Sec. 2.1.2).
The selection of the more suitable method for survey depends on project budget, environmental conditions (lighting, temperature, presence of dust, e.g.), surface properties, identifying the presence of highly reflective ones, possibility of obstructions, required detail and accuracy, the features and size of the object, and the background. For example, in presence of low-textured objects laser scanner is preferable to photogrammetry, on the contrary, for artefacts placed on unsafe urban contests, the use of photogrammetry with UAV is more suitable than the terrestrial survey. Further factors that can influence the survey process are the sensor type, the acquisition time, the focal length, the exposure time, and the expertise of the operator who realizes the acquisition. Moreover, in survey process is important to annotate the scan/photo position and resolution, the type and number of marks/targets and their position.

These may consist in marks/target placed on the original as easily recognizable points, or images of the object. Marks are placed on the object on the base of its shape and an accurate recording of their position (using a GPS and/or a Total Station) are crucial to establish the accuracy of the acquisition. Registration may also be performed without marks, but usually this procedure reduces the accuracy of the overall dataset.

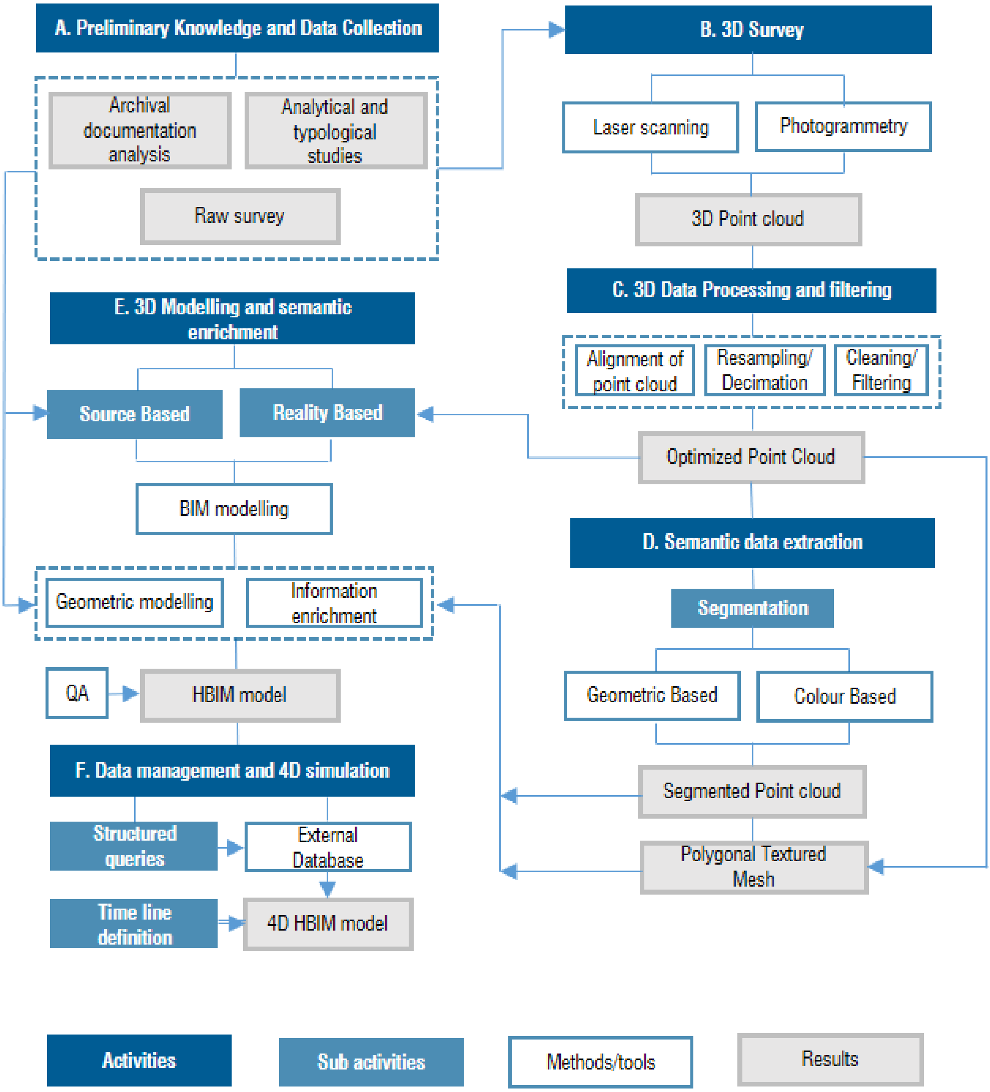


Fig. 21 Proposed workflow

Each scanner position and orientation angles must be defined according to a local or global site coordinate system. Indoor areas may require the set-up of a lighting system, so the position of every light must be decided and recorded, especially when RGB capture is expected.

The direct output of this stage are point-clouds. In the proposed workflow the point clouds are useful for three main purposes: generating an accurate metric reference to allow the real-based modelling in BIM environment; extract colourimentrical and geometrical data to support analysis of state of conservation and isolate architectural components in point clouds; elaborating the 3D texturized mesh, orthophotos and UV maps to be linked to the BIM model.
The elaboration of point cloud generated from photogrammetry has been done in Agisoft Photoscan © and/or Agisoft MetaShape©[5]. Instead the point clouds generate using TLS has been managed in Autodesk ® ReCap[6].

C. 3D Data Processing and filtering:

Generally, clouds acquired with TLS or photogrammetry must be aligned in one complete model because it is not possible to scan the object in one scanning step, availing of common parts which are made to coincide using target placed on the artefacts before survey activities as descripted in (B). Then they have to be pre-processed and filtered. In this thesis, (as explained in Sub-Sec. 3.1) point clouds from TLS have been aligned using Autodesk ® ReCap using *Cloud to Cloud* method, evaluating the final alignment through the parameters Overlap, Balance and the Number of points < 6mm. Instead point clouds from photogrammetry by Agisoft Photoscan © and/or Agisoft MetaShape©. Point clouds from photogrammetry aren't in the correct scale, then the model have been scaled through direct measures or points acquired via Total Stations.
The evaluation of the correct dimension of the photogrammetric point-cloud has been carried out through the Surface Deviation Analysis (SDA) (Sub. Sec. 2.3.2.1) in Cloud Compare, using C2C, considering the point cloud laser scanner as metric reference.
For combining the results of the two techniques (laser scanner and photogrammetry) the point clouds elaborated in Agisoft Photoscan © and/or Agisoft MetaShape© have been exported in *pts format, and embedded in Recap Pro®. The quality of

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[5] MetaShape: https://www.agisoft.com (Accessed on February 08, 2022)

[6] ReCap: https://www.autodesk.it (Accessed on February 08, 2022)

alignment has been evaluated with the algorithm ICP (Iterative Closest Point) in Cloud Compare through RMS (Root Mean Square), alignment error max and alignment error min parameters.
The point clouds are used to generate different outcomes (Sub-Sec. 2.1), so they have to be processed with different software. Indeed, point clouds are usually formed by a large amount of data, where many coordinates are redundant. To improve the information available, it is advisable to filter the clouds before starting post-processing activity (i.e. generate meshes, segmentation, etc.).
For each dataset, different processing procedures may be performed such as cleaning the range maps from noisy data or cleaning the borders of each scan in order to avoid redundant and noisy outputs. Sometimes may be necessary to apply dataset decimation and resampling to reduce the file size and the geometric complexity of the model.
Starting from in the representation phase, it is required to decode and organise the raw information obtained from digital survey in order to represent the morphological complexity of heritage buildings understanding the shape and geometry of the elements to be represented as well as their mutual relationships for building complete and intelligible representations. In this thesis cleaning of the boundaries and outliers and resampling operation have been performed using Cloud Compare (Daniel Girardeau-Montau, 2020) and Autodesk ® ReCap.
The output of this stage are the optimized point-clouds which will be the base to start following stages (D) and (E).

D. *Semantic data extraction:*

From Preliminary knowledge and Information Collection (A) and 3D survey (B) is possible to collect different kind of information that may contribute to the creation and the semantic enrichment of the BIM model. In the proposed framework, a further step consists in the manual or automatic extraction of semantic data from 3D point cloud through colourimetrical or geometric segmentation techniques.
As explained in Sec 2.2, point cloud segmentation can be achieved through a plurality of methods, diversified according to the data grouping criteria, on the basis of some

properties or features (like geometry, colour, size, shape, scale patterns, e.g.). Specifically, geometric segmentation is mostly deployed for detecting building components through geometric primitives within 3D point clouds. Furthermore, in this work colour-based segmentation on 3D data has been performed for the detection of decay patterns recognizable for their predominant colours or their chromatic differences. The results of the segmentation process can be used i) for qualitative or quantitative analysis ii) for the 3D modelling process (parametric, solid, mesh generation, i.e.) iii) for adding extracted features to the model as parameters.

In Sub-Sec 3.2, implemented Colour-based and Geometric-based segmentation methods, to extract semantic data from 3D data will be shown.

Colour-based methods are distinguished in Colour range-based (Sub-Sec. 3.2.2), Cloud-based (Sub-Sec. 3.2.3), and Texture-Based (Sub-Sec. 3.2.4). The difference consists in the format of data input and the typology of standard (Sub-Sec. 2.2.4) or supervised or unsupervised machine learning (Sub-Sec. 2.2.5) algorithm adopted. In Range-based and Texture-Based methods, the colour properties of orthophoto and UV maps, extracted from textured polygonal meshes obtained from photogrammetry point cloud, will be analyse. Instead, in Cloud-based method data input will be directly photogrammetry point clouds resampled in (C) with CloudCompare, for reducing the computational costs. As described in (B) photogrammetry point cloud, orthophotos, and UV maps have been elaborated in Agisoft MetaShape ©. Insights relatives to implemented methodologies and their validation will be explained in Sub-Sec 3.2.

Furthermore, Geometry-based segmentation, by RANSAC in Cloud Compare has been applied on laser scanner and photogrammetry point clouds (Sub-Sec. 3.2.6).

Outputs of this phase are segmented clouds and relative information about extension in dimensional and percentage terms which may be connect to BIM model as parameter like hypertext reference or URL generating it by online viewers (Sketchfab[7], WebSetNet, e.g.) or through external Relational Database System (Sub-Sec. 2.4) added to the model in (E) and managed in (F).

[7] Sketchfab: https://sketchfab.com (Accessed on February 08, 2022)

E. 3D modelling and information enrichment

Following the aim of creating a semantically set of objects for describing documentation of architectural elements, in the proposed workflow, the "as built" model components have been represented starting from 3D survey and archive information using the prior existent drawings for boolean operations, parametric object placement, or the "Scan-to-BIM" process. In some cases, when the model represents also decay assessment the model is called "as damage".

Modeling strategy has been chosen depending on the element to be represented. *Reality-based* modelling (Sub-Sec. 3.1)(Russo & Guidi, 2011), based on the digital acquisition of 3D survey of existing artefacts, and *source-based* modelling (Apollonio, 2018), which consist in a virtual reconstruction of damaged or lost construction and decorative elements (Sub-Sec.2.3).

The state of the art (Sub-Sec. 2.3) has shown that Scan-to-BIM may be performed as i) the automatic conversion of point cloud/meshes - captured via laser scanning or photogrammetry - into BIM objects with plug-ins capable of processing geometry recognition algorithms (Paiva et al., 2018) or converting meshes into NURBS (Banfi et al., 2017) or ii) the import of point clouds into parametric modelling tools, in order to be used as a metric reference for manual procedures (López et al., 2018).

Parametric modelling (starting from system families of Revit Architecture©) was used for both kinds of modelling, instead for reality-based modelling also meshes has been generated.

The textured polygonal meshes obtained from the segmented point clouds have been processed for very irregular elements or shapes (decorative apparatus, frescos, alterations, e.g.), whose standardization by parametric modelling would cause loss of accuracy and precision. Indeed, the meshes can be inserted directly into the BIM model as a solid element, or, in alternative, they can be connected as parameter to the model like hypertext reference or URL generating it by online viewers (Sketchfab, WebSetNet, e.g.). This activity allows the acquisition of an accurate understanding of three-dimensional geometry and surfaces without losing information.

In this framework, the polygonal meshes from laser scanner point cloud are generated using through the Poisson Surface Reconstruction (Kazhdan et al., 2006) and/or the Delaunay Triangulation (Lee & Schachter, 1980) in Cloud Compare. Indeed, for photogrammetric point clouds has been used Agisoft Metashape©.

For other architectural elements (walls, columns, vaults, e.g.), the Scan-to-BIM process, using parametric modelling has been preferred. Therefore, in addition to the geometric representation, the adoption of the BIM methodology allows the consideration of other types of information (relationships, attributes, etc.) and the correct definition of level of graphic detail and informative. How explained in Sub-Sec. 3.1 in this thesis three Level of Detail (low, medium, high) have been used.

After the modelling process to evaluate the Quality Assessment of the BIM model has been evaluated through the Surface Deviation Analysis has been performed (Sub-Sec. 2.3.2.1) referring to LOA as explained in (USIBD, 2016) using FARO® As-Built™ for Autodesk Revit®[8].

The comparison of all the outputs of the Preliminary Knowledge Framework (A) and the 3D Survey (B), and Semantic data extraction (D) enhances the documentation of historical and technical preceding analysis and the identification of previous transformations and interventions, the material-constructive characterization and decay mapping, and the interpretation of condition assessment, such information to be included into the parametric model. This set of attributes is inherent to constructional and material features, description of decay patterns, report and motivation of the previous interventions, useful to semantically enrich the model. These kinds of information may be insert in the BIM authoring software as instances of parameter and/ or connecting the model to an external database through Relational Database Management System (RDBMS) (Sec.2.4.1). The method for the addition of information to an HBIM model has been performed in Sub-Sec. 3.3.

F. *Data management and 4D simulation.*

[8] FARO As-Built: https://www.faro.com(Accessed on February 08, 2022)

The proposed management of HBIM information system (explained in Sub-Sec. 3.3) takes advantages through the use of Relational Database Management System (RDBMS) which allows the management of information or included in external database created in Access and/or Excel or added directly in BIM environment and that can be imported/exported from the 3D model via database management tools and compatible with the ODBC Driver of the employed multi-model-based management system. Indeed, Autodesk® Revit® permits the export of object parameters as external database via database management tools (i.e. the Ideate BIM link plug-ins (Ideate, n.d.), Revit DB link ('Access Autodesk Revit DB Link', n.d.), and the export tools embedded in the software.

Designing a database is a process made of the following steps: a) Analysis: this phase concerns the process of creating a conceptual data model: the result is an entity-relationship model. b) Design: is the process that creates the logical data model; c) Implementation: is the process of creating a physical model for a specific database system (Sub-Sec. 2.4.1).

The Navisworks® Manage software has been tested for the management of the "as-built/as damage" HBIM model, as it is a BIM tool for viewing and managing information systems, despite being created for cost and time coordination; moreover, it supports the control of database and the data management via Structured Query Language (SQL) in order to have the possibility of simultaneously modifying the models in both the software products.

The last step is the 4D-HBIM simulation realized in Navisworks® Manage[9]. Each element of the HBIM model was associated to its time parameter for representing constructive evolution and the current state of conservation in a time line. The 4D-HBIM simulation of previous events and the correlation of related information could support the identification of the causes of current decay patterns associated to human interactions with the building.

[9] Navisworks: https://www.autodesk.it/products/navisworks (Accessed on February 08, 2022)

3.1 A NOVEL PROPOSAL FOR AS-BUILT HBIM MODEL

The research issues that emerge from methodological critical review in Sec. 2 concerning the BIM process for heritage buildings are related to different aspects.

First of all, the advanced automated methods of survey techniques, Terrestrial Laser Scanner (TLS) and Close-Range Photogrammetry (CRP), produce a cloud of points, which has the capacity of capturing very fine details but, at the same time, the conversion to a 3D model is still intricate and time-consuming.

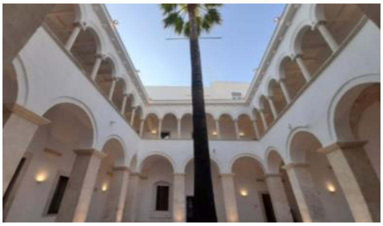
Another aspect regards the geometric accuracy which can be obtained using standardized parametric elements in relation to the irregularity and specificities of historical buildings. Indeed, the realization of "as-is/as-built" models refers to the BIM of existing buildings where the model reflects the real conditions of the construction. To develop a reliable HBIM model, one of the challenges is to convert the point cloud data into a three-dimensional information model as accurately as possible.

In this Sub-Section, a new proposal, for implementing (E) 3D modelling and information enrichment (Sec. 3), to obtain geometrically accurate BIM models is defined. Specifically, starting from the Scan-to-BIM process, parametric representation methods have been tested starting from adaptive models for construction elements such as vaults, system families and loadable for walls, arches, trusses, etc. and solid modelling for decorative apparatuses.

In addition, the possibility of constructing the three-dimensional model with three levels of geometric detail (low, medium, and high), and of integrating output of reverse engineering as textured meshes has been developed. The accuracy of the model has been quantified through the use of the Surface Deviation Analysis (SDA).

3.1.1 CASE OF STUDIES

This approach has been tested on historic masonry buildings characterized by different functional use, state of conservation, geometry, morphology, materials, technical components, and localization (Table 3).

Denomination	Location	Photo	Year of Construction
1. Santa Croce Monastery	Modugno, Bari, Italy		1618
2.Church of San Domenico	Molfetta, Ba-ri, Italy		1636
3.Ognisanti Church	Trani, Bat, It-aly		12th century

4.The Arago-nese Castle	Taranto, Italy		1486
5.Baths of Diocletian (the rooms X-XI and a part of VIII of the National Roman Museum)	Rome, Italy		298 -306
6. Tomb of the Platorini in the Baths of Diocletian	Rome, Italy		I sec.

Table 3 Selected cases of studies

3.1.2 RESULTS AND DISCUSSION

From the analysis of the current literature HBIM (Sub-Sec. 2.3) emerges an increasing use of parametric modelling starting from 3D reconstructions via reverse engineering methods, thus combining traditional and innovative geometric surveys. In this section the "as built" 3D models have been constructed to document the condition statement of the buildings. For this reason, reality-based modelling (based on products of 3D digital survey techniques) have been preferred. However, for the inaccessible environments for the digital survey because not enough illuminated or for diffused scaffolding has been resorted to the traditional direct survey.

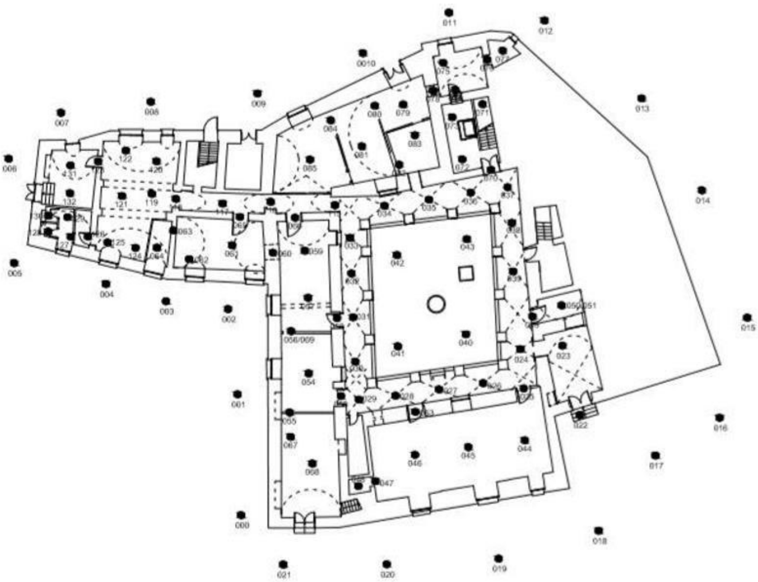


Fig. 22 Acquisition plan where coded dots represent scan position (Santa Croce Monastery, Modugno, Italy)

Referring to the steps of the workflow shown in the Sec 3, the 3D survey campaign (B) has been realized using terrestrial laser scanner (TLS) (Sub-Sec. 2.1.2) for the whole structure and aerial and terrestrial Close Range Photogrammetry (CRP) (Sub-Sub-Sec. 2.1.3) for limited portions (roof plan, decorations, capitals, etc.). For ensuring the whole covering of the building or of its portion, the pacification of an acquisition plan has been drawn up to optimize the ratio between the number and

resolution of the scans/photos, the acquisition time and the overlapping response (Fig. 22).
The instrument used has been the Faro Focus 3D 120 CAM2 which allows an accuracy of 2 mm, a range from 0.6 m up to 120 m, a measuring speed of 976,000 points/second, a vertical and horizontal field of view of 305. and 360 angular. For each station have been set: the 20-25% of overlap and a constant distance of about 10 m between subsequent scans. Regarding the amplitude of the angle of grip this has always been set as a *target all 360*, the resolution has been set as an average resolution, that is 1 cm to 10 m. In Data processing and filtering (C), the scans have been carried out with the help of Autodesk ® ReCap software. The point clouds of every single scan have been checked, cleaned of superfluous data, aligned and fused together through *cloud-to-cloud* method to obtain the 3D reconstruction model of the whole building (Fig. 23Fig. 246).

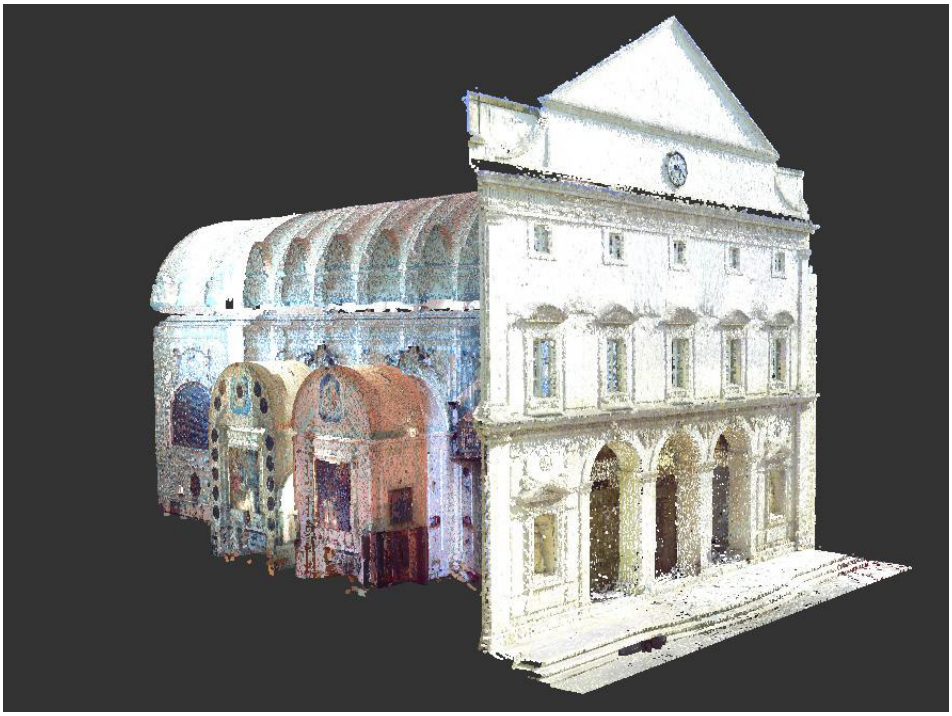


Fig. 23 TLS point cloud assembled with cloud-to-cloud method (Church of San Domenico, Molfetta, Italy)

Fig. 24 Section of point cloud of Santa Croce Monastery, Modugno, Italy

Fig. 25 Section of point cloud portion of Ognissanti Church, Trani, Italy

Fig. 26 Point cloud of Baths of Diocletian, Rome, Italy

The alignment results have been evaluated through the parameters Overlap, Balance and the Number of points < 6mm. The Overlap is a percentage of data that measures common features throughout the project; in particular, a high percentage of overlap ensures that the hidden parts of objects detected in a scan are visible in adjacent scans. The Balance, which must exceed 20%, shows the percentage of common functions in scans; the value indicates whether two surfaces overlap correctly but are slightly offset from each other. The third parameter, finally, indicates the percentage of points at a distance of less than 6 mm; this value should always be greater than 90%. The Balance was the most difficult to obtain correctly as the variation of boundary conditions such as atmospheric conditions could influence it. An example of report extracted from Recap in Table 4.

Scan Name	Overlap	Balance	Points < 6mm
Taranto001	49.0%	31.7%	99.6%
Taranto002	48.2%	31.0%	97.5%
Taranto003	43.0%	42.3%	97.3%
Taranto004	28.0%	41.0%	95.7%
Taranto005	26.8%	35.8%	95.0%
Taranto006	47.7%	11.3%	99.6%
Taranto007	51.1%	20.6%	98.9%
Taranto008	43.7%	17.4%	98.5%
Taranto009	10.7%	45.8%	99.1%
Taranto010	33.8%	34.3%	99.7%
Taranto011	30.7%	22.3%	99.0%
Taranto012	22.7%	28.6%	99.9%
Taranto013	42.2%	25.8%	99.9%
Taranto014	18.8%	23.8%	99.9%
Taranto015	10.5%	50.1%	98.5%
Taranto016	71.6%	8.2%	99.6%
Taranto017	82.4%	5.9%	99.6%
Taranto018	57.9%	11.6%	99.8%
Taranto019	68.1%	3.4%	98.5%
Taranto020	73.3%	6.6%	99.4%
Taranto021	59.5%	10.4%	99.8%
Taranto022	64.6%	15.4%	99.9%
Taranto023	53.1%	12.1%	99.8%
Taranto024	67.8%	5.6%	99.8%
Taranto025	58.8%	37.0%	99.7%
Taranto026	20.2%	42.3%	99.6%
Taranto027	68.6%	8.7%	99.8%

Table 4 Part of the report extracted from Recap about The Aragonite Castle of Taranto, Italy

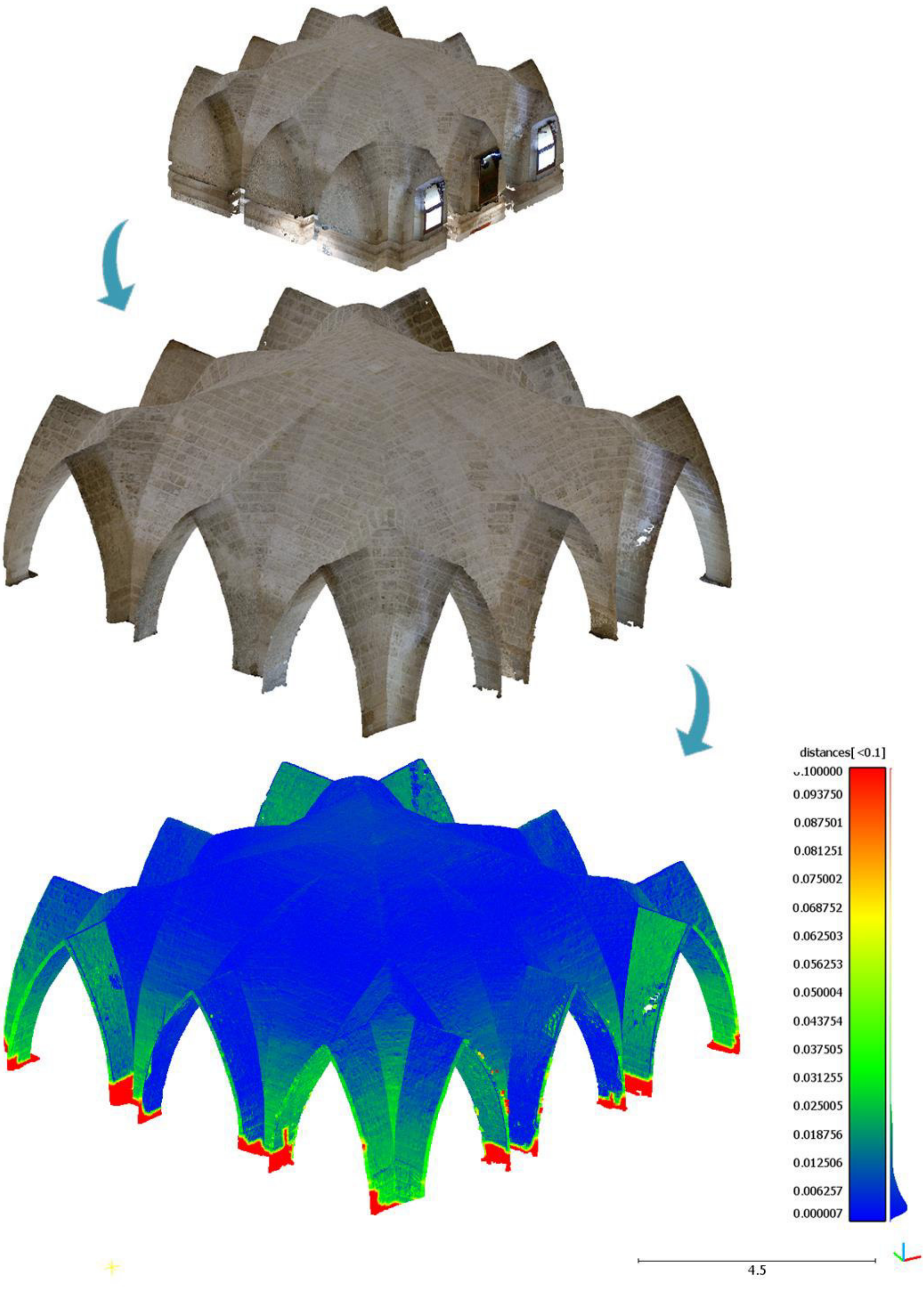


Fig. 27 On the top: Original Point cloud of a pavilion vault with lunettes obtained from terrestrial photogrammey. In the middle: Segmented portion of the vault. Bottom: Results of comparison between the CRP and TLS point cloud (Church of San Domenico, Molfetta, Italy).

For terrestrial photogrammetric acquisitions has been used a Sony DSC-QX100, with sensor resolution 20,2MP, sensor size 13,2 mm x 8,8 mm, sensor format CMOS Exmor R® da 1", image resolution 5472 x 3648 px) installed on a telescopic rod via a two-axis gimbal. For aerial photogrammetry DJI SPARK with sensor resolution12 MP. For each consecutive photo has been calculating an overlapping of 60% increased to 80% for corner acquisitions at a constant distance evaluated on the base of the case of study. Dense points cloud has been obtained using Agisoft Metashape. Point clouds from photogrammetry aren't in the correct scale, then the model have been scaled through direct measures or points acquired via Total Stations.

The evaluation of the correct dimension of the photogrammetric point-cloud has been carried out through the Surface Deviation Analysis (SDA) (Sub-Sec. 2.3.2.1) in Cloud Compare, using C2C, considering the point cloud laser scanner as metric reference (Fig. 27). This algorithm allows computing Cloud-to-Cloud distance.

For each point of the point cloud, the algorithm searches the nearest point of the compared one and computes the distances. The threshold distance has been chosen considering scene or architectural element complexity, level of detail required in 3D modelling phase, etc. In general, the maximum distance considered between the two cloud has been calculated considering the size of the smallest object to be represented in the scene. In different situations due to the complexity and articulation of historic building envirionment, it was necessary to divide the point cloud into less complex portions (Fig. 27).The results of SDA have been visualized in colour-coded deviation map obtained from the software by colouring each surface of the 3D reconstruction according to the different distances. The distribution of the points in relation to their distance from the chosen reference has been summarized by generating histograms presenting on the y-axis the number of points and on the x-axis the values of the previously chosen deviation threshold (Fig. 28).

For combining the results of the two techniques (laser scanner and photogrammetry) the point clouds elaborated in Metashape have been exported in *pts format, and embedded in Recap Pro®, in the point cloud obtained by the laser scans. The quality of alignment has been evaluated with algorithm ICP (Iterative Closest Point) in Cloud

Compare which firstly finds the correspondences between the scans by choosing the closest point and secondly minimizes the distance error among them to obtain an optimization of the cloud overlap in terms of RMS (Root Mean Square), alignment error max and alignment error min.

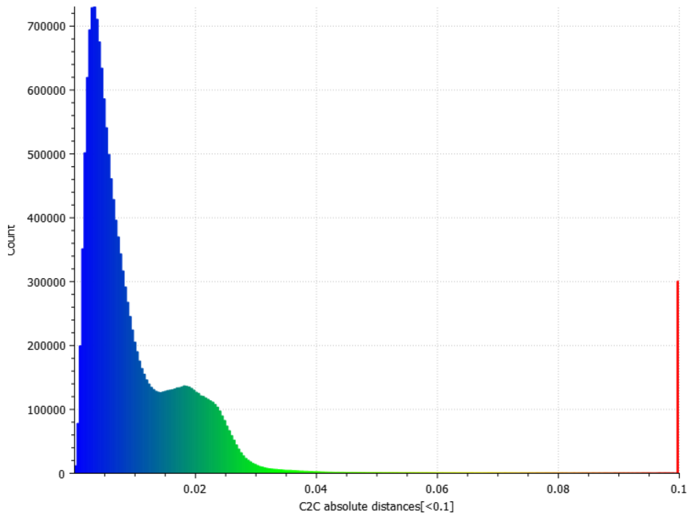


Fig. 28 Histogram of Surface Deviation Analysis relative to Fig. 27

Before starting BIM model construction results another stage has been Semantic Data Extraction (E) to facilitating the recognition and the isolation of architectural components. About this stage has been widely discussed in Sub-Sec. 3.2.

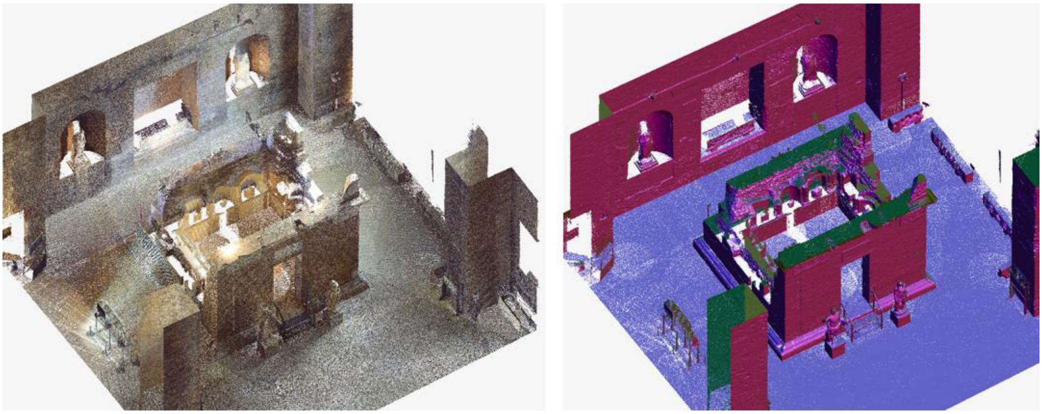


Fig. 29 Geometric segmentation of point cloud of the Tomb of the Platorini in the Baths of Diocletian, Rome (Italy) (Verdoscia et al., 2021a)

Specifically, automatic geometric and colourimentrical segmentation of point clouds properties cloud using standard and Machine Learning algorithms has been implemented (Sub-Sec. 3.2) for reducing manual input; speeding up the classification of point data (Fig. 29), the removal of superfluous elements (e.g. furniture, electrical equipment, etc.) implementing the automatic recognition of similar architectural elements and extracting geometrical characteristics about area, volumes, etc. (Fig. 30).

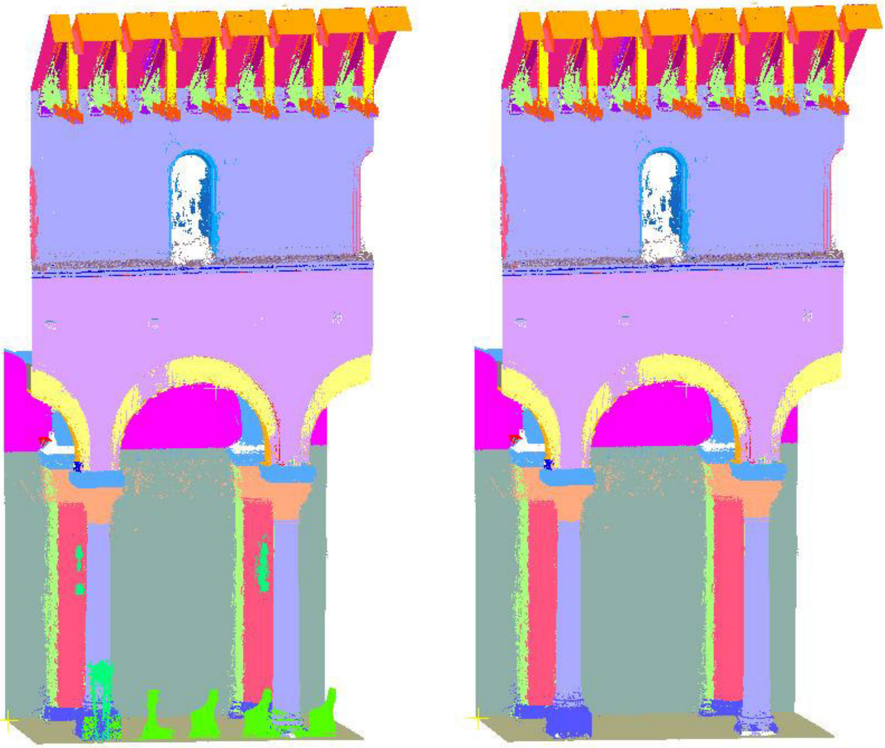


Fig. 30 On the left: Geometrically segmented point cloud. On the right: Segmented point cloud in which not useful elements have been removed

In some cases, to isolate entire portions of the building had to resort to manual segmentation (Fig. 31).

The point clouds are useful for two main purposes in (E):

- elaborating the 3D texturized mesh to be added to the BIM models.

- generating an accurate metric reference for BIM parametric modelling;

The 3D textured meshes obtained from the segmented point clouds have been processed for very irregular elements or shapes (decorative apparatus, frescos, alterations, e.g.), whose standardization by parametric modelling would be particularly difficult and can cause loss of accuracy and precision.

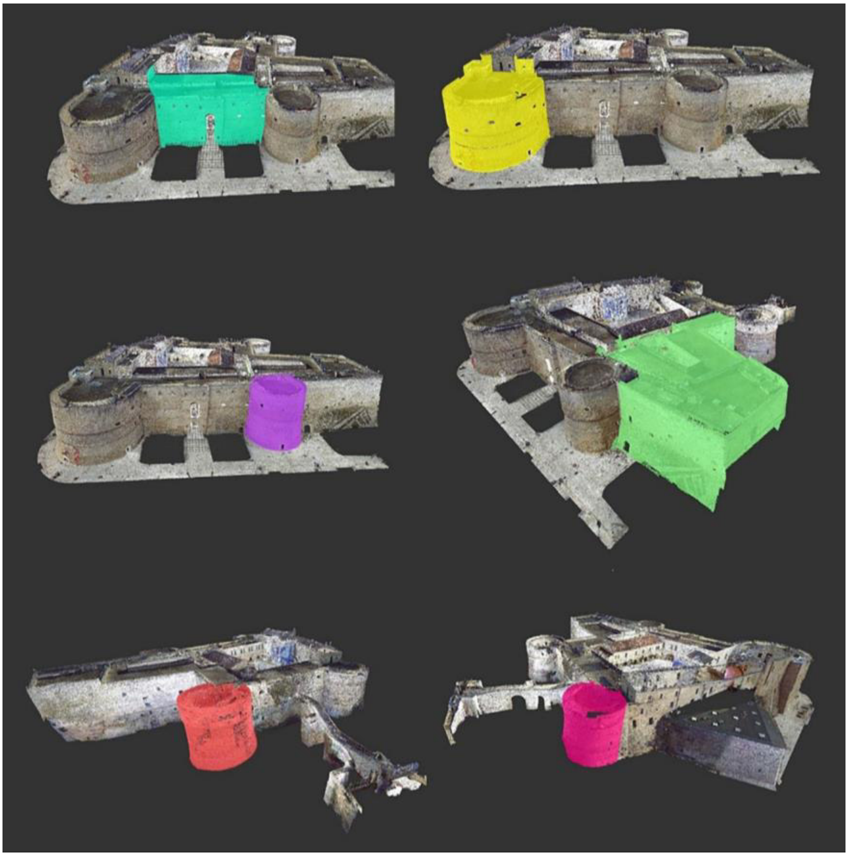


Fig. 31 Manual segmented point cloud of The Aragonese Castle of Taranto, Italy (Verdoscia et al., 2020a)

In this framework, the polygonal meshes from laser scanner point cloud are generated using through the Poisson Surface Reconstruction (Kazhdan et al., 2006) and/or the Delaunay Triangulation (Lee & Schachter, 1980) in Cloud Compare (Fig. 32). Indeed, for photogrammetric point clouds has been used Agisoft Metashape© (Fig. 33). Therefore, the meshes can be inserted directly into the BIM model as a solid element, in alternative, they can be connected as parameter to the model like hypertext reference or URL generating it by online viewers (Sketchfab, WebSetNet, e.g.). This activity allows the acquisition of an accurate understanding of three-dimensional geometry and surfaces without losing information.

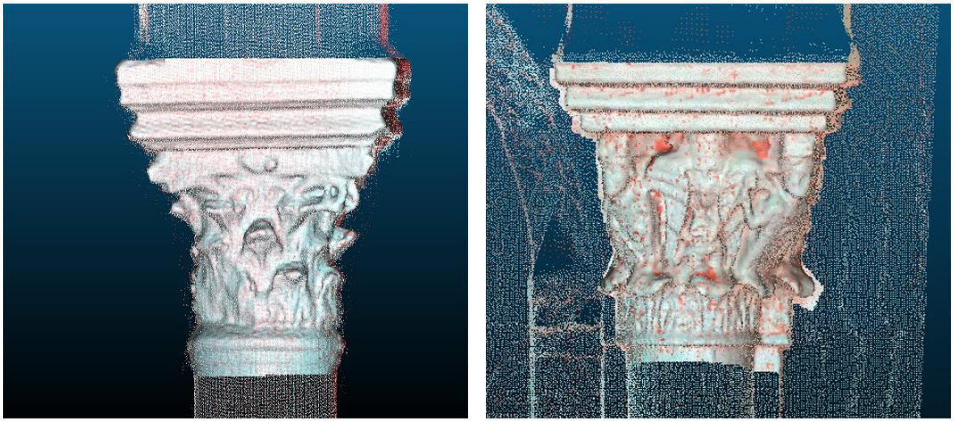


Fig. 32 Mesh of the capitals extracted from TLS point cloud of Ognissanti Church, Trani, Italy

Fig. 33 Textured meshes of the capitals (left) and entrance portal decoration (right) extracted from CRP point cloud of Santa Croce, Monastery, Modugno, Italy

The meshes has been exported from the respective software or in *dxf or *obj format and imported into Revit Architecture©. Dynamo Studio Autodesk was used to import the*obj. Dynamo is a visual programming tool in which users can graphically define, using icons, operating sequences, create custom code parts and create scripts with various text programming languages. In particular, in Dynamo, programming scripts consist of "nodes", displayed as rectangular icons, linked together to form the command sequence graphically.

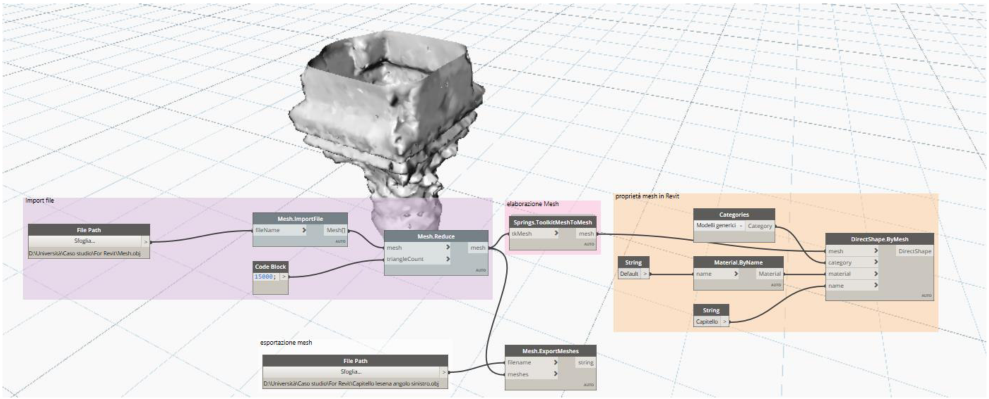


Fig. 34 Mesh of capital imported in Revit using Dynamo (Ognissanti Church, Trani, Italy)

Fig. 35 Meshes of capitals added to BIM model through Dynamo (Ognissanti Church, Italy)

Each node performs an operation; sometimes it can be as simple as memorizing a number or a more complex action like transforming meshes. In this research the use of Dynamo has allowed not only to insert the mesh in the Revit model, but also to increase or decrease the number of polygons and modify the material (Fig. 34-35).
The modelling strategy was chosen depending on the element to be represented. The parametric modelling, in Revit Architecture©, has been preferred for most of the represented architectural elements (walls, vaults, windows, columns, etc.). Starting from the system families, in fact, it is possible to access a library of already modelled construction components and adapt the parameters already pre-set to the needs required or to integrate the same parameters by adding others.
For other architectural elements, parametric modelling has been preferred using the point clouds as a metric reference covering most of the architectural elements present in the selected case studies. Editing tools, loadable or local families, and generic adaptive models and conceptual masses have been used. The compositional grammar of the parts was analysed with the aim of addressing the issue of the different LoD and the assessment of the geometric accuracy of the 3D model.
According to the characteristics of the buildings, or the artefacts, it is necessary to define the appropriate level of detail (LoD) in order to reproduce a model which is similar to the original. The LoD strictly depends on the data collected and the different operational objectives foreseen. In the present work, the three-dimensional parametric BIM elements have been built from a point cloud, minimizing the number of steps, avoiding lack of accuracy, quality of data and details, and taking into account both building rules and proportional relations between the shapes.
Some elements have been modelled according to the constituent semantic elements according to three different LoD: *low, medium, high*.
Specifically, for the architectonic elements modelled at low LoD, generic solid with shape, thickness, and approximate position have been considered; at medium LoD, elements have been modelled in their real dimensions, technical and material characteristics, at high LoD the parametric model has been linked to the polygonal textured mesh (Fig. 36 -37).

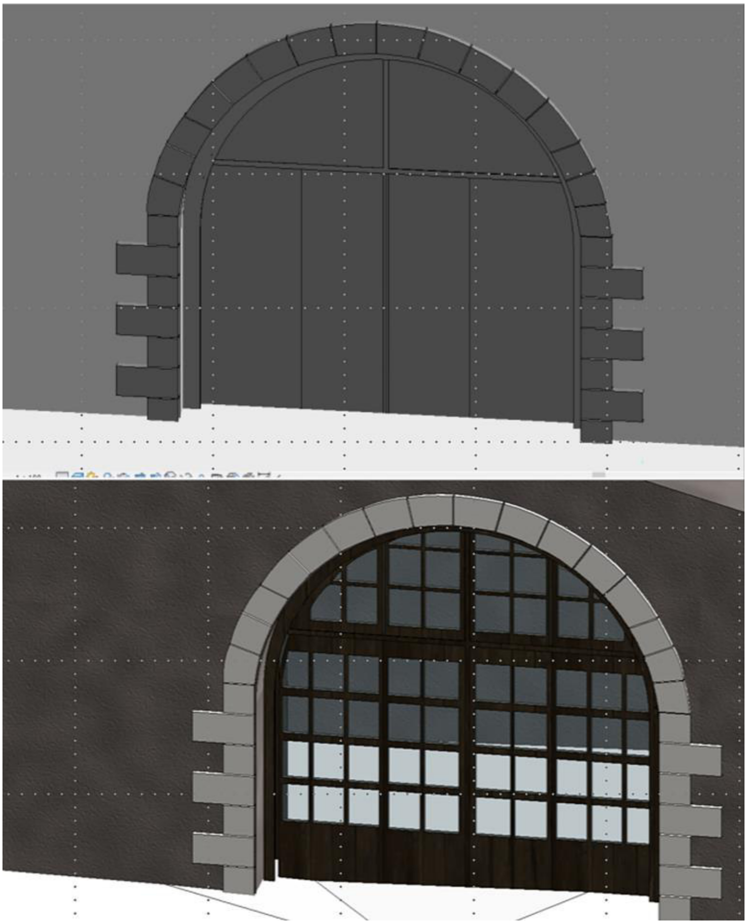


Fig. 36 Portal of Aragonese Castle of Taranto modelled in low (on the top) and medium level of detail (bottom)(Verdoscia et al., 2020a)

Fig. 37 Entrance portal at medium and low level of detail (Santa Croce Monastery, Modugno, Italy)

For example, for the Tomb of the Platorini in the Baths of Diocletian (Fig. 38), the volumetric elements constituting the sepulchre have been identified, designing in the same loadable family three different representations of the same elements, which can be activated by selecting specific display options in Autodesk Revit®
At low level of detail, architectural elements have been created from local models obtained by polygonal generators. Such elements, although maintaining a formal separation which allow the attribution of eventual specific information parameters, are characterized by a high representative simplification. On the contrary, after setting a medium level of details, the loaded family displays a texturing of the outer layers of the volumes. Such texture has been obtained elaborating a RGB mapping, extrapolated from the points matrix and optimized through the study of the local UV coordinates, preserving the appearance of the materials and the style of the objects. Finally, after setting a high level of detail, the software automatically shows a third version of the Tomb, extrapolated from a polygonal mesh reconstructed from a point cloud after a process of decimation and optimization, and elaborated by Cloud Compare.

Fig. 38 On the top: (left) Parametric model at low LOD, (right) medium LOD; Bottom: (left) medium LOD model placed in the space, (right) High LOD (Verdoscia et al., 2021a).

Apart from offering a customizable geometric discretization, the multi-LoD approach makes it possible to select different display options, and so the representation of the objects, according to specific needs.
It is considered useful to briefly mention those which were the steps of realization of the generic adaptive models and the conceptual masses for the times. As for the barrel vaults, in a first phase an adaptive point was placed in the space and a reference plane was selected as the host for the subsequent points that were later connected to the plane. As for the realization of the lunette vaults, we proceeded starting from the barrel vault previously modelled, in fact this was reduced to a bezel by cutting the solid geometry with a vacuum. Vacuum modelling has also gone through the creation of a profile in environment generic adaptive models. The same procedure has been followed for cross vaults.

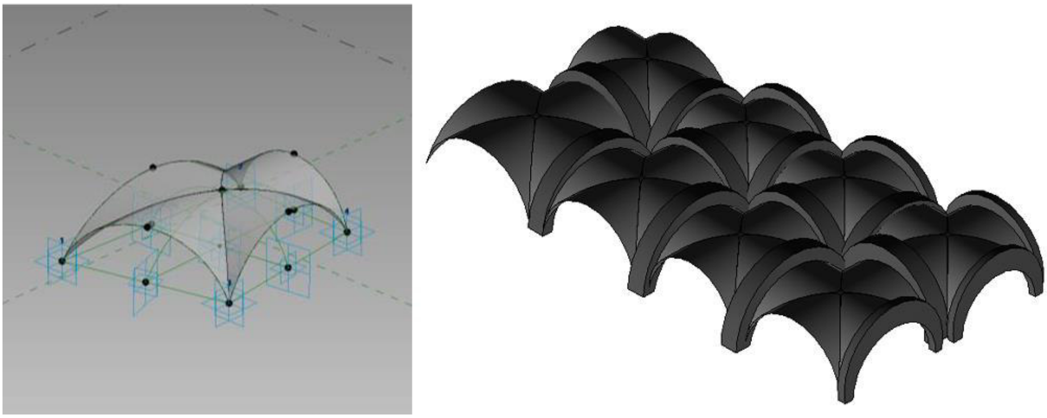


Fig. 39 Left: adaptive model of cross vault; right: Cross vaults of the arcade in front of the entrance of Ognissanti Church generated from adaptive model

The adoption of adaptive families for each type of time has accelerated the time of modelling because depending on the geometric specificities it was enough to simply adapt the family (Fig. 39).
Windows, trusses, portions of column (stem and base) were modelled using system families. Extrusions of profiles on a path have been used for frames, mouldings and entablatures.

After the modelling phases explained the whole As-Built HBIM model of the cases study has been obtained.

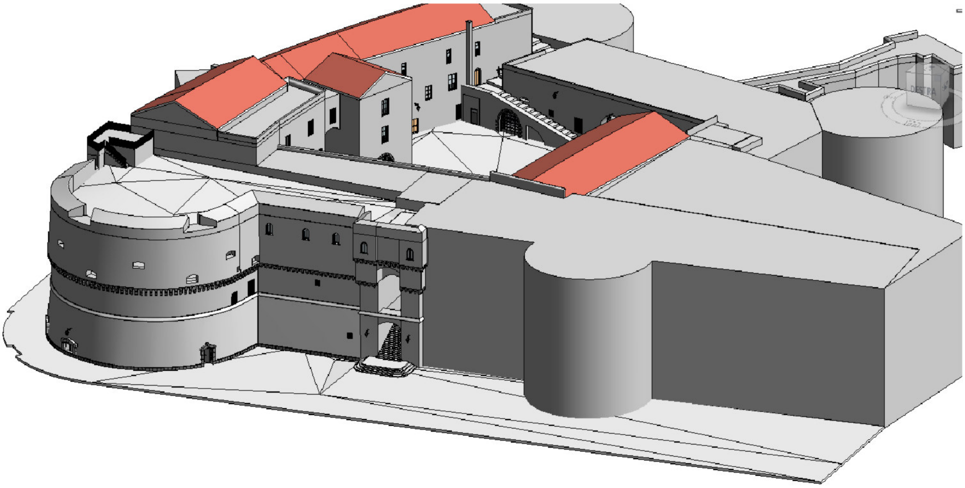


Fig. 40 As Built HBIM model (low and medium LoD) of Aragonese Castle, Taranto, Italy

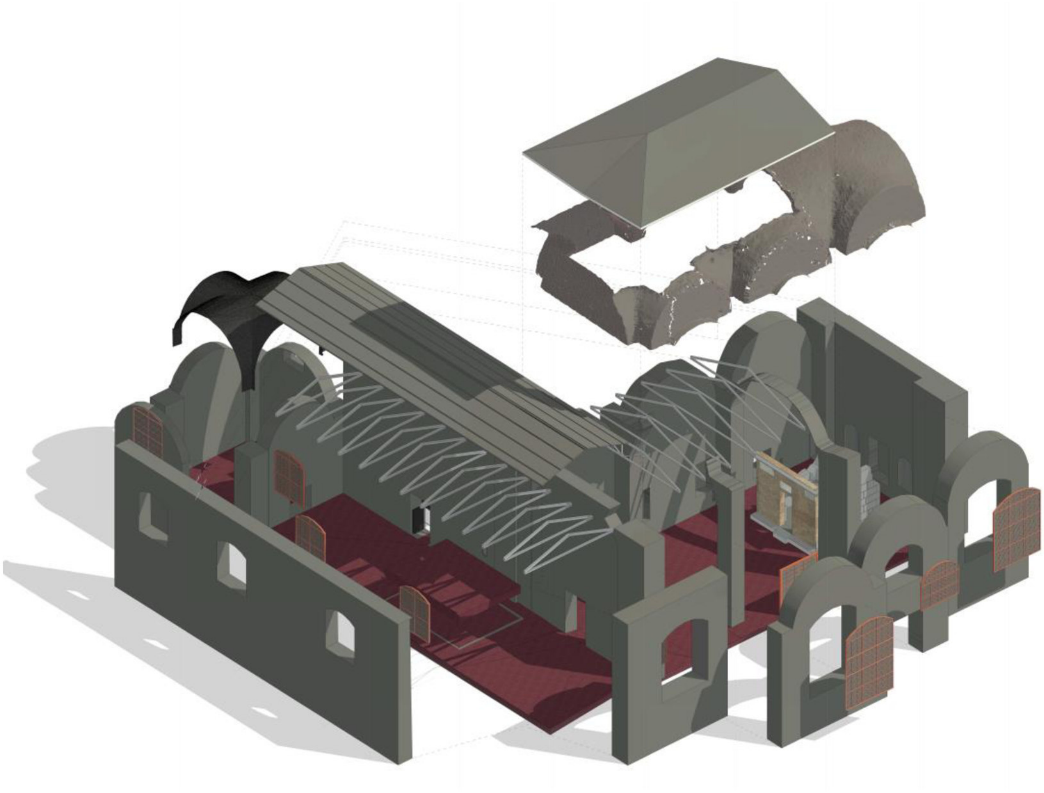


Fig. 41 As-built HBIM model of Baths of Diocletian and Platorini Tomb, Rome, Italy.

In Fig. 40 is shown the BIM model of the Aragonese Castle of Taranto represented at medium LoD on the left, and low LoD on the right. In Fig. 41 a mixed LoD of Baths of Diocletian is shown. Indeed, the majority of architectural elements is represented at medium LoD, except the vault at LoD high.

To provide an overview of the geometric accuracy of the model represented at medium LoD, after the modelling process the BIM model has been evaluated through the Surface Deviation Analysis performed using FARO® As-Built™ for Autodesk Revit® (Sub-Sec. 2.3.2.1) referring to the range of threshold of LOA20 as explained in USIBD, 2016.

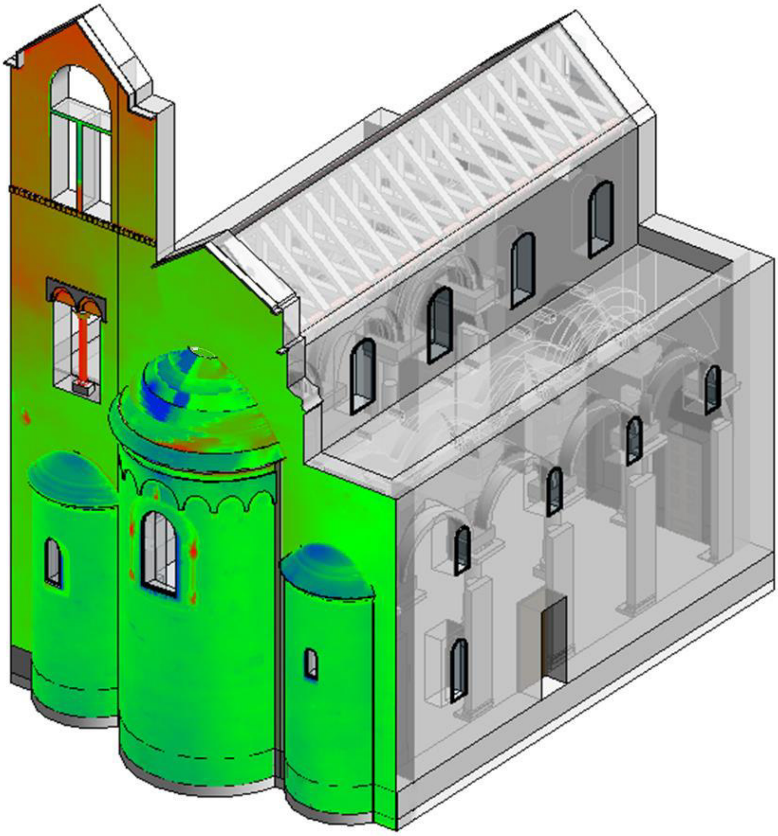


Fig. 42 Surface Deviation Analysis applied to facade Est of Ognissanti Church. Threshold +/-0,02m

Specifically setting the threshold at +/- 0,02 m, we can see in Fig. 42, results qualitatively sufficient for the majority of the extension of surfaces selected. Less appreciable results were obtained where the cloud of points had a lower density of points such as near the bell tower or on the protruding portions of the apses due to the position of the instrument placed on the ground floor during the acquisition phases. Were reconsidered less appreciable results in comparison even in the construction elements that had gaps due to degradation, as you can see in Fig. 43, where the edges of the stone ashlars that make up the arches of the porch of the monastery of Santa Croce have losses of material

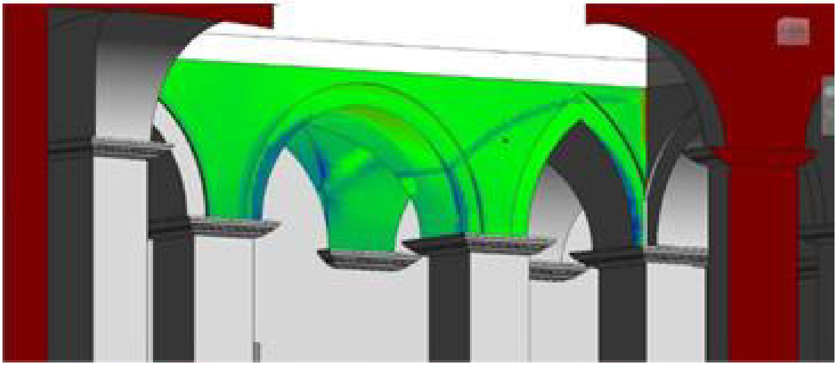


Fig. 43 Surface Daviation Analysis applied to facade Sud of Santa Croce Monastery. Threshold 0,02m

The first consideration is considered negligible, as it can be solved through a better positioning of the instrument (in this case the laser scanner). The second problem is also negligible since the purpose of this work consists in the representation of an “As-built” model, in which the state of degradation of the materials is not considered as in a model “As-damage”.

The following table summarises the techniques and data on the digital survey process and BIM modelling for each case study.

Case of study	3D survey					Pre-processing Point Cloud Alignment			Modelling Technique			
	Survey Technique			Survey Data		RMS (cm)	Max error (cm)	Min error (cm)	LoD			LOA
									L	M	H	
1	TLS		X	n. scans	288	0,5	0,7	0,3	-	X	X	LOA20
				n.points	110 MLN							
	CRP	UAV		photos	13							
		cameras		n.points	7,688,512							
2	TLS		X	n. scans	39	0,4	0,5	0,2	X	-	-	-
				n.points	34,107,818							
	CRP	UAV	-	photos	306							
		cameras	X	n.points	6,821,563							
3	TLS		X	n. scans	55	-	-	-	X	X	-	LOA20
				n.points	307,148,542							
	CRP	UAV	-	photos	-							
		cameras	-	n.points	-							
4	TLS		X	n. scans	210	0,5	0,8	0,3	X	X	X	LOA 20
				n.points	181 MLN							
	CRP	UAV	X	photos	45							
		cameras	-	n.points	5,819,919							
5	TLS		X	n. scans	45	-	-	-	X	X	X	LOA20
				n.points	172,940,352							
	CRP	UAV	-	photos	-							
		cameras	-	n.points	-							
6	TLS		X	n. scans	7	-	-	-	X	X	X	LOA20
				n.points	11,768,432							
	CRP	UAV	-	photos	-							
		cameras	-	n.points	-							

Table 5 Data and techniques about 3D digital survey process and BIM modelling

3.1.3 CONCLUSIONS AND FUTURE DEVELOPMENTS

In literature, the main issue emerges in the field of representation technique in BIM environment is the geometric accuracy which can be obtained using standardized parametric elements in BIM software in relation with the irregularity and specificity of historical buildings. Indeed, the realization of "As-is/As-built" models refers to BIM of existing buildings where the model reflects the real conditions of the construction.

To develop a reliable HBIM model, one of the challenges is to convert the point cloud data obtained from the 3D digital survey techniques into a three-dimensional information model as accurately as possible.

In this Sub-Section a new proposal to obtain geometrically accurate BIM models is defining. Specifically starting from the Scan-to-BIM process, parametric representation methods have been tested starting from adaptive models for construction elements such as vaults. Their advantage is that they can be used as library objects adopted to all constructive elements of the same typology. Other types of parametric modelling used consist in the adoption of system families and loadable for walls, arches, trusses, etc. The parametric nature is a great advantage as they can be modified and updated as needed and used to integrate information to the model.

The adoption of point clouds and manual and automatic segmentation techniques has resulted in the possibility of isolating the construction elements, speeding up the modelling process, and facilitating the creation of meshes.

The possibility of defining three levels of geometric representation (low, medium and high) has been evaluated thanks to the possibility of visualizing BIM models at multiple levels of detail. The highest level, exploiting the interoperable characteristics of BIM authoring software, has been defined by integrating textured meshes obtained from point cloud processing

The disadvantage of mesh inclusion is the computational weight. Historical buildings rich in valuable elements and irregularities may require a large amount of elements generated by this method. To solve this problem, Dynamo has been used. Through the composition of a script it was possible to increase or reduce the number of polygons in the course of modelling.

A further disadvantage of the use of mesh is the impossibility of being enriched with informative parameters. However, the realization of multi-level models of graphic depth would allow exploiting the advantages of parametric modelling.
Future developments may concern the automatic segmentation of point and mesh clouds based on the required level of detail, and in identifying the type and quantity of information to be included at each LoD.

3.2 AUTOMATIC POINT CLOUD SEGMENTATION THROUGH MACHINE LEARNING AND MODEL-BASED APPROACH

In the field of Architectural Heritage, the identification within point cloud or polygonal models of architectural elements and chromatic differences, that are typical of the property of materials or conditions of conservation, can become a valuable study tool as above explained in Sub-Sec. 2.2.

The main goal of following sections is to develop, explore and validate reliable and efficient automated procedures for the automatic semantic segmentation of 3D reconstruction of heritage scenarios. Through automatic semantic segmentation the author aims to:

- Identify, quantify and extract different evidence of surface alteration of the states of conservation of materials;
- Identify and extract different types architectural elements (vaults, columns, capitals, etc.);
- Connect the kind of architectural element on which surface alteration evidences have been detected,
- Prepare semantic data extracted propaedeutic for conservation activities purposes through HBIM.

In the present work, (D) Semantic data extraction has been developed using optimized point clouds and textured meshesderiving from (B) 3D survey and (C) Data processing and filtering. To take into account a complete description of the condition assessment and the relative architectural component, it was blending together a Colour-based and Geometry-based segmentation. Following methods were investigated to elect the most suitable for the research purpose.

1. Colour-based segmentation has been exploited developing:

   - Range-based method: it is developed on supervised learning approach using region growing algorithm where seeded point are individuated in a colour range chosen on orthophotos directly extracted from point cloud (Galantucci et al., 2020)(Sub. Sec 3.2.2).

   - Cloud-based method based on unsupervised learning approach through hierarchical segmentation directly applied on point cloud (Sub-Sec. 3.2.3).

   - Texture-based method: it uses supervised learning approach through random forest methods for a semantic extraction of chromatic data from UV maps obtained from textured polygonal meshes (Sub-Sec. 3.2.4).

2. Geometry-based segmentation, by RANSAC, for the identification of architectural element and for isolating elements on which chromatic evidences are detected (Sub-Sec. 3.2.6).

3.2.1 CASE OF STUDIES

The research carried out in following sections has been validate testing the implemented methods on some cases of study chosen for their characteristics typical of Architectural Heritage. In fact, they are constituted of masonry walls and vaults, in some cases coated from plaster and affected by surface decay phenomena. Bellow a brief description of each of them:

- The convent of "San Leonardo" is an ancient building located within the consolidated urban fabric of the old town of Monopoli (Bari, Italy). Its construction dates back to 1555, when the original core of the monastery was built, until the late 18th century. The fabric is characterized by an irregular plan developed in two levels in elevation, around the main cloister. Each space is covered by barrel, cross or mirror vaults. The presence of a small crypt, decorated with frescos, increases the historical artistic value of the whole convent. (Chiulli et al., 1984)(Fanizzi, 2018) Fig. 44.

- The ex-convent of Cappuccini is located in Conversano (Bari, Italy) and its construction dates back to 16th century. The building shows a complex architectural stratification of considerable historical interest which, however, is difficult to understand due to the countless changes made over the years and the various uses adopted. The building consists of two level around a main cloister and the plan is irregular. Each indoor environment is covered from barrel or cross vault (Fig. 49–1).

- The chapel of San Luigi is part of the Minoia farm complex in Polignano a Mare (Bari, Italy). Its construction could date back to the seventeenth century. it is constructed entirely of stone and on the main facade has a curvilinear tympanum with two lateral pinnacles. Internally the chapel is composed of a single room with a rectangular plan covered by a star vault decorated with floral motifs. In the area reserved for the faithful there is a barrel vault (Chiarappa & Myriam, 2002)(Fig. 49-2) .

- The rural church of Santissimo Salvatore, in Loseto (Bari, Italy), was constructed in 1418. The chapel consists of two main buildings: an exterior courtyard and a small temple, equipped with a bell tower surmounted by a tympanum without the bell, Inside, there are frescoes depicting religious images (Fig. 49-3).

- The Ognissanti church, in Trani, (BT, Italy) was founded in early 12th century. The apses and the sculptural decorations have been attributed to the following century. Directly facing the port of Trani, the church has three apses, typical elements of Roman architecture, interesting for their both by their semicircular shape and by the gradual light effects generated by the present windows. The main facade has a large porch adjacent to the three entrance doors. Inside, the Church is divided into three naves separated by six granite columns characterized by capitals in composite order on which rest double-ring arches. Along the internal perimeter of the Church, there are a total of fourteen semi-columns in composite style with capitals that are not homogeneous with each other, because some of which have not maintained their original shape due to a process of erosion. The side naves have ogival vaults. The central nave is surmounted by a system of wooden trusses (Fig. 68).

3.2.2 COLOUR-RANGE METHOD

The following method has been implemented to detect irregular surface alterations such as damp spots in 3D point cloud of a masonry fabrics obtained from 3D survey (B) (Sub-Sec 2.1.3). It is the result of the application of region-based method (Sub-Sec 2.2.4.1) focusing on clustering points according to the similarity of their colour attribute (colour triplets, computed on the basis of their geometrical proximity).

The underlying consideration is that, among the various kinds of moisture phenomena, especially the area of biological colonization, appears in quite limited colour intervals, for example ranging from black and grey to green, regardless of surface nature and micro-climate conditions.

Hence, the proposed pipeline employs the computation of the colours, expressed in RGB triplets, and the subsequent clustering of points based on them (Nguyen & Le, 2013); and region-based methods to exploit neighbourhood information, to group together points with a similar colour property and to isolate them from the rest of the model (background). Specifically, the adopted region-based algorithm starts from a seed point inside the object and it gradually expands the region up to the boundaries (Zhang, 2006)

As descripted in Sub-Sec. 2.2.2 in the RGB colour space the metric distance does not correspond to the colorimetric distance between colours. For this reason, in order to realize an accurate segmentation of points based on the identification of a correct colour range, it is necessary to convert the RGB model into a more suitable one, like YCbCr.

The definition of the procedure consisted in the creation of two different routines:

- the first one is applied to orthophotos in order to define the reference colour range Sub-Sec. 3.2.2.1;
- the second one is performed on dense point clouds to realize the segmentation Sub-Sec. 3.2.2.2.

For the first routine it was chosen to operate on orthophotos because they are geometrically corrected photographs that has been 'orthorectified' such that the scale of the photograph is uniform. An orthophotograph can be used to measure exact distances. For the segmentation of no planar objects like vaults, our approach suggests to export from the models the orthophoto or orthomosaic (a raster image made by merging orthophotos).

It is important to underline that image formats apply a certain level of compression, causing a loss of information and presumably altering the RGB values of each pixel. Therefore, for the application of the following method it is preferable using *.png (Portable Network Graphics) file format, a raster-graphics file-format that supports an efficient data compression and guarantees an acceptable accuracy with respect to the original image.

Both the routines have been implemented in MathWorks® MATLAB, an interactive environment for the numerical computation and a programming language and applied on 3D models previously generated in Agisoft Photoscan©.

3.2.2.1 Identification of the colour range

At this stage, in order to identify an adequate colour interval to perform the point cloud segmentation, a specific script have been created, which works on an RGB image, where each pixel is described by an RGB triplet.

In particular, a series of iterative cycles have been implemented on orthophotos retrieved from 3D models deriving from (B) and (C) stages (representing areas affected by moisture), and further processed in order to find the most frequent triplet of RGB values (seed point), with the aim of extracting only those colours belonging to the range of interest.

Orthophoto is a photographic image whose central projection has been transformed into an orthogonal projection. In this way, with this transformation, it is possible to eliminate all distortions caused by the camera. Hence, it is a geometrically corrected photograph with a uniform scale. An ortho-photograph can be used to measure exact distances.

In the proposed method, firstly, the orthophoto is imported in MathWorks® MATLAB and three matrices are extracted, corresponding to the three colour-channels (RGB). The matrices are organized in n-rows and m-columns representing the width and the height of the image (in pixels), and the values within the cells are the R, G or B values of each pixel.

Then, a first iterative cycle has been defined, to combine the R, G and B values into a single matrix (3 x n° pixels), where each column corresponds to a single pixel and each row to a colour channel. Once this matrix is computed, background pixels are removed from the matrix.

The extraction of the most frequent value (RGBxef, chosen as seed points) is realized within the range of the foreground pixels, by searching the triplets composed by the most recurrent values of each channel. In addition, the maximum (RGBmax) and the minimum (RGBmin) RGB values, respectively the clearest and the darkest value, identified as boundaries of the foreground range.

3.2.2.2 Point cloud processing and segmentation

The second routine is focused on analyzing and segmenting the point cloud, according to the result of the first routine, whose output is a colour interval composed by the minimum (RGBmin), the maximum (RGBmax) and the most frequent triplet (RGBxef). When importing a point cloud in MathWorks® MATLAB, in *.ply (polygon file format) or *.pcd (point cloud data) file-format, it is possible to read it as an object and to access a number of matrices, corresponding to the properties of the point cloud (Location, Color, Normal, Intensity, Count, XLimits, YLimits, ZLimits).The Location property is expressed in XYZ coordinates, while the Colour property is expressed in RGB triplets, where the colour matrix (n x 3)is organized in a n number of rows corresponding to the number of points of the cloud, and three columns representing the three colour-channel red, green and blue. This colour map should be firstly converted in the colour space YCbCr, as a consequence of the previous considerations about the RGB model. The new colour matrix is inserted within the point cloud. Also the colour range deriving from the first routine is converted to find the correspondent triplets in the YCbCr colour space, so that it is possible to calculate the Euclidean distances between the reference value (YCbCrxef) and the minimum (YCbCrmin) and maximum value (YCbCrmax) respectively (1), (2). The lowest among D1 (1) and D2 (2) is chosen as reference distance Dref for the cloud segmentation.

$$D_1\,(YCbCr_{xef}, YCbCr_{max}) = \sqrt{(Y_{ref} - Y_{max})^2 + (Cb_{ref} - Cb_{max})^2 + (Cr_{ref} - Cr_{max})^2}$$

(1)

$$D_2\,(YCbCr_{xef}, YCbCr_{min}) = \sqrt{(Y_{ref} - Y_{min})^2 + (Cb_{ref} - Cb_{min})^2 + (Cr_{ref} - Cr_{min})^2}$$

(2)

After the computation of D3 (3), the Euclidean distance between each colour value of the point cloud (YCbCrpoint) and the reference value (YCbCrxef), the segmentation is performed through a comparison point to point with the reference distance Dref.

$$D_3(YCbC_{rxef}, YCbCr_{point}) = \sqrt{(Y_{ref} - Y_{point})^2 + (Cb_{ref} - Cb_{point})^2 + (Cr_{ref} - Cr_{point})^2}$$

(3) $|(Y_{ref} - Y_{max})^2 + (Cb_{ref} - Cb_{max})^2 + (Cr_{ref} - Cr_{max})^2$

These steps are necessary to create a filtering matrix, which must be applied to the original RGB matrix of the point cloud, so that the segmented regions are kept in their original colour and the others are transformed in black, carrying out a sort of binarization of the point cloud.

3.2.2.3 Results and discussion

The methodological pipeline illustrated above has been applied to an architectural heritage, the convent of “San Leonardo” (Sub-Sec. 3.2.1) (Fig. 44). Particularly, the analysis was focused on an architectural volume covered by a sequence of three masonry cross-vaults, adjacent to the main cloister, with the purpose of investigating dampness spots consistently affecting the vaults intrados.

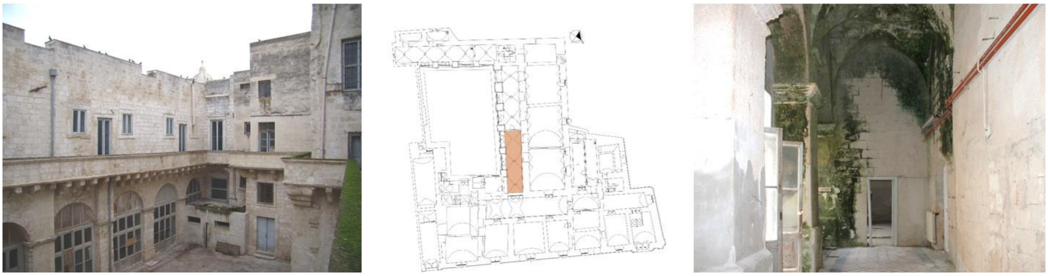


Fig. 44 a) External atrium , b) Ground floor plan (localization of architectural volume), c) Architectural volume

During stage (B) the area was scanned and virtually reconstructed (C), according to the digital photogrammetric technique (Sub-Sec 2.1.3) whose parameters used are summarized in Table 6. The 3D models were generated using Agisoft Photoscan © (Fig. 45).

Equipment:	Mirrorless camera (20 MP sensor, fixed focal length lens16 mm) Tripod, Distolaser
Scanning parameters:	Average shooting distance: 3,5 m N° photos: 232 Area: 2,85 m x 10,40 m Max height: 6 m Min height: 4,40 m
3D model:	Tie points: 121’022 Dense point cloud: 22’589’827 points Ground resolution: 0,80 mm/px

Table 6 Parameters of photogrammetric process

Fig. 45 3D textured model obtained in Agisoft Photoscan ©(Galantucci et al., 2020).

For the sake of reducing processing requirements, the three cross-vaults were considered separately, so that smaller point clouds were analysed. Each of them is in the order of magnitude of 3,000,000 points. As an example, when imported in MathWorks® MATLAB through the built-in function *pcread*, the point cloud of the central vault, made by 2.850.090 points, was accessible as an object with its matrices of Location, Color and Normal (matrix size: 2850090x3).
In the specific case, the automatic detection was focused on the identification of the various forms of biological colonization, attested within the green colour range. For the application of the first routine, an orthophoto of the vault intrados was retrieved from the 3D model and then processed, so that three significant values in the green interval were found: the *reference value* (R:91,G:91,B:86), the *minimum* or darkest (R:68,G:70,B:65), and the *maximum* or clearest (R:190,G:199,B:194)(Fig. 46).

Fig. 46 On the top: Orthophoto of the intrados of the three cross-vaults, below Orthophoto with only green colours extracted

Once defined, the colour interval was directly introduced in the second routine as a new variable. These values were converted in their correspondents in the YCbCr space, as the original point cloud, thanks to the function *rgb2ycbcr* (Fig. 47). The *reference distance* was the lowest among the two distances: in this case, the one between the minimum and the reference value, equal to 0.0229 (1).
The point cloud segmentation was the result of a comparison point to point of the Color matrix (expressed in YCbCr) with the *reference distance*. Indeed, every point located at a lower or equal distance to 0.0229 was included in the segmented regions. The remaining points, instead, were excluded and considered as background.

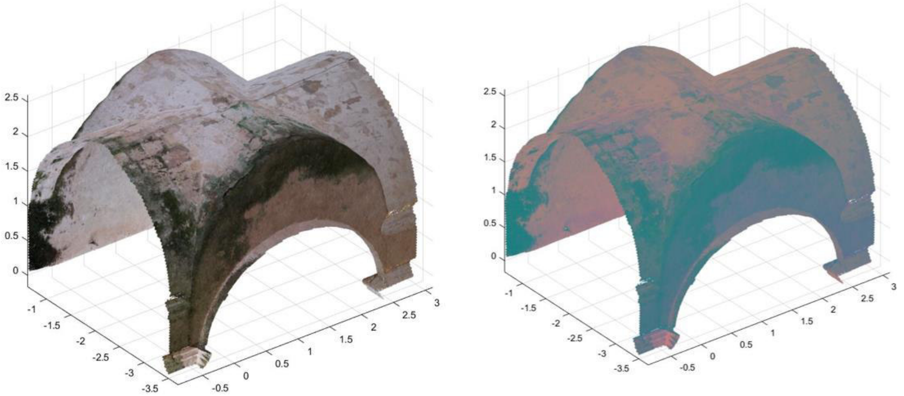


Fig. 47 The cross vault in RGB colour space (on the left) in YCbCr colour space (on the right)(Galantucci et al., 2020)

After these steps it was possible to quantify the number of segmented points and the extent of the dampness phenomena on the whole structure. In the specific case, the incidence was of 222,052 points over the total 2,850,090 points, which means a percentage of about 8% (Fig. 48).

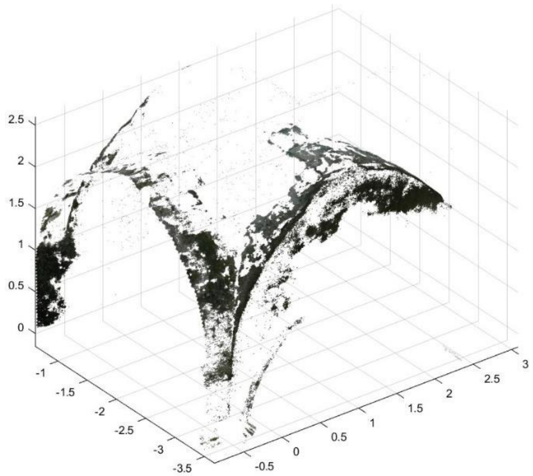


Fig. 48 Result of the point cloud segmentation, based on the isolation of green areas, connected to dampness phenomena (Galantucci et al., 2020).

The overall extension of the moisture pattern on the cross-vault can be quantified also in terms of area (m^2), on the basis of the average point cloud density (pt/cm^2), retrieved from the photogrammetric reconstruction of the dense point cloud.

In the specific case, the point density was retrieved from the photogrammetric reconstruction of the dense point cloud, and its value is of 8,59 pt/cm^2. As a result, the total affected area is of 2.63 m^2 over a total area of the cross-vault of 33.18 m^2.

3.2.3 CLOUD-BASED METHOD

As previously anticipated, the second method proposed for (D) - Semantic data extraction - is the Cloud-based segmentation, through unsupervised machine learning using Hierarchical Clustering. The aims of the method are firstly detect the deterioration of the masonry surface and to test the reliability of the method on a heritage objects with more complex topology and few chromatic differentiations on the texture.

The specific routine has been applied directly on colour attributes of 3D point clouds, to distinguish, qualify, and quantify, various typologies of chromatic alterations and objects on irregular masonry architectural components (Musicco et al., 2021).

Given the complexity and heterogeneity of their characteristics, the great advantage is that there is no need for pre-fixed labels, because they are introduced by the hierarchical algorithm itself. The outputs are clusters of points (groups of similar examples data), segmented isolating different colour ranges, which correspond to the chromatic alterations.

As previously stated in Sub-Sec. 2.2.2, in the RGB model there is not a perceptive conformity with human eyes, because the luminance component is not considered therefore, the original RGB point clouds were converted in HSC, YCbCr, YIQ and YUV. Subsequently, the hierarchical clustering using the agglomerative approach has been adopted. The specific routines for conversion and segmentation have been elaborated in MathWorks® MATLAB.

The first step consists in grouping points that are in close proximity into a hierarchical cluster tree using the linkage function. The linkage function uses the distance information to determine the proximity of objects to each other. As objects are paired into binary clusters, the newly formed clusters are grouped into larger clusters until a hierarchical tree is formed.

In the specific case, for the computation of the distance between clusters, the Ward's minimum variance method was used, which minimizes the total inner-cluster variance. It is a recursive algorithm, which starts from the squared Euclidean distance between singletons clusters, and at each step achieves the pair of clusters that leads to minimum increase in total inner-cluster variance (Ward, J. H., 1963).

The total inner-cluster variance, defined as the sum of the squares of distances among all the elements in the cluster and its centroid, according to the following equation (1):

$$d(r,s) = \sqrt{\frac{2n_r\, n_s}{(n_r + n_s)}}\, ||\bar{x}_r - \bar{x}_s||_2 \qquad (1)$$

where $\bar{x}_r$ and $\bar{x}_s$ are the centroids of clusters *r* and *s*

n_r and n_s are the number of elements in clusters *r* and *s*

As anticipated, the clustering algorithms have been applied to point clouds converted in four colour-spaces (HSV, YCbCr, YIQ, YUV), and then compared, in order to find the clusters, in which there is an optimal separation among colour ranges, corresponding to the various kinds of pathologies and objects.

The comparison among the clusters took place in two subsequent steps. The first was carried out among the clusters corresponding to the same form of colourimentric differences and subsequently with a manually segmented grand truth. The goal was to identify the colour space whose division into clusters was closest to reality.

The comparison was performed initially in a qualitative manner, through a visual analysis, and subsequently in a quantitative manner through the use of histograms for evaluating the distribution of points in relation to the isolated colour range.

Results of the descripted pipeline are discussed in the following section.

3.2.3.1 Results and discussion

The methodological pipeline has been applied to three case studies (Sub-Sec. 3.2.1), which are architectural volumes covered by masonry cross or barrel vaults and facades, both belonging to masonry ancient buildings typical materic and morphological characteristics.

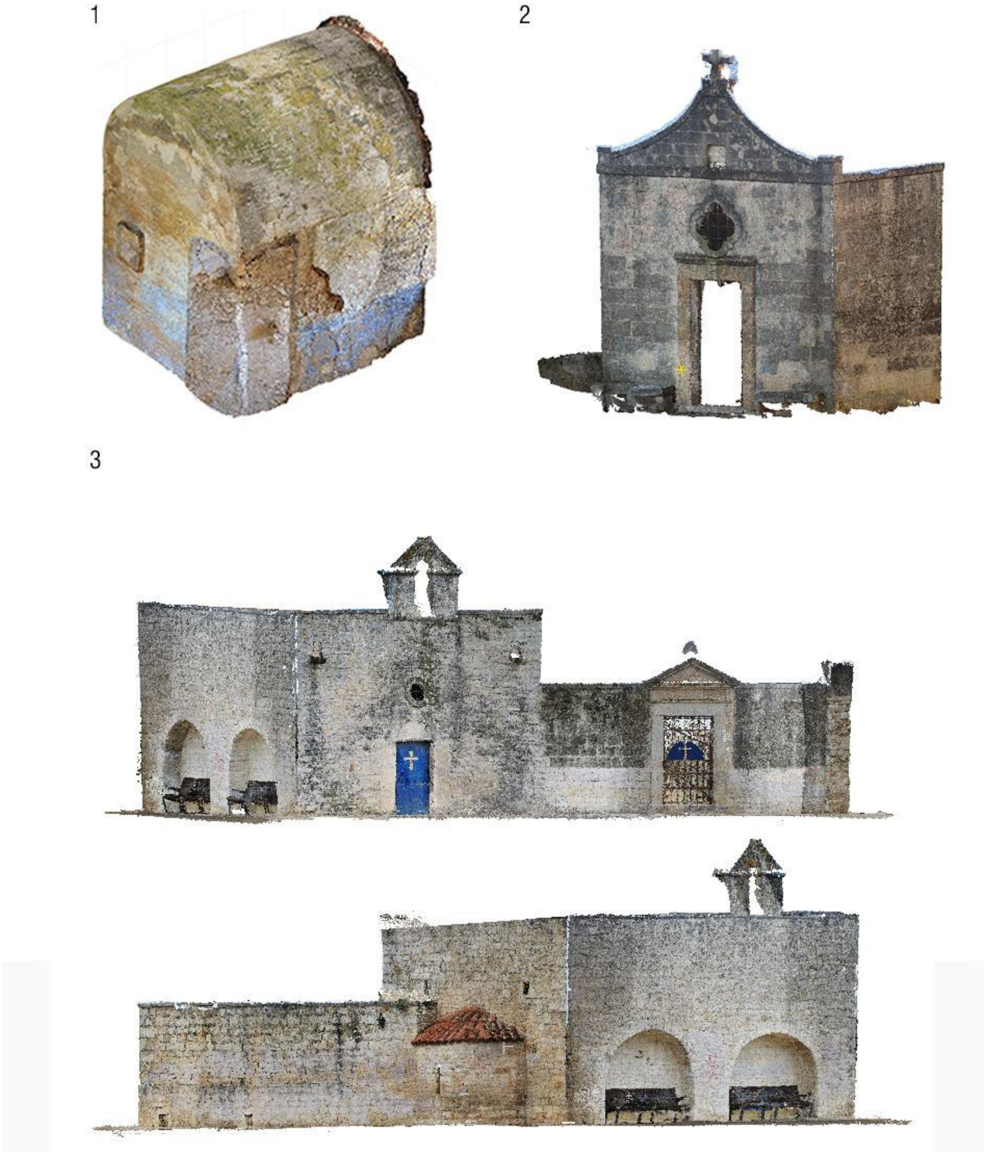


Fig. 49 Cases of study: 1) Barrel vaulted architectural unit of the Cappuccini ex-convent, 2) Facades of S.Luigi, 3) Facades od S. Salvatore.

The cases studies are (Fig. 49):

- Case 1: A barrel vaulted architectural unit of the Cappuccini ex-convent (16th century, Conversano, Bari, Italy);
- Case 2: External facades of rural church of San Luigi, Polignano a Mare (Bari, Italy).
- Case 3: External facades of rural church of Santissimo Salvatore, Loseto (Bari, Italy);

The on-site survey of their state of conservation led to the identification of five main classes of pathologies, as described in the Illustrated glossary on stone deterioration patterns (ICOMOS, 2008): biological patina, biological colonization, spots, deposits, chromatic alteration and moist areas.

The cases have been scanned and virtually reconstructed through digital photogrammetry, with Agisoft Metashape©. The equipment and the parameters are indicated in Table 7. The obtained point clouds have been sampled in CloudCompare, for reducing computational costs. The specific routines for segmentation have been elaborated in MathWorks® MATLAB.

Parameters	Case 1	Case 2	Case 3
Camera	NIKON D3100	Nikon D750	IPhone 12
Sensor resolution	4608 x 3264 pixel	3590 x 2400 pixel	4000 x 3000 pixel
Focal length	18 mm	22 mm	26mm
Area	56 m^2	71 m^2	251m^2
N° points	28,979,012	3,98,000	222,182,221
N° sampled points	254,693	541,205	2,112,074
GSD	0.35mm/pix	1,71 mm/pix	1.9 mm/pix

Table 7 Equipment and parameters of digital photogrammetric reconstruction

The hierarchical algorithm, illustrated in Sub-Sec- 2.2.5.3, has been applied to point clouds converted in the four colour-spaces (HSV, YCbCr, YIQ, YUV) to understand in which space there is an optimal separation among colour ranges, corresponding to the various kinds of deterioration pattern or objects with distinct colours.

The comparison was operated with the results of on-site visual survey and the ground truth (produced by a manual segmentation of the original point cloud).

Therefore, starting from the subsampled point cloud, the appropriate level to cut the dendrogram has been found for each case study.

In particular, the Case 1 was considered a unique point cloud, instead, for the Cases 2 and 3, it was necessary to partition point clouds distinguishing each façade due to different typologies of colourimentric differencies among them.

As a result of the experimentation, the proper number of clusters to be considered is 5 for Case 1 (Fig. 50), 2 (façade Est), 3 (façade Ovest), and 5 (façade Nord) for Case 2. 5 (façade Ovest)-6 (façades Nord-Est-Sud) for the Case 3.

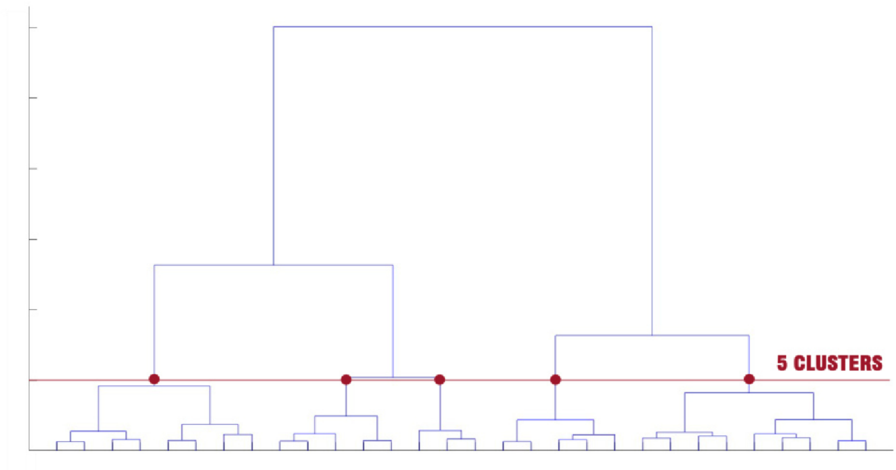


Fig. 50 Dendrogram of Case 1. Red line: pruning at 5 clusters; X-axis: clusters; Y-axis: Ward's distance (Musicco et al., 2021)

For each one, an inferior number is not sufficient to distinguish the variations of the chromatic components, while a superior number generates too small clusters.

In Fig. 51 there is an example of the application of the hierarchical clustering with a pruning level of 3 clusters. It is possible to observe that in all cases different colours have been grouped together, producing an unacceptable result.

Fig. 51 Hierarchical Clustering applied to cases studies selecting level of 3 clusters

Hierarchical Clustering have been applied for each colour spaces (5 cluster for each colour space) for a total number of 20 clusters for the Case 1, 40 for the Case 2 and 92 for the Case 3.

Subsequentally, after a qualitative comparison of the clusters in pairwise on the basis of their chromatic correspondence, HSV appeared to be the most performing in the isolation of colours (Fig. 52-57).

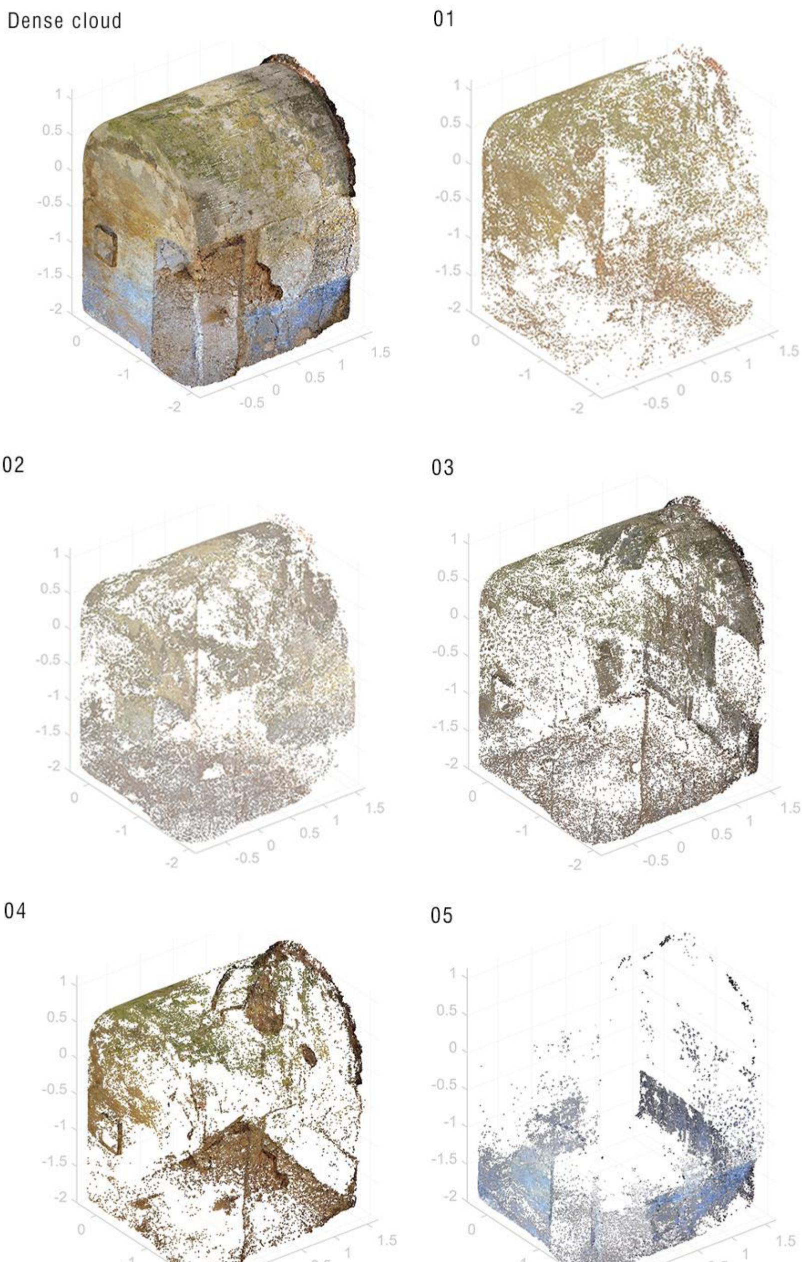


Fig. 52 Clusters in HSV (Case 1): original point cloud; 1) moist area (18%); 2) biological patina (26%); 3)biological colonization (20%); 4) spots/deposit (20%); 5) staining (13%)

Fig. 53 Clusters in HSV Case 2: Ovest: 01) biological Colonization (23%): 2)moist area (43%); 3) unaltered (34%), Nord:01) moist Area (44%); 02) biological Colonization (60%); 3) deposit/spot (16%); 4) biological patina (48%); 5) unaltered (29%); Est: biological colonization (43%); biological patina (43%).

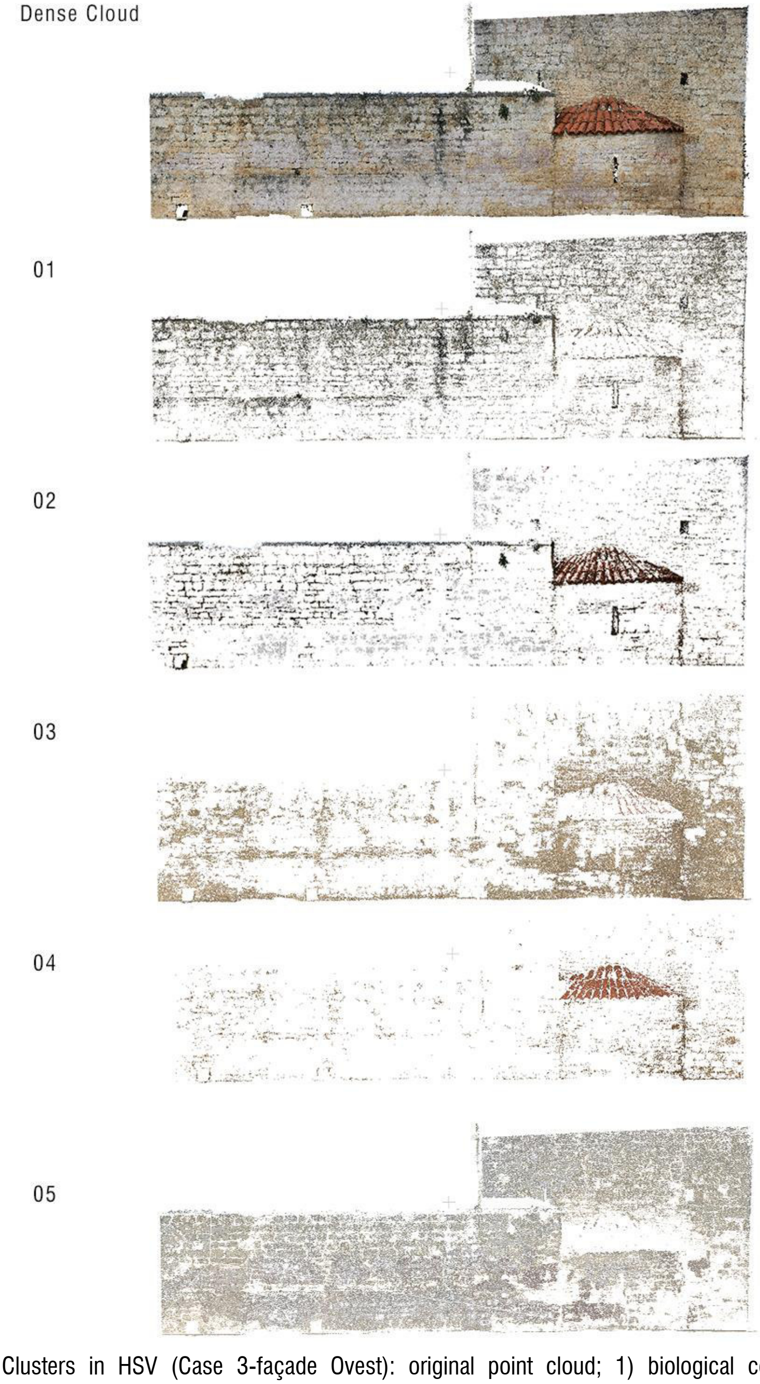


Fig. 54 Clusters in HSV (Case 3-façade Ovest): original point cloud; 1) biological colonization (20%); 2) spots/deposit (28%);3) moist area (38%); 4) roof tiles (12%) 5) unaltered surface (69%);

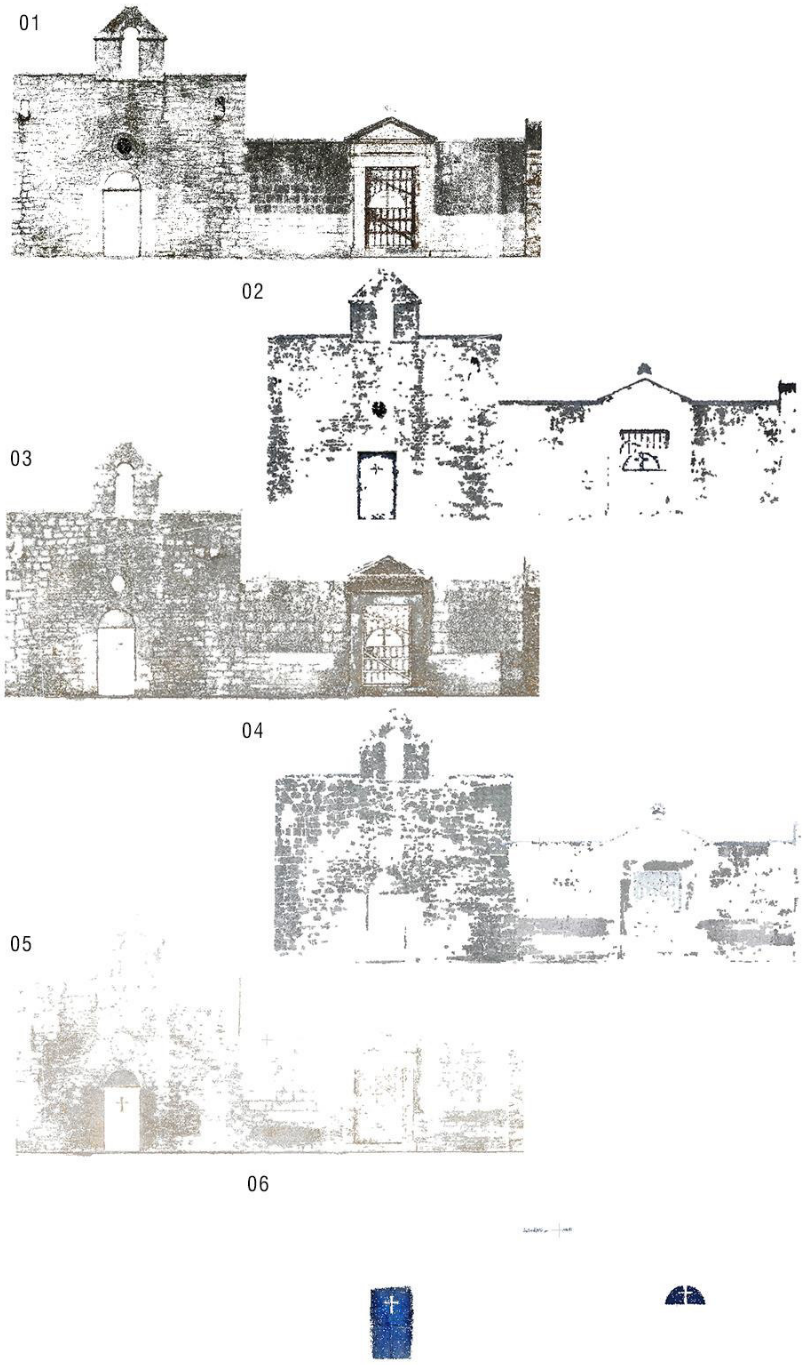


Fig. 55 Clusters in HSV (Case 3-façade Est): 1) biological colonization (46%); 2) spots/deposit (17%);3) moist area (75%); 4) biological patina (67%) 5) unaltered surface (24%);6) doors (7%)

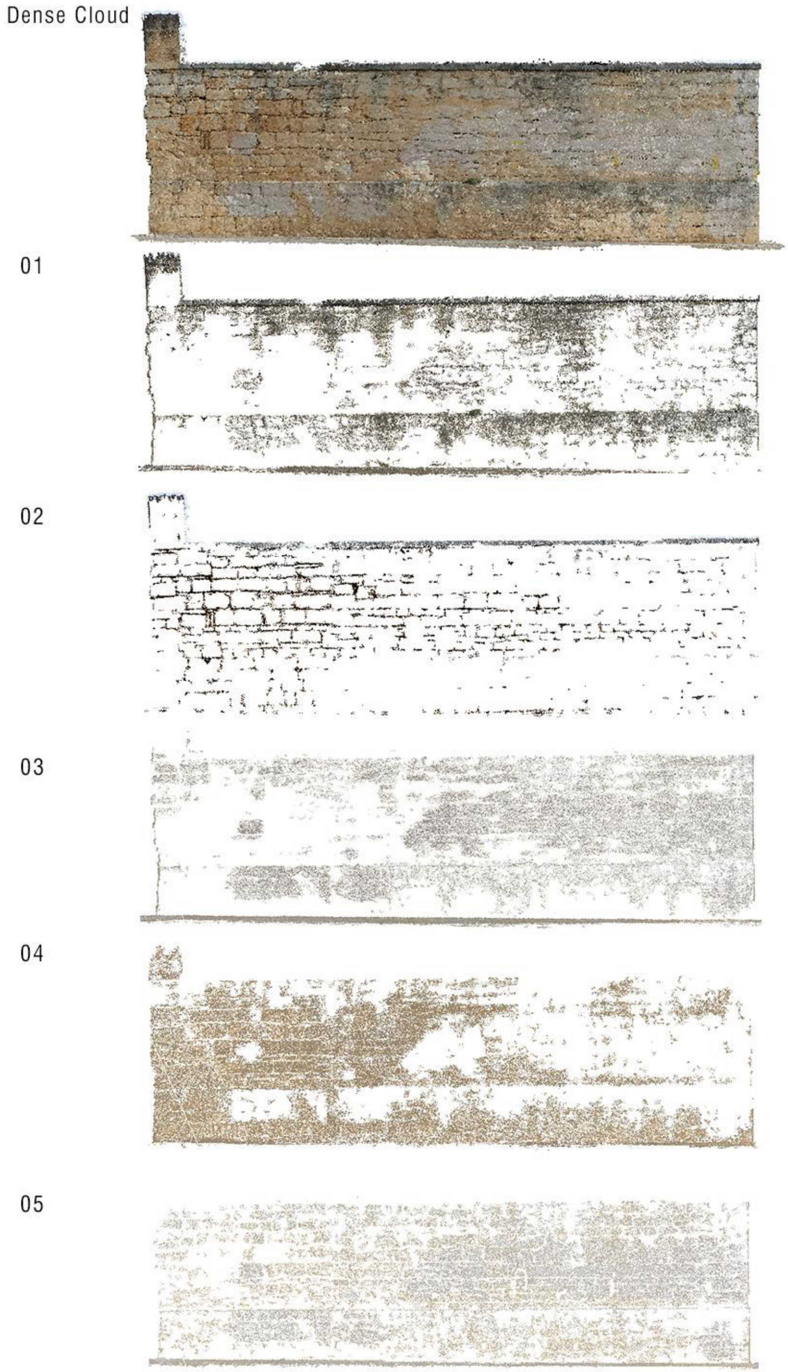


Fig. 56 Clusters in HSV (Case 3-façade Sud): 1) biological colonization (41%); 2) spots/deposit (11%);3) moist area (37%); 4) biological patina (52%) 5) unaltered surface (39%);

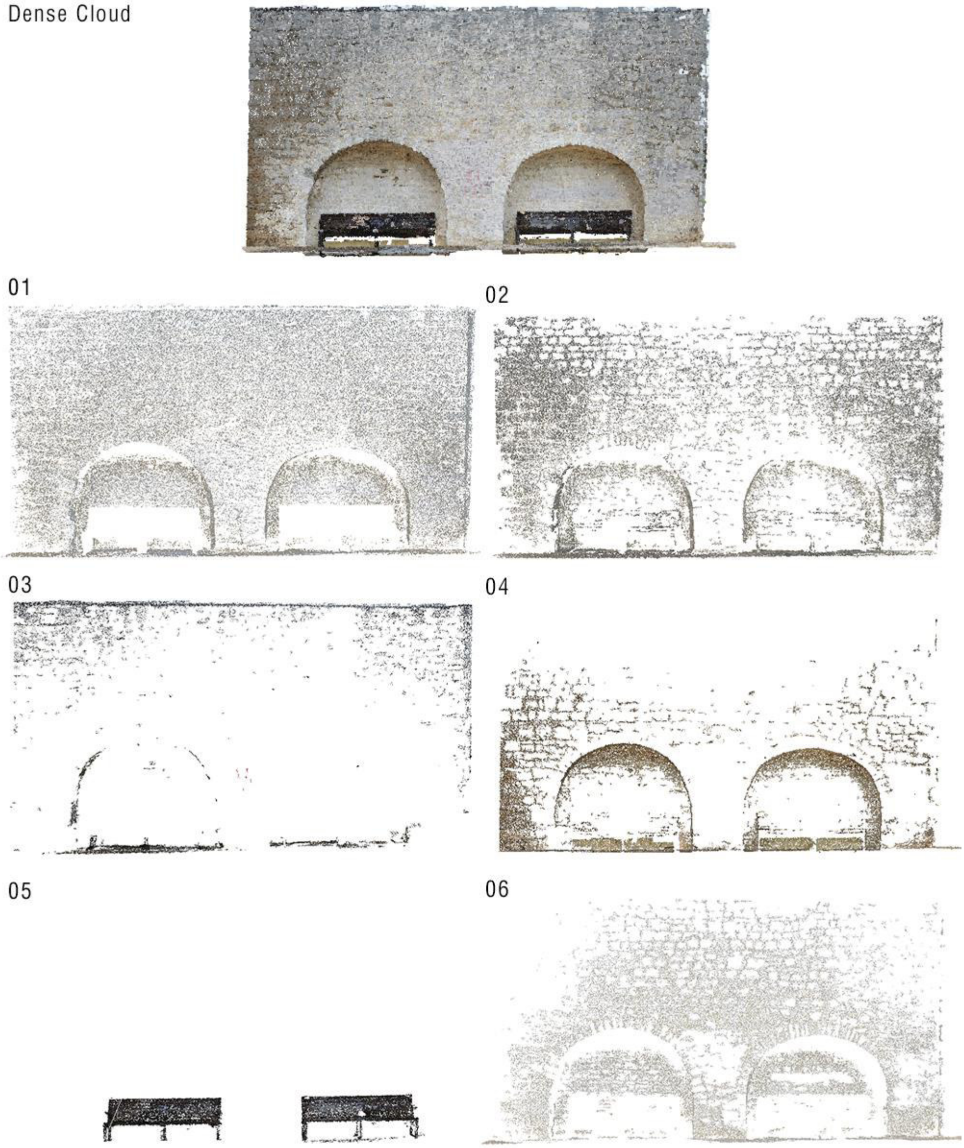


Fig. 57 Clusters in HSV (Case 3-façade Nord): 1) biological patina (31%); 2) biological colonization (61%); 3) spots/deposit (16%);4) moist area (14%); 5) benches (18%) 6) unaltered surface (36%);

To validate this hypothesis, for each of the clusters segmented in HSV, an analogous one has been identified in the other three colour-spaces, through the evaluation of the clusters' histograms (RGB distribution evaluated both with the three channels split and unified).

Taking into account the overlapping, only those clusters with the highest percentage have been considered as analogous (Fig. 58 left), while clusters with a little percentage have been excluded (Fig. 58 right).

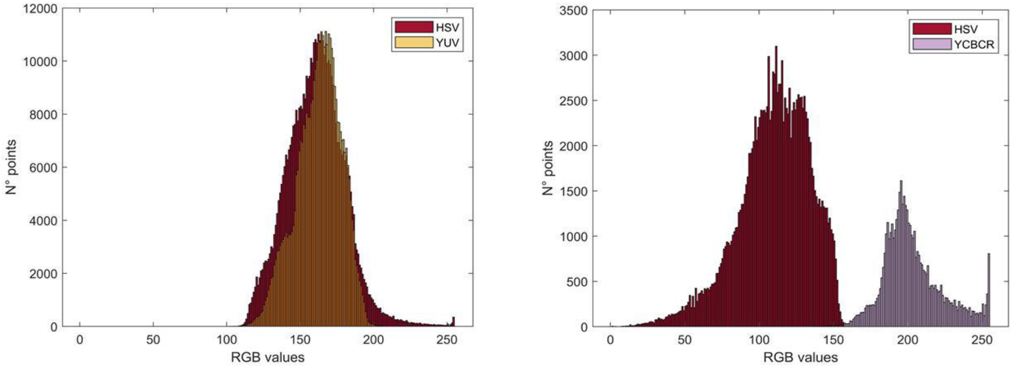


Fig. 58 Clusters' histogram overlapping (left: 75% overlapping; right: 0.12 % overlapping) (Musicco et al., 2021).

A further passage concerns the overlapping of the four analogous clusters' histograms with the ground truth (manually segmented clusters), as illustrated in Fig. 59.

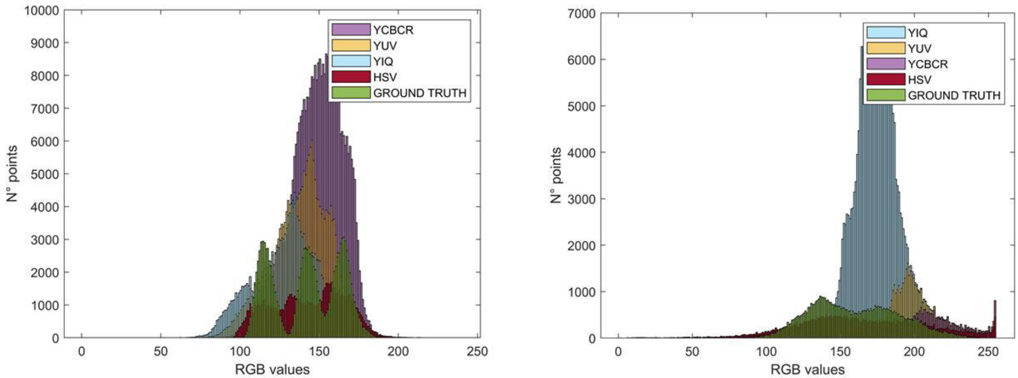


Fig. 59 Overlapping between analogous clusters histograms (unified RGB) of the four colour spaces and the ground truth. Case 2: moist area (left); staining (right) (Musicco et al., 2021).

The HSV histograms are the ones with the most similar trend with respect to the corresponding ground truth. In fact, on the one hand in the other colour spaces more points are included in the same cluster, containing parts that are not consistent with the analysed alteration (Fig. 59 left); on the other hand, in HSV the detected colour range is wider (Fig. 59 right), because unlike in the other spaces (YCbCr, YIQ, YUV), the luminance component doesn't outweigh the chrominance ones.

Indeed, the resulting segmentation in these colour spaces splits the same colour range and the corresponding decay pattern and some elements (doors, benches, etc.) in more than one cluster.

Also, the comparison of the number of points and the related percentage of each analogous cluster of the four colour spaces with its equivalent ground truth, confirmed that HSV is able to better isolate specific colour ranges, associated with the chromatic difference, and it is more reliable both in terms of colour interval and in terms of extension (number of points; area, based on the average point density; extension-percentage).

		GROUND TRUTH		HSV		YCBCR		YIQ		YUV	
N° points tot	pt		254.693		254.693		254.693		254.693		254.693
		Moist Area									
N° points	pt		47.840		45.840		44.745		118.194		81.002
Point Density	pt/m^2		4.548		4.548		4.548		4.548		4.548
Area	m^2		10,52		10,08		9,84		25,99		17,81
Extension	%		19%		18%		18%		46%		32%
		Biological patina									
N° points	pt		66.236		66.363		44.745		69.352		82.872
Point Density	pt/m^2		4.548		4.548		4.548		4.548		4.548
Area	m^2		14,56		14,59		9,84		15,25		18,22
Extension	%		26%		26%		18%		27%		33%
		Biological Colonization									
N° points	pt		49.567		52.000		43.120		43.624		59.029
Point Density	pt/m^2		4.548		4.548		4.548		4.548		4.548
Area	m^2		10,90		11,43		9,48		9,59		12,98
Extension	%		19%		20%		17%		17%		23%
		Spots/Deposit									
N° points	pt		49.763		49.211		43.120		43.624		59.029
Point Density	pt/m^2		4.548		4.548		4.548		4.548		4.548
Area	m^2		10,94		10,82		9,48		9,59		12,98
Extension	%		20%		19%		17%		17%		23%
		Staining									
N° points	pt		32.549		32.279		95.972		69.352		82.872
Point Density	pt/m^2		4.548		4.548		4.548		4.548		4.548
Area	m^2		7,16		7,10		21,10		15,25		18,22
Extension	%		13%		13%		38%		27%		33%

Table 8 Case 1 - point cloud segmentation: ground-truth (manually labelled portions); HSV clusters; correspondent clusters in the other colour space

From Table 8, it is possible to observe that, in the five classes (moist area, biological colonization/patina, spots/deposit, unaltered surface, staining), the extension in percentage has a maximum variation of 1% between the ground truth and HSV, while in the other colour spaces the diversity range is wider.

As a consequence, it was possible to quantify the extension of each decay pattern in the three case studies using hierarchical segmentation in HSV colour space:

- Case 1: moist area 10 m^2; biological patina 14,59 m^2; biological colonization 11,4 m^2; spots/deposit 10,8 m^2; staining 7,10 m^2 ;
- Case 2: Façade Ovest: biological colonization 3,55 m^2, moist area 6,8 m^2; unaltered 5,27 m^2, Façade Nord: moist area 6,82 m^2; biological colonization 9,38 m^2; deposit/spot 2,3 m^2; biological patina 7,57 m^2; unaltered 4,55 m^2; Façade Est: biological colonization 6,7 m^2; biological patina 6,7 m^2;
- Case 3 : Façade Nord (Table 9): moist area 9,81 m^2, biological colonization 34,60 m^2, 9,40 m^2, unaltered 25,4 m^2, benches 10,31 m^2, biological patina 22,14 m^2 , Façade Est (Table 10): moist area 53,15 m^2, biological colonization 32,50 m^2, deposit 12,42 m^2, unaltered 22,09 m^2, doors 2,0 m^2, biological patina 20,04 m^2; Façade Sud (Table 11):moist area 22,76 m^2, biological colonization 25,16 m^2, deposit 6,7 m^2, unaltered 23,54 m^2, chromatic alteration 17,59 m^2, biological patina 31,60 m^2; Façade Ovest (Table 12): 24,52 m^2, biological colonization 32,0 m^2, deposit 17,95 m^2, unaltered 44,23 m^2, tiles 8,0 m^2.

In Table 9,Table 10, Table 11, Table 12 the segmentation results, in terms of number of point, area and percentage obtained for the Case 3, are reported.

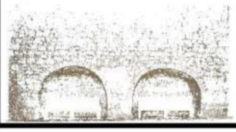
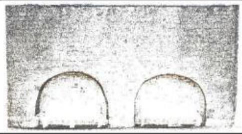
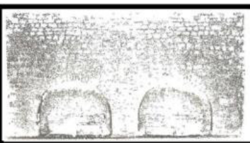
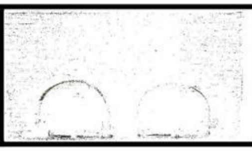
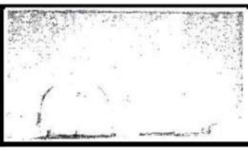
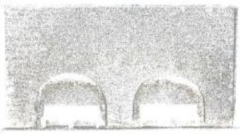
		Ground Truth		CLOUD-BASED	
original model N° points Area	 pt m^2		 457.369 57		 379.105 57
moist area N° points Area Extension	 pt m^2 %		 51.271 23,96 34%		 84.868 9,81 14%
biological colonization N° points Area Extension	 pt m^2 %		 105.772 32,43 57%		 106.040 34,60 61%
spots/deposit N° points Area Extension	 pt m^2 %		 10.343 8,32 14%		 29.773 9,40 16%
unaltered surface N° points Area Extension	 pt m^2 %		 95.965 27,41 48%		 101.536 25,40 36%
object N° points Area Extension	 pt m^2 %		 72.567 11,99 21%		 56.888 10,31 18%
biological patina N° points Area Extension	 pt m^2 %		 121.451 47,64 84%		 202.990 22,14 31%

Table 9 Results of Cloud-Based method using HSV in comparison with Ground Truth of Façade Nord of Case 3

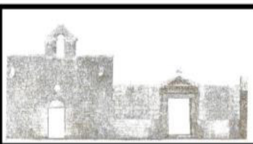
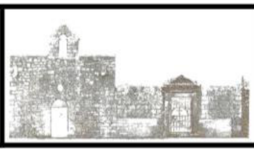
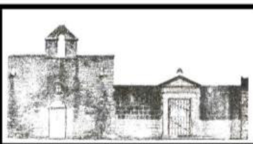
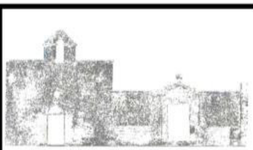
		Ground Truth		CLOUD-BASED	
original model					
N° points	pt		719.759		667.290
Area	m^2		70		70
moist area					
N° points	pt		225.007		260.315
Area	m^2		53,30		53,15
Extension	%		76%		75%
biological colonization					
N° points	pt		203.118		157.798
Area	m^2		38,90		32,50
Extension	%		55%		46%
spots/deposit					
N° points	pt		25.138		42.252
Area	m^2		12,80		12,42
Extension	%		18%		17%
unaltered surface					
N° points	pt		131.778		103.364
Area	m^2		17,15		22,09
Extension	%		24%		24%
object					
N° points	pt		40.479		17.353
Area	m^2		5,45		2,04
Extension	%		7%		7%
biological patina					
N° points	pt		94.239		86.208
Area	m^2		47,16		20,04
Extension	%		67%		67%

Table 10 Results of Cloud-Based method using HSV in comparison with Ground Truth of Façade Est of Case 3

		Ground Truth		CLOUD-BASED	
original model					
N° points	pt		490.315		471.274
Area	m ^ 2		60,33		60,33
moist area					
N° points	pt		112.512		101.540
Area	m ^ 2		33,90		22,76
Extension	%		56%		37%
biological colonization					
N° points	pt		63.955		85.505
Area	m ^ 2		25,21		25,16
Extension	%		41%		41%
spots/deposit					
N° points	pt		58.007		27.026
Area	m ^ 2		8,79		6,66
Extension	%		14%		11%
unaltered surface					
N° points	pt		72.552		88.336
Area	m ^ 2		21,82		23,54
Extension	%		36%		39%
chromatic alteration					
N° points	pt		45.735		67.327
Area	m ^ 2		15,16		17,59
Extension	%		25%		29%
biological patina					
N° points	pt		137.554		101.540
Area	m ^ 2		34,16		31,60
Extension	%		56%		52%

Table 11 Results of Cloud-Based method using HSV in comparison with Ground Truth of Façade Sud of Case 3

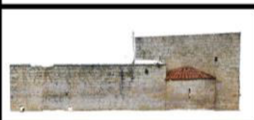
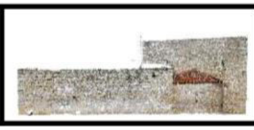
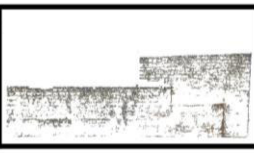
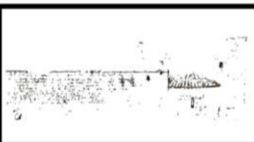
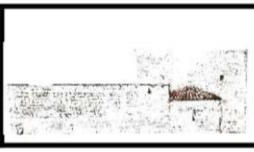
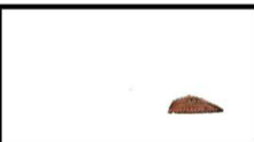
		Ground Truth		CLOUD-BASED	
original model					
N° points	pt		443.548		485.150
Area	m ^ 2		64		64
moist area					
N° points	pt		82.353		113.060
Area	m ^ 2		19,26		24,52
Extension	%		30%		38%
ological colonization/pati					
N° points	pt		76.623		81.863
Area	m ^ 2		24,73		31,99
Extension	%		38%		49%
spots/deposit					
N° points	pt		27.502		56.536
Area	m ^ 2		7,42		17,95
Extension	%		11%		28%
unaltered surface					
N° points	pt		231.413		214.018
Area	m ^ 2		46,76		44,23
Extension	%		73%		69%
objects					
N° points	pt		25.657		19.673
Area	m ^ 2		2,49		96,50
Extension	%		3%		12%

Table 12 Results of Cloud-Based method using HSV in comparison with Ground Truth of Façade Ovest of Case 3

Therefore, the HSV colour-space is the most consistent with the purposes of the colour segmentation, indeed it proves to be efficient in the accurate identification of a plurality of chromatic deterioration morphologies, both in terms of extension and colour interval. The same accuracy it was not observed in the segmentation of objects where lots of outcomes or loss of data was found, as we can see in Table 12. For this reason another method has been investigated in Sub-Sec. 3.2.6.

The application to three selected case studies enabled the validation of the proposed methodology, detecting a series of chromatic alterations on the masonry surface, previously recognized through a visual inspection of the environments. The advantage of this approach is the possibility to achieve both a qualitative and quantitative analysis of different morphologies of surface alterations, starting from 3D data, with semi-automatic procedures, in support of diagnostic activities.

A disadvantage consists in the fact that the operator, who performs the segmentation, must be specialized in the field of decay diagnosis since he must validate the results of the segmentation automatically obtained.

Another limitation of this procedure could be the difficulty to distinguish and isolate chromatic alterations on decorated surfaces, like frescoes, temperas or wall papers. Furthermore, the procedure may be associated to a process of classification for automatically obtaining labelled point clouds.

3.2.4 TEXTURE-BASED METHOD

As descripted in Sub-Sec. 2.2.5, to realize the segmentation of a point cloud using Machine Learning, it is also possible to operate through supervised approaches. In this section, colour segmentation has been performed trough texture-based segmentation method applied to 2D images representing texture information directly extracted from 3D digital models.

Starting from coloured 3D point cloud the pipeline develops in four principal steps (Grilli, 2020). Firstly, the texture surface model is generated, from which subsequently, orthoimages or UV maps are extracted. A further passage consists in the classification of the orthoimages or UV maps using different approaches tailored to the case study (i.e., Random Forest or Clustering). In the last step, the classified 2D images are re-projected on the 3D model.

Therefore, Texture-based method works on the 2D texture information deriving from the 3D models. According to the geometry and complexity of the considered 3D object, texture is produced as orthophoto (for planar objects)(Sub-Sec. 3.2.2.1) or UV maps (for 3D structures with certain level of complexity) which are 2D images produced from UV mapping process (or UV unwrapping) (Fig. 60). The process consists in projecting a 2D image to a 3D model's surface for texture mapping. The letters "U" and "V" denote the axes of the 2D texture because "X", "Y", and "Z" are already used to indicate the axes of the 3D object in model space. Therefore, UV maps are the flat representations of the surfaces of 3D models used to wrap textures. In most 3D applications (3ds Max, Agisoft Metashape©, Cinema 4D, and Blender) UV maps can be generated automatically.

To simplify the UV Unwrapping process, it is beneficial applying as a first step a remeshing to the 3D models. UV maps are then generated by adjusting and optimising seam lines and overlaps. Seams are the edges (or breaks) in geometry between UV islands and are inevitable for most models. Seams could cause problems during the classification process; areas of the models belonging to the same class may be split into different islands. These discontinuities between UV islands could bring to a misclassification. To avoid these kind of problems the users can command the UV unwrapper to cut the mesh along edges chosen following the shape of the case study.

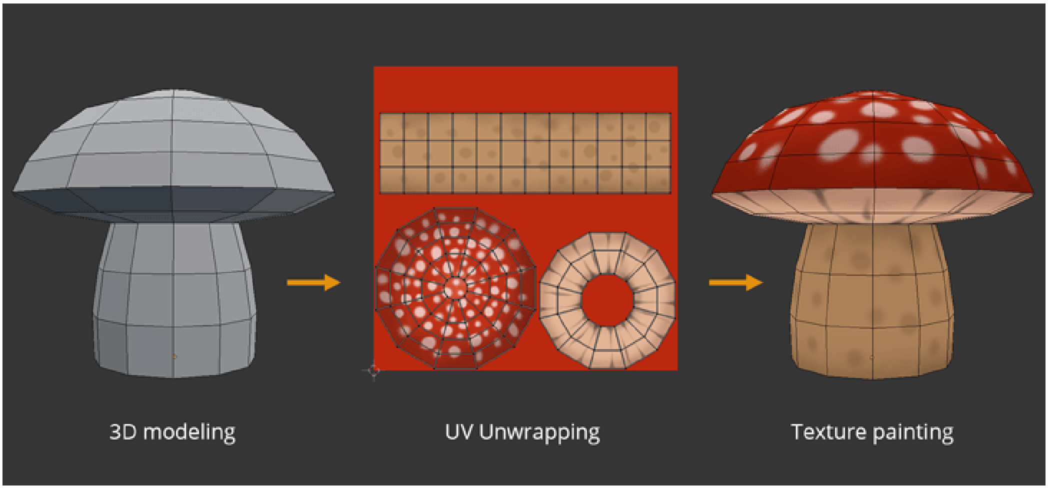


Fig. 60 Schematic representation of UV mapping process from /www.blendernation.com

In this work, UV maps, generated with Agisoft Metashape©, have been used due to the objects of study is three-dimensionally complex. The colour space chosen for the UV maps generation is RGB (Sub-Sec. 2.2.2).

For the classification of 2D images in the form of UV map or orthophoto, Weka (Waikato Environment for Knowledge Analysis) (Witten & Eibe, 2000) has been used. Weka is a collection of supervised machine learning algorithms for data mining tasks such as classification, regression, clustering, association rules mining, and visualization. In this contest, the plug-in Trainable Weka Segmentation (Fig. 61), contained in Fiji software of ImageJ, has been used. The plug-in combines a collection of machine learning algorithms (random tree, random forest, etc.) with a set of selected image features to produce pixel-based segmentations. The features available can be categorised as:

- edge detectors, which aim at indicating boundaries of objects in an image (e.g., Laplacian and Sobel filters, difference of Gaussians, Hessian matrix eigenvalues and Gabor filters);
- texture filters, to extract texture information (including filters such as minimum, maximum, median, variance, entropy, structure tensor, etc.);
- noise reduction filters, such as Gaussian blur, Bilateral filter, Anisotropic diffusion, Kuwahara and Lipschitz;
- chromatic valuation, which the aim is the extraction data about the hue, saturation, and brightness, etc.

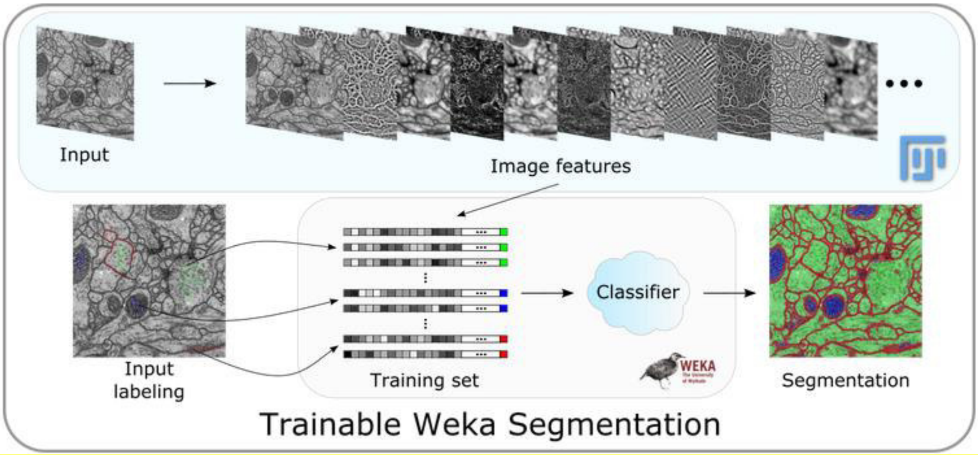


Fig. 61 Trainable WeKa Segmentation workflow

All the available classifiers are based on a decision tree learning method. In this approach, during the training, a set of decision nodes over the values of the input features are built and connected to each other in a tree structure. This structure, as a whole, represents a complex decision process over the input features. The result of this decision is a value for the label that classifies the input example. During the training phase, the algorithm learns these decision nodes and connects them. Among the different approaches, we achieved the best results in terms of accuracy through the RF method (Sub-Sec 2.2.5.1).

For exploiting the algorithm, an input region was manually annotated on the UV Maps and assigned to a class and to a colour. There are many types of annotation such as bounding box, polygon, etc. The choice of them depends on the characteristics and types of images and expected results in terms of accuracy. Bounding boxes are rectangles drawn by the annotator. In many cases a bounding box is sufficient to define the position of an object on the image. However, for objects that are not vaguely rectangle shaped, a bounding box is not precise enough. Annotation by polygon is much more refined but is more difficult to draw (Fig. 62).

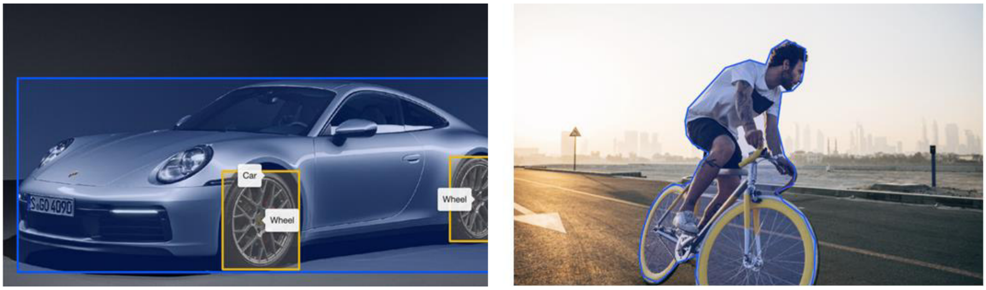


Fig. 62 Image annotation techniques: bounding box (on the left); polygonal annotation (on the right).

For all the case studies considered the annotations were done following the polygonal selection techniques. In this way, just some significant and well-distributed portions of the textures were rapidly highlighted.

Once each annotation has been assigned to a class it is possible to start the training process. The features of the input image will be extracted and converted to a set of vectors of float values, which is the format the Weka classifiers are expecting. If the training ends correctly, then the displayed 2D image will be completely segmented and the result will be overlaid with the corresponding class colours.

Starting from the classified orthophotos or UV Maps, it is possible to estimate the quantity that each class occupies over the total area investigated. In particular, the percentage is calculated as a comparison between the number of pixels classified as Class-X and the total number of pixels in the classified image (subtracting the background). These percentages can then be transformed into surface measures. While the orthophotos are directly measurable, the measuring accuracy computed on the UV maps could be affected by errors due to distortions generated during the UV unwrapping. Therefore, it becomes essential to work on equal-area projection UVs.

In the follow section results of Texture-based segmentation, applied on two cases of study, are shown.

3.2.4.1 Results and discussion

Texture-based method has been applied to the chapel of San Luigi (Case 2 in Sub-Sec. 3.2.3) and the rural church of Santissimo Salvatore (Case 3 in Sub-Sec. 3.2.3) whose descriptions are in Sub-Sec. 3.2.1.

Digital acquisitions and 3D modelling parameters of the two cases of study have been already descripted in Table 7. Textured meshes and corresponding UV Maps were generated through Agisoft Metashape©. The segmentation task aimed to detect the alteration of the masonsy surface and to evaluate the accuracy of the results with those obtained by the Cloud-based method (Sec. 3.2.3). Firstly, through polygonal annotation, training patches has been classified. The same forms of decay were considered as a class:biological patina, biological colonization, spots, deposits, chromatic alteration and moist areas (ICOMOS ISCS., 2008),. To increase the accuracy of the results, more than one training patch was noted for each class (Fig. 63). In addition, a class has been introduced for the unaltered surface and the background due to the plug-in subjects all the pixels of the image to the segmentation operation, including the white background. In Fig. 65 classification results on UV Maps are represented, and in Fig. 66 and Fig. 67 the same results have been re-projected on 3D model.

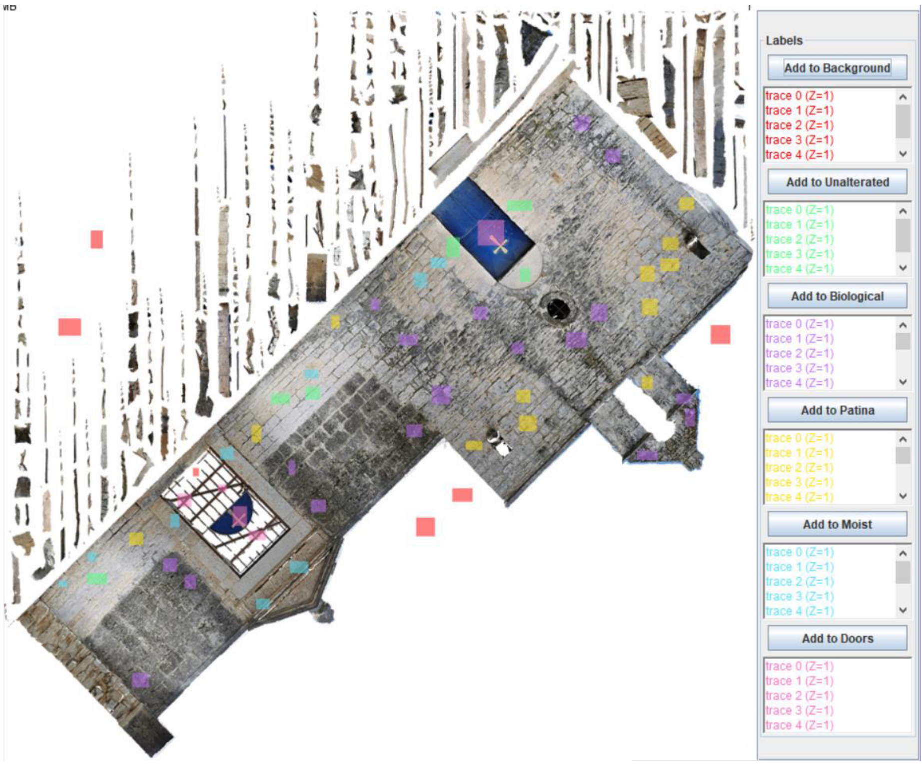


Fig. 63 Manually annotated training patches on the UV Map of the façade Est of the church of S. Salvatore

As for the Cloud Based method, also in this case the segmented regions were compared with the manually segmented ground truth.

For the deterioration typologies of the masonry surface with evident chromatic differences Weka has been able to groping pixels with similar features and for each degradation class it manages to locate the pixels in the same regions corresponding to the ground truth.

However, from a first qualitative analysis based on the comparison of images, lots of errors are visible. Firstly, it was not possible to obtain a distinct isolation between some classes such as for biological colonization and spot/deposit in Table 13 and biological colonization and biological patina in Table 16.

In addition, in some classes there are many outliers: in Table 13 the objects have been well identified, however many elements belonging to the perimeter of the facade have been incorrectly incorporated within the same class. Furthermore, for other classes Weka was unable to identify and separate the exact extension as for unaltered surface in Table 13, Table 14, Table 15, Table 16.

The qualitative assessments also obtained feedback in quantitative terms, considering the extension of the classes in the surface area and the percentage of the class out of the total. For each class between ground truth and portions individuated by Weka there is an average variation of 15%. The minimum variations are of the order of 0-1%, while the maximum of 60-40%.

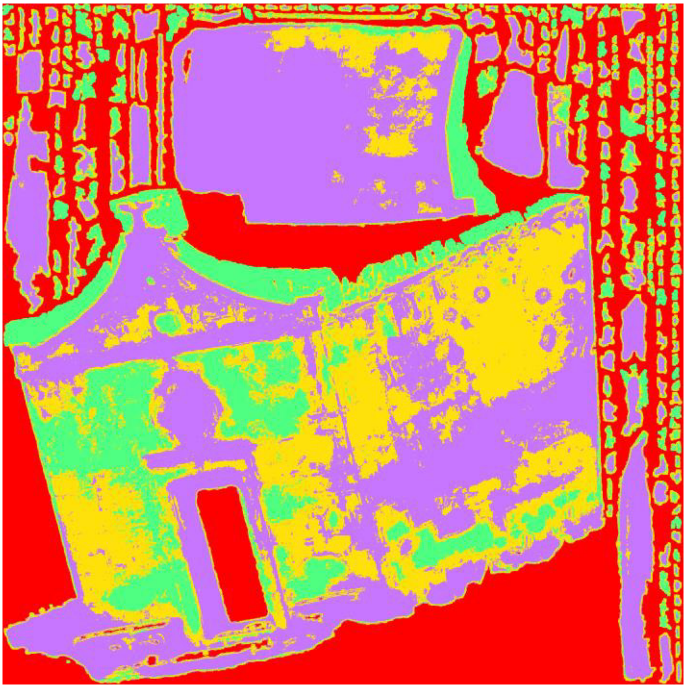


Fig. 64 Classification results on UV Map of S.Luigi Chapel

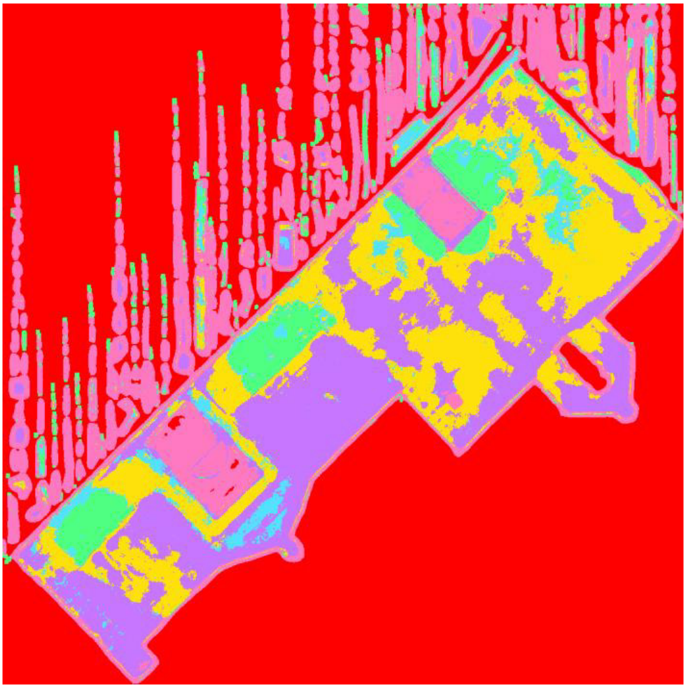


Fig. 65 Classification results on UV Map of S.Salvatore Church

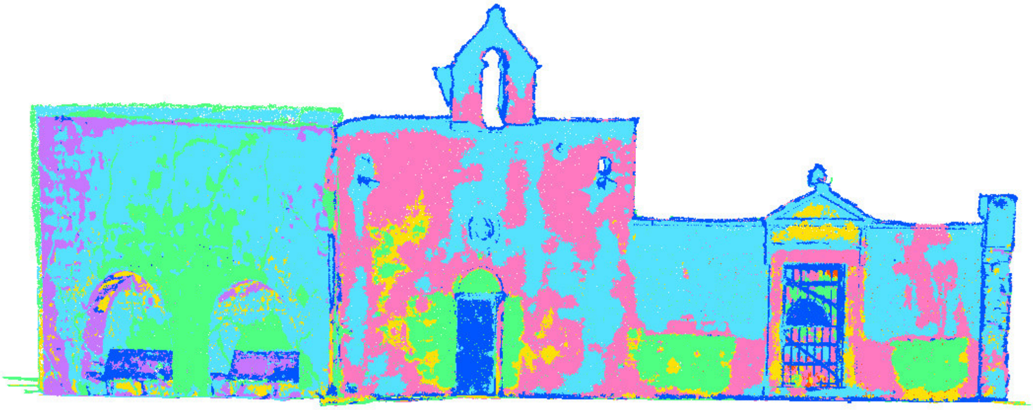


Fig. 66 The classified 2D images re-projected on the 3D model of S.Salvatore Church

Fig. 67 The classified 2D images re-projected on the 3D model of S.Luigi Chapel

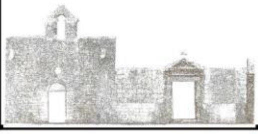
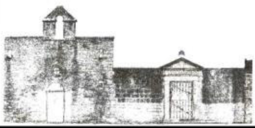
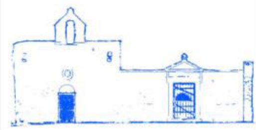
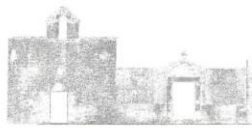
		Ground Truth		TEXTURE-BASED	
original model					
N° points	pt		719.759		727.016
Area	m ^ 2		70		70
moist area					
N° points	pt		225.007		45.768
Area	m ^ 2		53,30		6,70
Extension	%		76%		9%
biological colonization					
N° points	pt		203.118		252.612
Area	m ^ 2		38,90		27,66
Extension	%		55%		39%
spots/deposit					
N° points	pt		25.138		252.612
Area	m ^ 2		12,80		27,66
Extension	%		18%		39%
unaltered surface					
N° points	pt		131.778		67.754
Area	m ^ 2		17,15		8
Extension	%		24%		10%
object					
N° points	pt		40.479		108.270
Area	m ^ 2		5,45		13
Extension	%		7%		19%
biological patina					
N° points	pt		94.239		252.612
Area	m ^ 2		47,16		24
Extension	%		67%		34%

Table 13 Results of Textured-Based method in comparison with Ground Truth of Façade Est of S.Salvatore Church

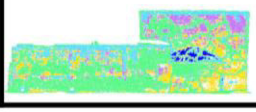
		Ground Truth		TEXTURE-BASED	
original model					
N° points	pt		443.548		509.464
Area	m ^ 2		64		64
moist area					
N° points	pt		82.353		57.106
Area	m ^ 2		19,26		12
Extension	%		30%		18%
ological colonization/pati					
N° points	pt		76.623		73.051
Area	m ^ 2		24,73		12,58
Extension	%		38%		19%
spots/deposit					
N° points	pt		27.502		36.191
Area	m ^ 2		7,42		7,67
Extension	%		11%		11%
unaltered surface					
N° points	pt		231.413		333.120
Area	m ^ 2		46,76		34,39
Extension	%		73%		53%
objects					
N° points	pt		25.657		9.996
Area	m ^ 2		2,49		1,60
Extension	%		3%		2%

Table 14 Results of Textured-Based method in comparison with Ground Truth of Façade Ovest of S.Salvatore Church

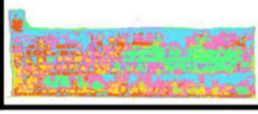
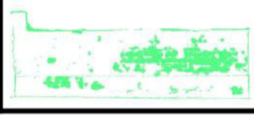
		Ground Truth		TEXTURE-BASED	
original model					
N° points	pt		490.315		491.247
Area	m ^ 2		60,33		60,33
moist area					
N° points	pt		112.512		78.470
Area	m ^ 2		33,90		8,74
Extension	%		56%		14%
biological colonization					
N° points	pt		63.955		93.360
Area	m ^ 2		25,21		10,30
Extension	%		41%		17%
spots/deposit					
N° points	pt		58.007		64.180
Area	m ^ 2		8,79		7,60
Extension	%		14%		12%
unaltered surface					
N° points	pt		72.552		96.643
Area	m ^ 2		21,82		10,91
Extension	%		36%		18%
chromatic alteration					
N° points	pt		45.735		55.837
Area	m ^ 2		15,16		6,58
Extension	%		25%		10%
biological patina					
N° points	pt		137.554		102.757
Area	m ^ 2		34,16		12,89
Extension	%		56%		21%

Table 15 Results of Textured-Based method in comparison with Ground Truth of Façade Sud of S.Salvatore Church

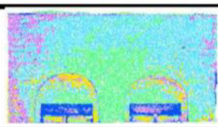
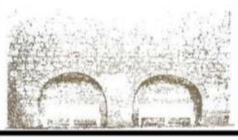
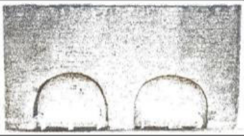
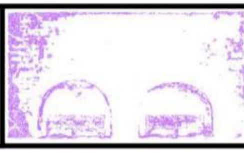
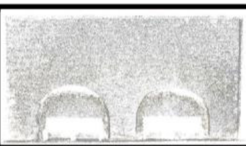
		Ground Truth		TEXTURE-BASED	
original model					
N° points	pt		457.369		485.176
Area	m^2		57		57
moist area					
N° points	pt		51.271		34.080
Area	m^2		23,96		5,33
Extension	%		34%		9%
biological colonization					
N° points	pt		105.772		222.216
Area	m^2		32,43		30,04
Extension	%		57%		53%
spots/deposit					
N° points	pt		10.343		90.812
Area	m^2		8,32		12,90
Extension	%		14%		22%
unaltered surface					
N° points	pt		95.965		105.543
Area	m^2		27,41		13,74
Extension	%		48%		24%
object					
N° points	pt		72.567		32.525
Area	m^2		11,99		4,70
Extension	%		21%		8%
biological patina					
N° points	pt		121.451		222.216
Area	m^2		47,64		30,00
Extension	%		84%		53%

Table 16 Results of Textured-Based method in comparison with Ground Truth of Façade Nord of S. Salvatore Church

3.2.5 COMPARISON OF COLOUR SEGMENTATION METHODS

In order to assess which of the two proposed methods, Cloud-based (CL) Sub-Sec3.2.3 and Texture-based (TX) Sub-Sec 3.2.4 was the most accurate in detecting chromatic alteration, the results obtained were compared in two different steps.

Firstly, point clouds obtained from the two methods have been compared through Surface Deviation Analysis (SDA) method (Sub-Sec 2.3.2.1) in Cloud Compare (Daniel Girardeau-Montau, 2020) with a ground truth (GT) manually generated. The analysis execute from the software point by point allows the recognition of the correctly predicted segmented points respectively as True Positive or True Negative class, and of the incorrectly predicted points as False Positive and False Negative. Once calculated TP, TN, FP, and FN it was possible to proceed with the evaluation of the values of Precision, Recall, F1-score, Accuracy. So for every kind of alteration a Confusion Matrix (Sub-Sec 2.2.6) has been structured for analytically evaluating the differences between segmented point clouds.

Moist Area		GT	CL	TX
N° points	pt	225.007	260.315	45.768
Percentage Points	%	31%	39%	6%
Area	m^2	53,30	53,15	6,70
Percentage Area	%	76%	76%	10%
Percentage Variation	%		-0,28%	-87,43%
TP	-		243276	38486
TP K	-		225.007	38.486
FP	-		35.308	7.282
FN	-		-	186.521
TN	-		118.790	252.887
Precision	%		0,86	0,84
Recall	%		1,00	0,17
f1-score	%		0,93	0,28
Accuracy	%		0,91	0,60

Table 17 Summary table of SDA and performance metrics results for most area decay of Façade Est of S.Salvatore Church.

Unaltered		GT	CL	TX
N° points	pt	231.413	214.018	333.120
Percentage Points	%	52%	44%	65%
Area	m^2	46,76	44,23	34,39
Percentage Area	%	73%	69%	54%
Percentage Variation	%		-5,41%	-26,45%
TP	-		210.541	275.161
TP K	-		210.541	231.413
FP	-		3.477	101.707
FN	-		20.872	-
TN	-		144.215	152.056
Precision	%		0,98	0,69
Recall	%		0,91	1,00
f1-score	%		0,95	0,82
Accuracy	%		0,94	0,79

Table 18 Summary table of SDA and performance metrics results for unaltered surface of Façade Ovest of S.Salvatore Church.

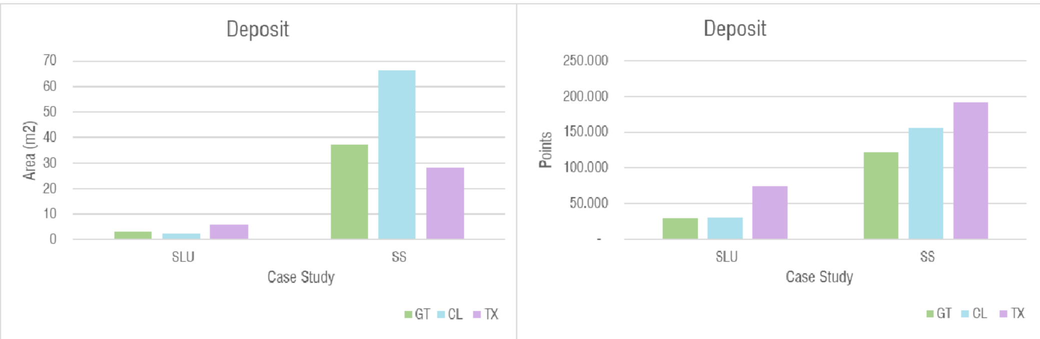
Biological Patina		GT	CL	TX
N° points	pt	273.843	266.199	107.226
Percentage Points	%	22%	22%	9%
Area	m^2	74,28	68,62	23,79
Percentage Area	%	27%	25%	9%
TP	-		218.666	58.174
FP	-		47.533	49.052
FN	-		55.177	215.669
TN	-		904.177	906.655
Precision	%		0,82	0,54
Recall	%		0,80	0,21
f1-score	%		0,81	0,31
Accuracy	%		0,92	0,78

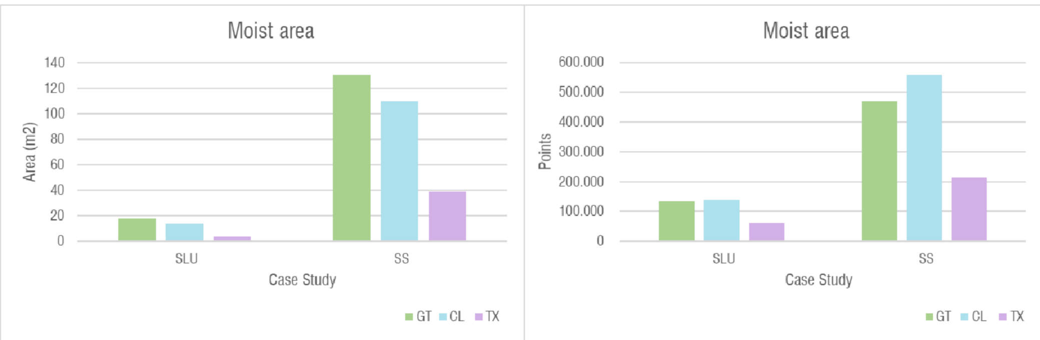
Table 19 Summary table of SDA and performance metrics results for biological patina of S.Luigi Chapel

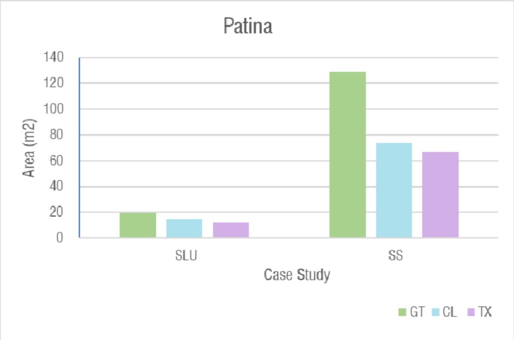
In Table 17,Table 18,Table 19, there are the results of the deviation analysis for three kinds of alteration considered as examples. The performance metrics such as

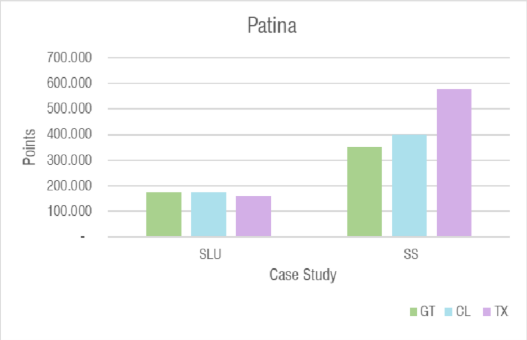
Precision, Recall, F1 Score and Accuracy values are much higher for the Cloud-Based method.

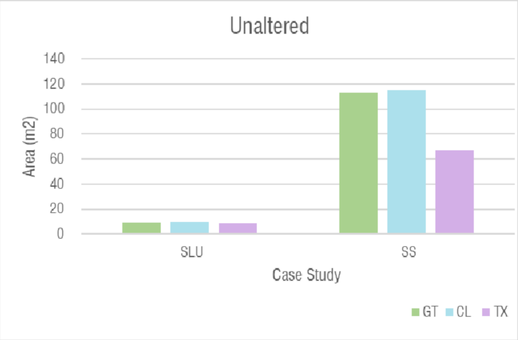
In following histograms, the y-axis represents the extension of segmented clouds in terms of area (m^2) on the left and n. of points on the right, instead on the x-axis is annotated an acronym for each case study SLU of S. Luigi chapter and SS for S. Salvatore church. Also from this representation of results it is possible to note how Cloud-based method is much more accurate than Texture-Based in comparison with ground truth.

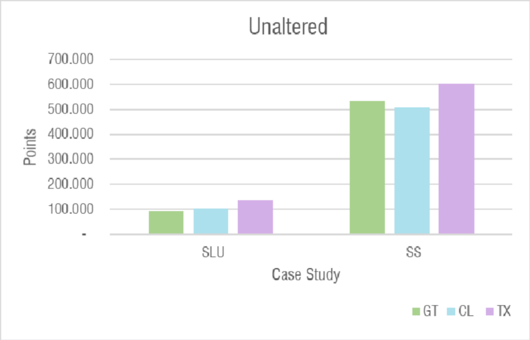





Patina
Area (m2)
140
120
100
80
60
40
20
0
SLU
SS
Case Study
GT CL TX


Patina
Points
700.000
600.000
500.000
400.000
300.000
200.000
100.000
-
SLU
SS
Case Study
GT CL TX


Unaltered
Area (m2)
140
120
100
80
60
40
20
0
SLU
SS
Case Study
GT CL TX


Unaltered
Points
700.000
600.000
500.000
400.000
300.000
200.000
100.000
-
SLU
SS
Case Study
GT CL TX

3.2.6 GEOMETRIC SEGMENTATION

In Sub-Sec. 3.2.2 Colour-based segmentation using the Cloud-based method has been able to isolate automatically not only chromatic alteration caused by decay, but also objects (benches, doors, etc.) characterized by a different colour range. However, the results it wasn't acceptable, due to chromatic homogeneity of an object isn't a condition usually finding. Therefore, it is necessary to integrate in segmentation process a segmentation method which may be use in most cases based only on geometric features.

The advantages are above all the following ones:

- The automatic discretization of original point cloud, reducing time of morpho-metric analysis and speeding up the phase of 3D modelling in Scan-to-BIM process;
- Used with the methods previously described in this section, for isolating elements on which chromatic evidences are detected.
- Extraction of qualitative and quantitative data focusing on the interest architectural element.

In this work RANSAC algorithm (described in Sub-Sec. 2.2.4.2) has been applied, through the use of the software Cloud Compare (Daniel Girardeau-Montau, 2020) and its plug-in "Ransac Shape Detection", which is based on the algorithm described in (Schnabel et al., 2007).

3.2.6.1 Results and discussion

The cases studies analysed through Geometric based method are the ex-convent of Cappuccini, the rural Church of Santissimo Salvatore (Fig. 49 Cases of study: 1) Barrel vaulted architectural unit of the Cappuccini ex-convent, 2) Facades of S.Luigi, 3) Facades od S. Salvatore.), and the Ognissanti Church (Fig. 68) described in Sub-Sec. 3.2.1.

The first two cases have been acquired with terrestrial photogrammetry technique and technical data have been already descriped in Table 6. Instead, the Ognissanti Church was recorded through TLS CAM2® FARO Focus 3D 120 with a total number of 55 scans (19 on the outer and 36 internal perimeter).

Fig. 68 On the top external facades, on bottom internal view of central nave of Ognissanti Church

The plug-in has a number of pre-set primitives such as plane, cylinder, sphere, torus, cone, therefore, the candidate shape primitives has been chosen after a previous morphological analysis of the case studies. In this contest, plane, cylinder and torus have been used.

In particular, a minimum radius was chosen for cylinder and torus by measuring the minimum element to be extracted on the point cloud and a minimum distance from primitive has been set considering the minimum thickness. In this way, it was possible to isolate elements through the definition of an order of magnitude for avoiding the segmentation of groups with a lower number of points.

In some cases, it was necessary to divide point cloud for reducing computational time and to submit to the algorithm a data set that can be reconduced to a maximum of three primitives to prevent errors in randomly selecting minimal sets from the point cloud. The smallest number of points, required to uniquely define a geometric primitive, is identified by the software as “minimum support points per primitive” and it has been set to 1000.

In a recursive way, the primitives have been tested automatically against all points in the data-set, in order to understand how many points, they are able to approximate. The procedure has been ended with the extraction of the shape that approximates the major number of points.

The limit of acceptance of the best candidate is related to a pre-determined probability, the “overlooking probability”, that there is no better candidate for the considered set of points. The remaining data are tested against a new primitive, following the same scheme.

In following figures results of geometric segmentation process are shown. In Fig. 69, RANSAC has been applied to an internal volume covered by a barrel vault. It is possible to see how the algorithm has isolated the walls in respect to the vault.

Fig. 69 Application of the RANSAC to the dense point cloud of barrel vaulted architectural unit of the Cappuccini ex-convent.

In Fig. 70, the façade Est of Santissimo Salvatore Church has been partitioned in its architectural components. Walls, moldings, gable, jambs, frames, doors are semantically segmented and manual classified.

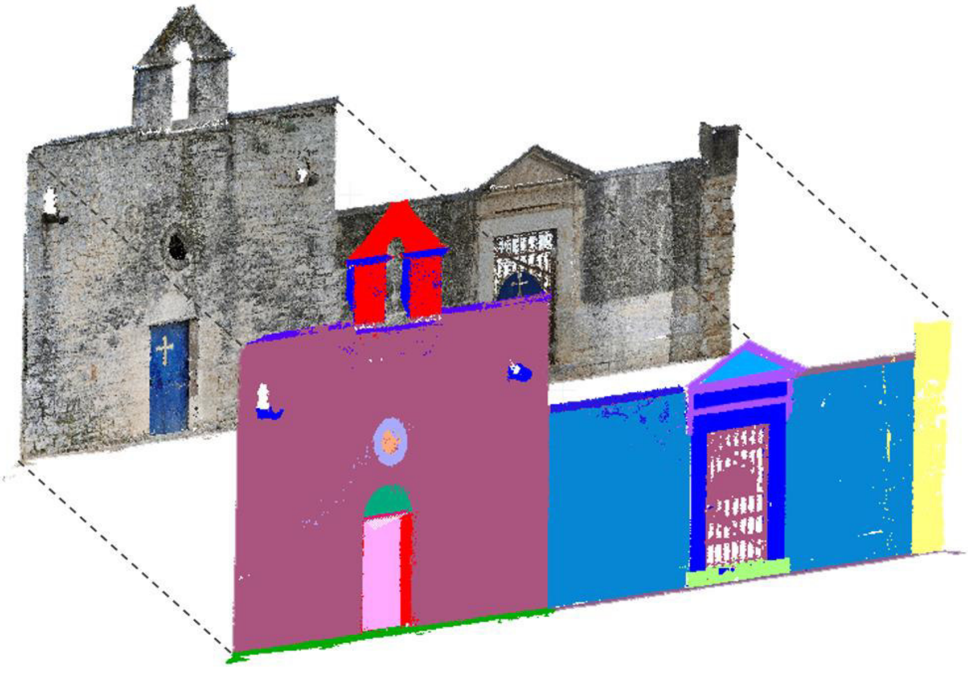


Fig. 70 Application of the RANSAC to the dense point cloud of façade Est of rural church of Santissimo Salvatore.

For the Ognissanti Church, the procedure has been more articulated due to the complexity of the point cloud (Fig. 71). It was necessary to divide the data set in three parts (upper, medium, and lower) and execute RANSAC for each one.
The segmentation of trusses, columns, capitals has been obtained. The segmented clouds have been the reference to the construction of BIM model as it is described in Sub-Sec. 3.1

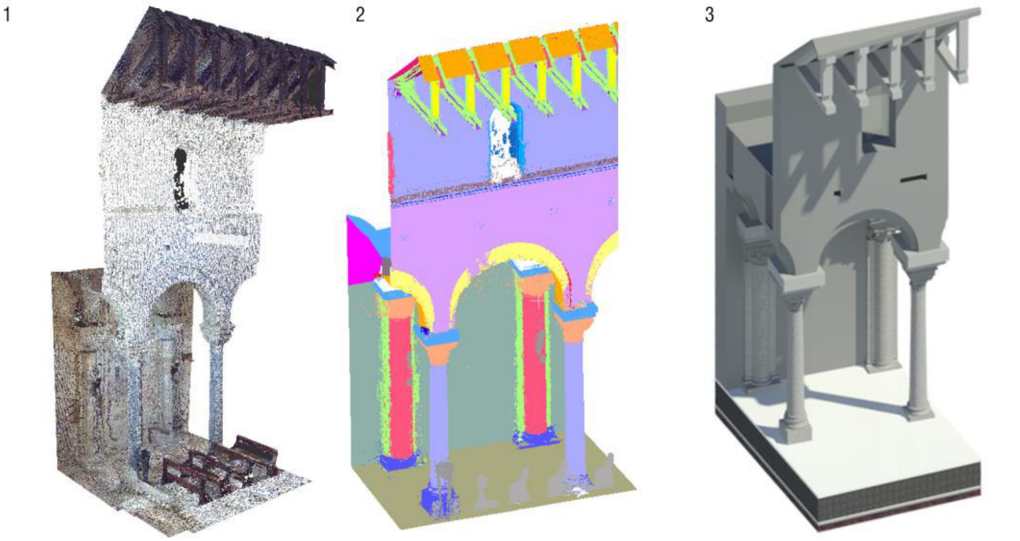


Fig. 71 Scan to BIM process integrated by automatic geometric segmentation of Ognissanti church 1) Original point cloud, 2) segmented point cloud by RANSAC, 3) BIM model.

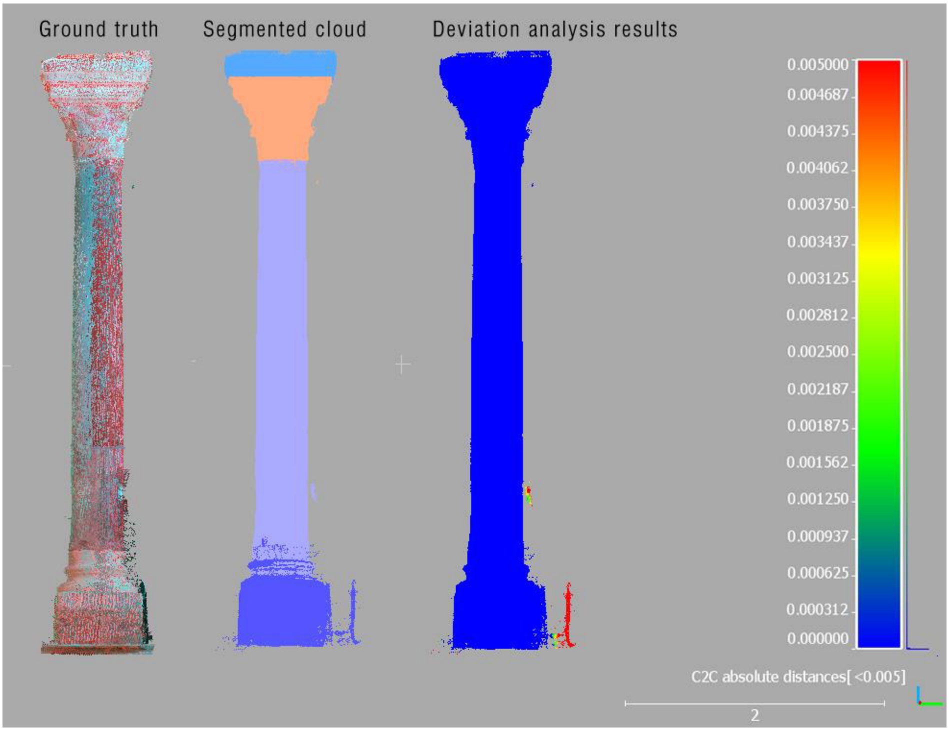


Fig. 72 Deviation analysis results

The segmentation results of all cases of studies have been accepted both from a morphological and metric point of view since them have been compared through deviation analysis (Sub-Sec. 2.3.2.1), with the manual segmented original point cloud, used as ground truth. The maximum distance considered between ground truth and segmented cloud was 0,005m (Fig. 72). In the cloud segmented through the RANSAC algorithm there are outliers belonging to other objects, whose size in terms of number of points and extension is considered negligible.

3.2.7 CONCLUSIONS AND FUTURE DEVELOPMENTS

The proposed methodologies have allowed a dual objective, first of all the discretization of raw 3D data to speed up the 3D modelling process and secondly the supporting prediagnostic purposes in the Architectural Heritage domain.

From a deep literature review revealed an evident lack of segmentation and classification approaches designed for the architectural environment directly applied to 3D data. In particular, the analysis of the colouring characteristics of the point

cloud is an area still little used for the extraction of semantic data to refine the process of documentation and storage. Therefore, the development of a process able to automatically classify architectural 3D data was considered to be highly demanded.
In this context, their application could be assimilated within the HBIM methodology of previous Sub-Section 3.1, for effective lifecycle management, supporting the semantic enrichment of “as-built” HBIM models in decay mapping and quantification, obtaining “as-damage” representation.
Evaluating the results obtained from the application of the three methods some considerations emerge.
With Colour-Range method (Sec 3.2.2) the objective was to investigate the presence of alterations on surfaces of masonry cross-vaults, with a complex shape and volumetric development. From the results obtained the advantages are represented, most of all, by the possibility to automatically detect damp spots, without losing information about the real extension and spatial distribution.
The limit of the procedure consists in the choice of the range of colours on which applying the methodological pipeline. In the case of alterations whose colorimetric characteristic creates a chromatic detachment with the rest of the structure, the obtainable results are qualitatively acceptable. Therefore, its application also in extracting and/or computing frescoed and decorated surfaces could be of considerable interest.
From these considerations is emerged the necessity of structuring other processes based on Machine Learning to investigate a wider range of alteration pattern and usable in more diversified contexts in order to refine the range of colour values and increase the level of accuracy of extracting shapes.
Cloud-based (Sub-Sec 3.2.3) and Texture-based (Sub-Sec 3.2.4) methods use algorithms such as respectively Hierarchical Clustering (Sub-Sec 2.2.5.3) and Random Forest (2.2.5.1) on a wide set of data represented from 3D point clouds for the first and UV maps for the second. In this way, the metrics pipeline has been become more rigorous, for quantifying various surface alteration extensions and incidence.

For the Cloud-based segmentation, different clustering methods have been investigated, and among them the Hierarchical Clustering has been preferred. The HSV colour-space is the most consistent with the purposes of the colour segmentation, because it proves to be efficient in the accurate identification of a plurality of chromatic decay morphologies, both in terms of extension and colour interval.

The application to three selected case studies enabled the validation of the proposed methodology, detecting a series of chromatic alterations on the masonry surface, previously recognized through a visual inspection of the environments. The advantage of this approach is the possibility to achieve both a qualitative and quantitative analysis of different morphologies of surface alterations, starting from 3D data, with semi-automatic procedures, in support of diagnostic activities.

The Texture-based method can automatically classify the textures of the heritage objects, starting from small annotations of the classes. The results of the 2D classification can then be projected and visualised onto the 3D geometries for a better understanding.

However, from a comparison of the results obtained from the two methods on the same case studies with a ground truth manually segmented it emerges that the Cloud-based method is the most accurate.

A limitation of this procedure could be the difficulty to distinguish and isolate chromatic alterations on decorated surfaces, like frescoes, temperas or wall papers.

On the other hand, the Geometric segmentation (Sub-Sec. 3.2.6) provided a general and straightforward method to classify heritage point clouds allowing the isolation of architectural components and the association of the detected deterioreted patterns on surfaces where they are located.

The presented machine learning-based approaches were proved to be beneficial for classifying large, varied, and complex scenarios.

With regards to the choice of the most appropriate approach, the author believes that in the heritage field each case study must be treated individually. This means that for every object under investigation, it is essential understanding which are the segmentation purposes, its needs, and the required classes. Once those are clarified, the most fit-for-purpose approach can be applied (texture- cloud or/and geometry-based), depending on the object's shape, complexity, dimension, presence of good texture, etc.

Furthermore, the use of reality capture and data processing has the potentiality of conducting remote decay surveys, with a huge variety of non-invasive and contactless methods. The main vantages of the proposed methods can be summarized as follows:

- reduced manual input;
- short time to classify and segment big data;
- high levels of accuracy;
- possibility to map the decays on point clouds or UV maps and then re-project them onto the 3D models;
- possibility to compute the areas that each class occupies, thus deriving useful data for monitoring and restoration purposes;
- automatic recognition of similar architectural elements in vast datasets, that can be potentially linked to parametric families within HBIM environments;
- applicability of the approaches to different kind of buildings, monuments or any other type of 3D data.

3.3 4D MODELS FOR THE INFORMATION MANAGEMENT SUPPORT CONSERVATION PROCESS

In this section an operative method has been proposed that starting 3D survey (B) and (E) from source-based and reality-based representation helps the management of the historical buildings' knowledge system by using relational databases and time parameter creating a 4D-HBIM simulation implementing the stage (F) - Data management and 4D simulation - of above described workflow in Sub-Sec. 3. The aim consists in the adoption of advantages of 3D digital survey and parametric HBIM models for a complete and flexible management of the large amount of multidisciplinary knowledge elaborated during the activities of documentation, survey, analysis, and conservation planning for supporting digital documentation and for allowing the knowledge process for conservation activities. The analysis of the existing research about HBIM and 4D reconstruction (Sub-Sec. 2.4) surveys gaps and challenges in literature reveals the absence of an operative method with the aims of collecting, classifying, managing and sharing information and data relating to construction phases, transformations and interventions over time, and recording the state of previous and current deterioration phenomena of an existing building, benefiting from the 4D Information Management as emerged in Sub-Sec. 2.5. These circumstances can cause the risk of misunderstanding the actual building conditions and pathologies' causes, as a result of the implementation of incompatible actions.
For this purpose, this research work concerns the introduction of the time parameter within an HBIModel as essential for a clear and immediate visualization of the morphological layout, the anachronistic constructive evolution, and the stratification of the interventions. (Bruno et al., 2019b; Verdoscia et al., 2020b). Furthermore, the challenge of 4D modelling is an efficient integration and management of multi-data sources (specifications, requirements, etc.), even as real support to the knowledge process and pre-diagnosis activities. The 4D-HBIM will be a constantly evolving interface on which to progressively add future refurbishment and restoration interventions, allowing interoperability among stakeholders.

The method will be validated with two cases of study, The Augustinian Monastery in Trani, and the Marchesale Palace of Laterza, both in southern Italy, chosen due to their constructive evolution and condition assessment typical of a large amount of historic building. They show degradation and kinematic motions related to the sequences of construction events, transformations and interventions.

3.3.1 Information management and 4D simulation

The framework follows the methodological workflow in Sec. 3 starting from (A) Preliminary Knowledge and Data Collection, (B) 3D survey ; (C) Data processing and filtering, (E) 3D modelling and information enrichment and implementing the (F) Data management and 4D simulation. The stage (D)-Semantic data extraction - has been omitted as not relevant for the purposes previously stated. By the way outputs of (D) can be connect to the BIM model through the procedure illustrate below.

In this section the 3D models have been realized both to document the condition statement of the buildings and to visualize their constructive analysis to support the phase of knowledge of the building in the recovery processes. For this reason, both source-based modelling (based on documentary sources) and reality-based modelling (based on products of three-dimensional digital survey techniques) have been used.

For the inaccessible environments through the digital survey, because not enough illuminated or that they had diffused scaffolding, has been resorted to the traditional direct survey (triangulation, e.g.).

The comparison of all the outputs of the Preliminary Knowledge and Data Collection (A) and the 3D survey (B) enhances the identification of previous transformations and interventions, the material constructive characterization and decay mapping, such information to be included into the parametric model (E). This set of attributes is inherent to constructional and material features, description of decay patterns, report and motivation of the previous interventions, useful to semantically enrich the model.

Then, the Information Management (concerns the creation of an Information System integrating the three-dimensional model and external databases via ODBC tools (Open Database Connectivity). The Navisworks® Manage software has been tested for the

management of the “as-built/as-damaged” HBIM model, as it is a BIM tool for viewing and managing information systems, despite being created for cost and time coordination; moreover, it supports the control of database and the data management via Structured Query Language (SQL). The BIM model has been exported as *.nwd from Autodesk® Revit® to Navisworks® Manage, in order to have the possibility of simultaneously modifying the models in both the software products. In Navisworks®, the building objects are firstly structured by macrogroups, distinct one from another according to the related construction phase and previous interventions, thus involving the time parameter. Subsequently, each macrogroup has been matched to the categories of properties. These categories of properties can be manually added or automatically inserted linking external databases. The proposed information system connects the geometric HBIM model to external relational database, which were created as Excel spreadsheets or exported from the HBIM model, through the database management tools and compatible with the ODBC Driver of the employed multi-model-based management system. Indeed, Autodesk® Revit® permits the export of object parameters as external database via database management tools (i.e. the Ideate BIM link plug-ins (‘Ideate BIM Link Software’ n.d.), Revit DB link (‘Access Autodesk Revit DB Link’ n.d.), and the export tools embedded in the software. The link of external databases into Navisworks® occurs with the configuration of the database via ODBC Driver, the Application Program Interface (API) for accessing the Database Management Systems (DBMS) within the “Datatools” plug-in. The user interacts with the relational databases via the Structured Query language (SQL), as it is the API for the Relational Database Management Systems (RDBMS).
SQL statements are employed for queries of information from a relational database and for gathering data for reports. The SQL string (1) matches the external database to the object in the model; the data fields correspond to the properties shown in the tables automatically created.

(1) *SELECT*from[Properties$] where”Element ID” =%prop(“Element ID”,”Value”)*

- SELECT: indicates the selection of all the boxes in the spreadsheet where the Database is contained;
- FROM: the file name in CSV format exported by Navisworks;
- WHERE: the name of the property corresponding to the ID element contained in the Database exported by Revit;
- PROP: the property tab name existing on Navisworks in this case ID element and one of the properties entered in this tab, in our case "Value".

The tables are organized in i) constructive macro-elements, ii) previous interventions and iii) description of crack patterns, introducing parameters, their description and data type.

Moreover, a more accurate “as-built/as-damaged” HBIM could be created through the integration of the parametric model with 3D photo-reconstruction (point cloud, textured mesh, etc.) as an URL attribute of the used web viewer Voxxlr®[10] (for point clouds) Sketchfab® (for meshes). The URL generated in the web viewer can be linked in the BIM Information Management software Navisworks® Manage.
The last step is the 4D-HBIM simulation in Navisworks® Manage. Each macrogroup of the “asbuilt/as-damaged” HBIM model was associated with its time parameter for representing constructive evolution and the current state of conservation in a time line. The 4D-HBIMM simulation of previous events and the correlation of related information could support the identification of the causes of current decay patterns associated with human interactions with the building.

3.3.2 CASE OF STUDIES

3.3.2.1 Preliminary Knowledge and Data Collection

The research carried out in following sections has been validate testing the implemented methods on two cases of study, the case 1, the Marchesale Palace of Laterza and the case 2, the Augustinian Monastery in Trani, South of Italy choosen due to their representative conditions of lots of historic buildings that underwent

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[10] Voxxlr : https://www.voxxlr.com (Accessed on February 08, 2022)

transformations and refurbishment over time and in degraded conditions, some caused by the succession of constructive events and incoherent actions.
The first step concerns the Preliminary Knowledge and Data Collection (A). The preliminary knowledge consists of historical and photographic memories, archival documents and prior drawings. In particular, the understanding of the constructive evolution begins from the study of historical texts and project documents, stored in the archives. Furthermore, a preliminary analysis of materials/construction techniques and analytical and typological studies about building conditions have been carried out. The output of this phase was the reconstruction of three main categories of data such as history of the buildings, constructive transformations, refurbishment interventions already suffered. From this first stage the following considerations have been deducted:

Case 1: The Marchesale Palace (Fig. 73) is located in Laterza (Southern of Italy) and its construction began in 1393 as stated along the cornice of the north portal where is wrote *"hoc opus fecit magister iacobus triegiano de angilo et magister angilo, eius nepos, anno domini m.ccc.-xxx-xiii. prime indictionis"* (Fig. 74).

Fig. 73 Photo of the author of The Marchesale Palace of Laterza: (on the left) External view of principal façade, (on the right) Façade of the internal courtyard.

Its assessment consisted of a thick curtain wall on a square plan of about 40 meters on each side and a tower in the south corner. The central entrance hall had two main entrances; one to the south towards the town and the other to the north, which connected the castle to the outside by means of a drawbridge. The structure was surrounded, in fact, by a moat, which is no longer visible today and by walls with walkway, equipped with vertical slits and alternating battlements. In 1546 the castle became a Renaissance residence. The major transformations were the creation of new apartments (as described in ledger of payments of the family, precisely "Volume 57")(Fig. 74), by raising the main floor of the north and west side, which were connected with the tower (south-west corner) already existing and still recognizable today, and the related main access staircase. The palace kept the square plan, the main entrances, the walls and the wooden door of the old castle. But the main interventions that have given the building its current appearance are those concerning the vertical divisions and the construction of a new building adjacent to the north-east side of the building. The vertical splitting of the high rooms on the ground floor of the west wing and the creation of the current first floor for residential purposes, involved a whole series of openings, new or obtained from the existing windows. The fresco dedicated to Sant'Anna on the upper internal part of the entrance portal also dates back to this period (Fig. 74).(Galli, 1940)(Bongermino, 1993) (Catucci, 2007).

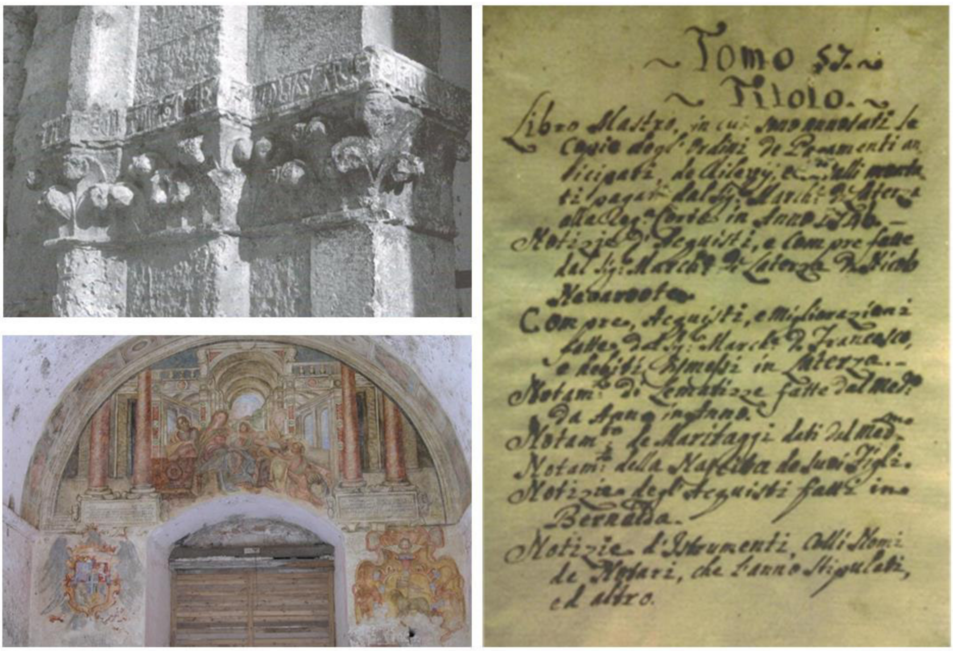

Fig. 74 Photos of the author: On the top the cornice of the north portal with inscription of 1393, bottom

Two earthquake, the first in 1960 and the second in 1980 caused widespread damage to a large part of the structure. As it is possible to read in the Report of the project of the 29.06.1991, stored to Superintendence for Heritage archives A.A.A.S. of Puglia, the second earthquake caused the collapse of the vault in the main hall of the main floor, in addition to bad and widespread cracks(Losito et al., 1991). The conservation activities on the building, executed in 1980-1985, realized after the earthquake, consisted in (Fig. 75): the scaffolding of numerous vaults on the top floor, the use of tie rods that connected the exterior facade to the west with the respective courtyard, and also on the northwest corner, construction of a roof with trusses and metal sheets for the salon where the roof had collapsed visible in Fig. 76.

Fig. 75 Photos of the report of the project of the 29.06.1991:Consolidation works realized in in the period 1980-1985

Fig. 76 Current condition of the intervention areas

Another consolidation intervention consisted in the creation of a floor curb through reinforced perforations and injection of cement mixture (Fig. 77).

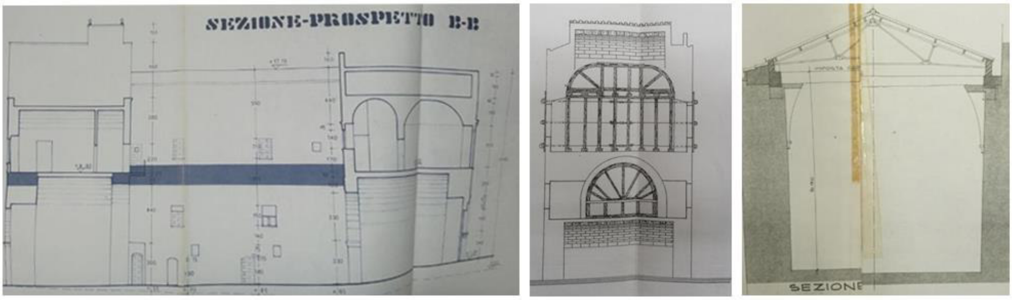

Fig. 77 Photos of technical drawings of the interventions realized in the period 1980-1985.

From the 1980 the building was abandoned until 2002 when the palace was converted as museum “MuMa”, council chamber, and info-point for the tourists.

Case 2:The construction of the former Augustinian Monastery (Trani, Italy) began in the 16th century (Fig. 78). The building was systematically expanded from the XVI to the XVIII century by the Augustinian monks in accordance with the functional needs, concessions and economic availability and has undergone a series of demolitions, reconstructions, structural interventions and functional adjustment between 1809 and 1960 due to the repeated change of use suffered during these years. The geometric-material description of the building can not be separated from the knowledge of its constructive evolution because the building today presents heterogeneous in its internal distribution, in the construction systems and in the state of conservation. Nowadays, the building presents heterogeneous interior distribution, different constructive systems and conservation status. Inside, as described in document “Stato dei monasteri della provincia di Bari”[11]we can recognize (Fig. 79):

- Unit 1 (1530): The oldest building nucleus, built until 1640, is spread over two floors and incorporates the main facade that is symmetrical with respect to the access portal, on the ground floor covered by a rustic ashlar and plastered first floor. It consists of six rooms on the first floor and four larger rooms on the ground floor behind Piazza Gradenico. On the ground floor near the main door on the left there is a monumental staircase that leads to the upper floor.

- Unit 2 (1640): composed from six basement rooms and the corresponding ground floor[12];

- Unit 3 (1754-1757): composed by the elevation of the Unit 2 and the completion of the cloister and the spaces overlooking it.

[11] Bari State Archives: "State of the Monasteries of the Province of Bari", "Culto e dip.", issue 4, fl 63-71.

[12] State Archives of Trani: Notarial Protocol of Andrisani M., issue 233, fl. 142v. -144v.

Fig. 78 Photo of the author of Augustinian Monastery: On the top: left, external façade of Unit 1, right, external façade of Unit 2-3, bottom: left, external façade internal cloister, right, a room of Unit 1 on the ground floor.

Unit 2 and 3 share the façade which is completely different from that of Unit 1. It develops on three levels identified through the presence of string courses and the crowning also in this case has a very protruding cornice. Unit 2 is connected to the ground floor of the Unit 1 through a small staircase in the cloister.

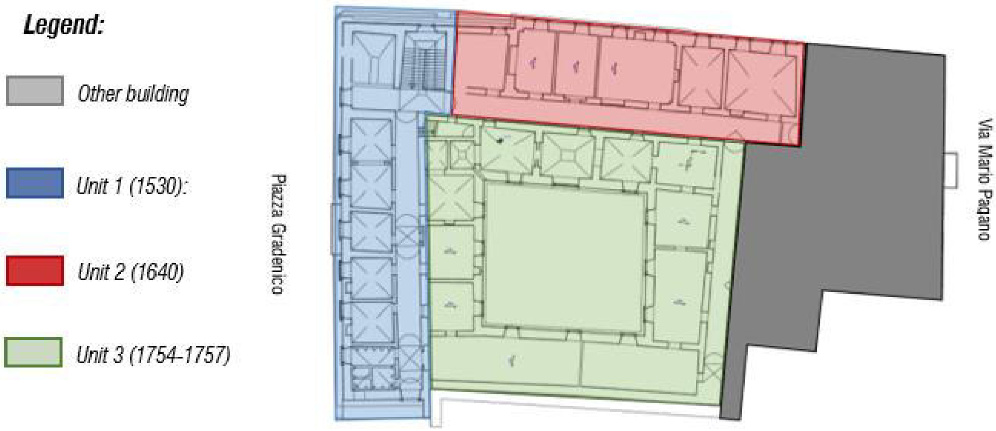

Fig. 79 Constructive evolution of the monastery

The aim of the previous interventions was the functional upgrade; the stratification of these interventions is still recognizable. In 1847, the monastery was converted into a hospital. After the abandonment in 1969, the building underwent a series of structural interventions and maintenance of foundations, roofs, façades because of serious settlements, not yet completely solved. In particular, the entire foundation has been reinforced with an underpinning made up of piles in order to solve the settling of primary rotation of the external façades, caused by heterogeneous foundations and soil. The kinematic movement is more complex where the units around the cloister. The low resistance of the soil, estimated by tests in 1992, and the demolition of some vaults replaced with hollow-clay/concrete slabs has jeopardized the static equilibrium (Saponara, 1984)(Petrignani & Camarchia, 1992). Furthermore, the absent structural connection of the18th-century porch (Unit 3) and the 16th-century unit (Unit 1) contributed to the settling. In 2005, the continuous seepage of rainwater from the roofs caused damp spots on the main façade. Therefore, in 2007, some localized interventions were carried out concerning the cleaning of the main façades, the installation of the waterproof layer and the eradication of spontaneous vegetation. The corroded rebar of the concrete joist were rehabbed and the hollow-clay/concrete slabs consolidated by Fiber Reinforced Polymer (FRP) at the intrados (Fabozzi, 2007).

3.3.2.2 The architectural survey and the data optimization

In this research, the geometric survey has been carried out starting from TLS (terrestrial laser scanner) for the Case 1 acquisitions or the prior CAD and paper drawings integrated with photogrammetry for the Case 2.

Case 1: For the Marchesale Palace the 3D survey (B) has been operated using TLS, planned starting for prior paper drawings. The use of UAV was neglected because the building is in the historic urban centre. The laser scanner used was FARO Focus 3D X 130. A set of 205 acquisitions has been executed using a 1/8 resolution and 4X quality for a total time of 6 minutes and 20 seconds for each scan, obtaining an accuracy between the points of 7 mm over at a maximum distance of about 5 m away from the surfaces. In addition, the visual inspection has been enhanced to glean typological and material information of masonry walls, floors, finishing, and their state of conservation. A total number of 205 was used for the whole building.

Fig. 80 Merged scan acquisitions in Recap

To ensure a correct overlap between successive scans, the planning of the target points has considering a maximum distance not advanced to 10 m in order to have a constant step also in the restitution of the 3D cloud. The absence of projections, furniture and other obstacles allowed to obtain three-dimensional acquisitions without holes. One of the main issues addressed during the survey was the lighting conditions of the detected environments. For some indoor environments it was necessary to use torches. In this case the tool allows the acquisition of measurements, but is obviously not able to acquire the texture of the elements. However, since the colouring data was not necessary for the objectives of the research work, the scans carried out allowed to obtain a geometric survey useful for the subsequent modelling process.

Fig. 81 The whole point cloud of the building resulting from data processing and filtering activity

For the thirth stage (C) Data processing and filtering the scanned data have been merged with Autodesk® ReCap ™ through the manual recording procedure consists in the identification of three points present in both the scans to be bound. The points were detected using target elements on surfaces. Considering a cartesian system, the points chosen as targets were taken so as to belong to three different planes, for obtaining the better alignment. The resulting cloud consists of a very large number of points with many superfluous elements (built around, light poles, machines, etc.) (Fig. 80). With a manual segmentation such outlier elements have been eliminated (Fig. 81). Once the process has been completed, the quality of the final result has been evaluated through the parameters overlap, balance and the number of points < 6mm.

The Overlap is a percentage of data that measures common features throughout the project; in particular, a high percentage of overlap ensures that the hidden parts of objects detected in a scan are visible in adjacent scans. The balance, which must exceed 20%, shows the percentage of common functions in scans; the value indicates whether two surfaces overlap correctly but are slightly offset from each other. The third parameter, finally, indicates the percentage of points at a distance of less than 6 mm; this value should always be greater than 90%. The medium value of overlap is about 31,3%, balance 76,4%, point < 6mm 99,2%, then the point cloud has been considered an optimal base to continue the following stages.

Case 2: The survey of Augustinian Monastery has been done updating prior CAD through traditional direct survey for the whole building and terrestrial photogrammetry (B) for the most representative rooms for their constructive techniques and the state of conservation: a room at the ground floor and the main stairwell with evident cracking and deformations; in addition, they presented the most suitable environmental conditions, such as light, colour variations, workers' safety and, likewise, the possibility to move within the space free from scaffolding. Also in this case the it was not possible use UAV system because the building is in the historic urban centre. The existing drawings in the format *.dwg were not consistent with the current condition found by a first survey *in situ*, so it was necessary to update them.
The objective of the manual survey was to verify the dimensions of the rooms, of the wall sections, the location of the internal partitions, the height of the key and of the vault of the plants provided in *.dwg format and to understand the intended use of the rooms, the type of masonry and the identification of the transformations and interventions undergone described in the previous paragraphs (Sub-Sec.3.3.2.1).
Given the complex structure of the building has been defined a coding of the rooms for facilitating the survey operations and for managing the different environments depending on their intended use: rooms, toilets, stairwells, etc.
The code has been defined as a numerical sequence in relation to the reference level therefore due to the monastery complex is developed on three total levels: basement, ground floor and first floor have been associated the codes: XSXX, PTXX, P1XX (Table

20). The 2D CAD produced has been the base for the elaboration of BIM model (Fig. 82-88).

Reference level	Level Code
Basement	XSXX
Ground Floor	PTXX
First Floor	P1XX

Table 20 Reference Code Level for facilitating the survey activities

Intended use	Reference level	Room code
Room	XSXX	XS01, XS02…
Room	PTXX	PT01, PTO2…
Room	P1XX	P101, P102…
Stairwell	PTXX – P1XX	VS01
Toilet facility.	P1XX	W01, W02…

Table 21 Reference Room Code for facilitating the survey activities

Fig. 82 2D drawings of external facades

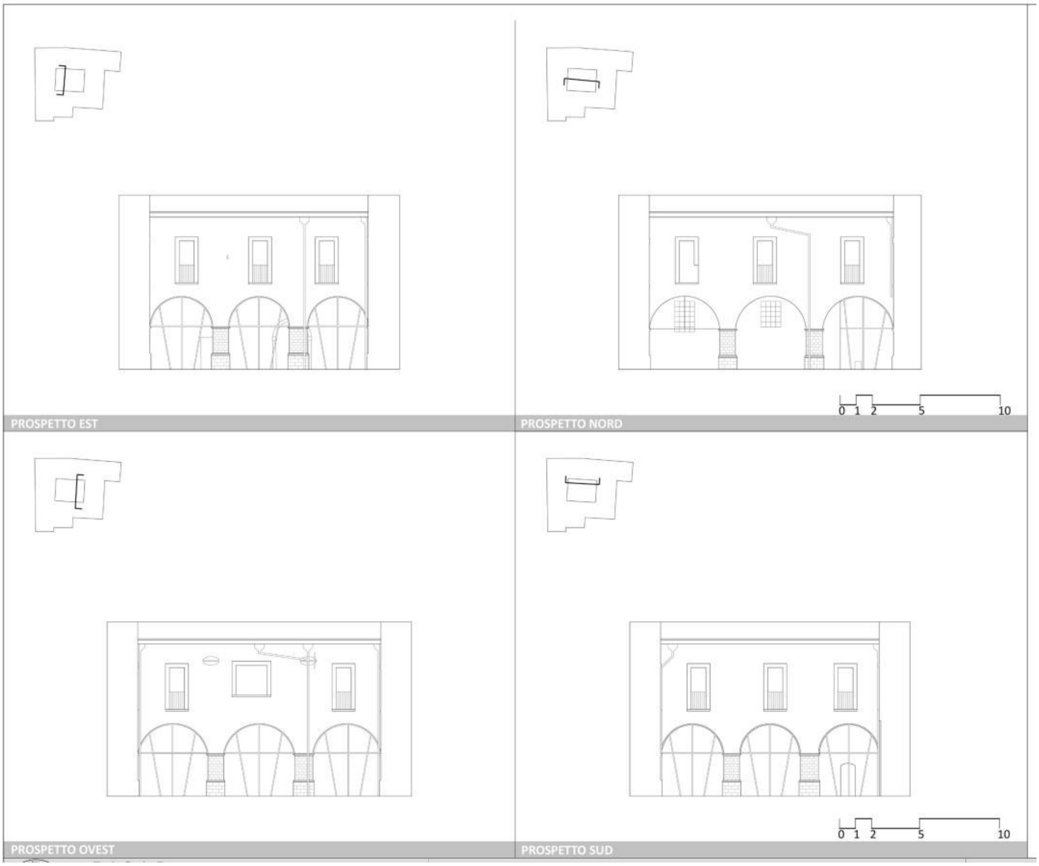

Fig. 83 2D drawings of internal courtyard facades

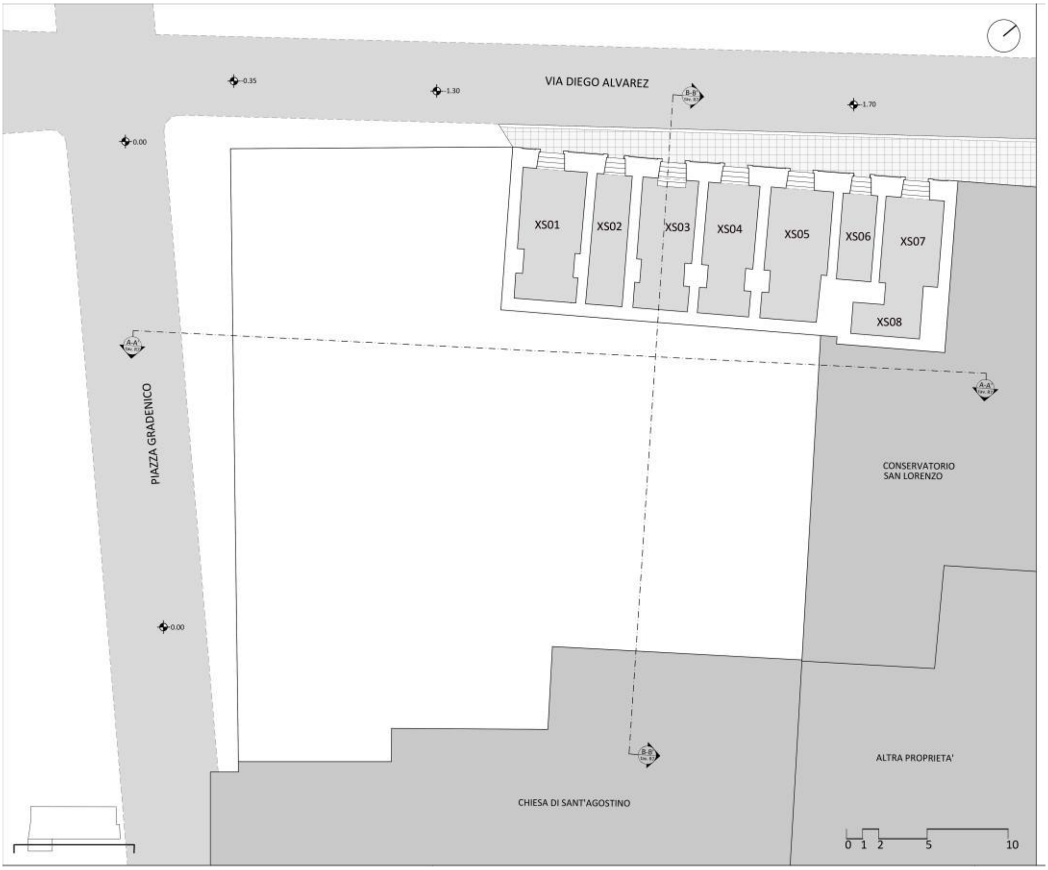

Fig. 84 Basement plan

Fig. 85 Ground floor plan

Fig. 86First floor plan

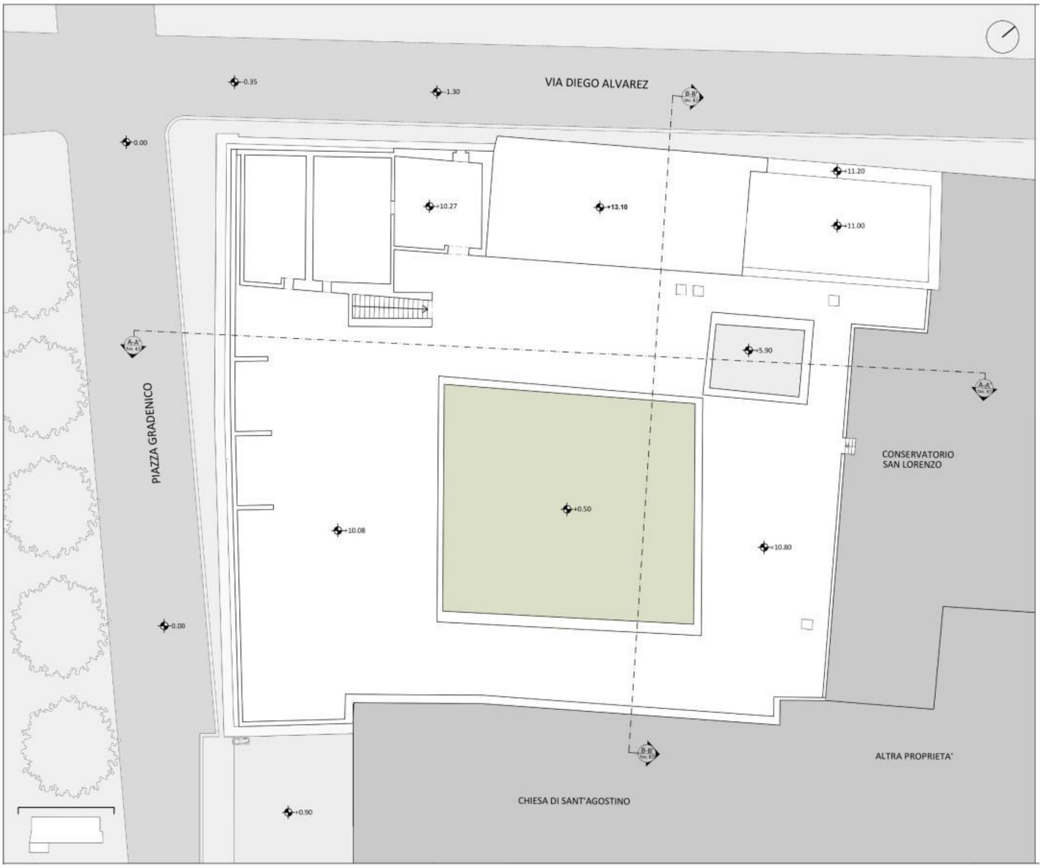

Fig. 87 Roofing plant

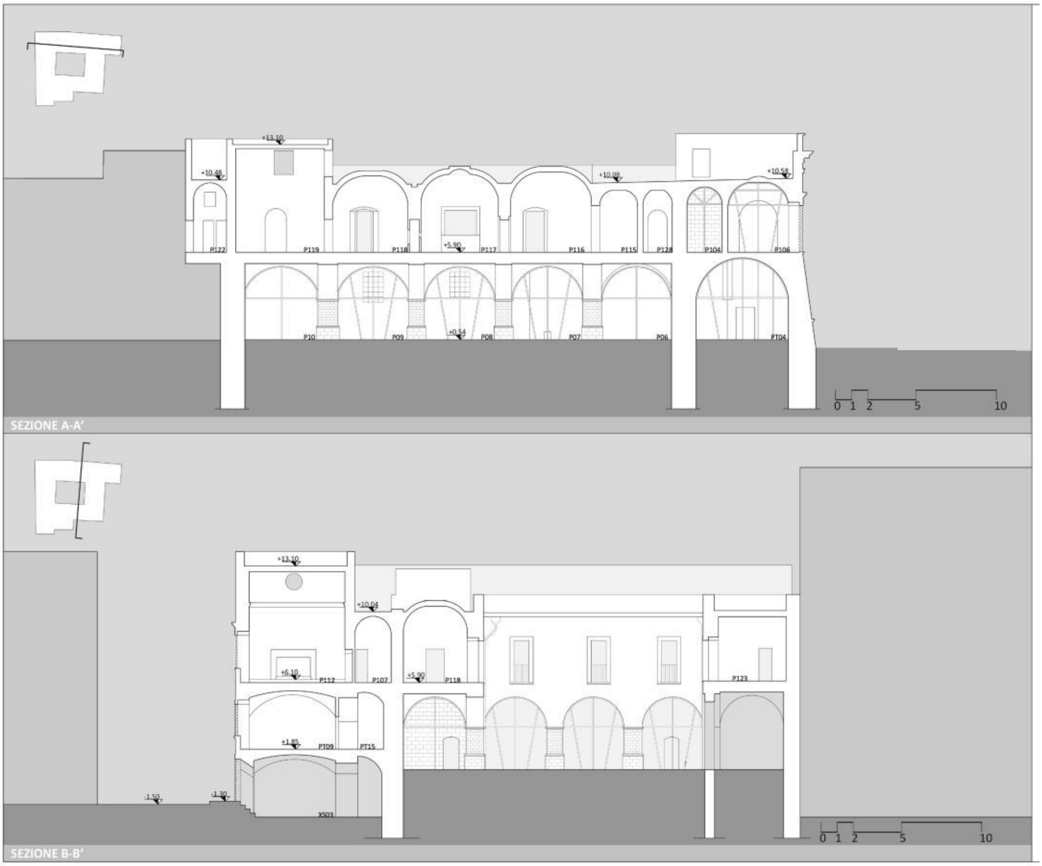

Fig. 88 Sections

The choice of the parts to acquire with photogrammetric survey took into account the most representative rooms of the type of building, the state of degradation of the building and the boundary conditions such as light, colour variations, the safety of operators and the possibility of being able to move within the environment.

Considering these measures, excluding a priori the rooms whose horizontal closure of the roof is a slab in latero-cement and given the presence of scaffolding, the PT02 room and the VS01 stairwell were considered.

The equipment for the photo acquisition was a CANON D600 reflex, 18-55 mm optics, following an acquisition plan to ensure the overlap of photograms (70%) and the overall effectiveness of the acquisitions and subsequent processing.

Fig. 89 Portion of dense point cloud of PT02

In the PT02 and VS01, the set of photos was taken at a distance of 1.40 m and 3,00m from the ground.

Fig. 90 Portion of dense point cloud of VS02

For Data processing and filtering (C) the set of photographs was used for the 3D rendering in the form of a point cloud and photorealistic reconstruction (textured mesh) via image matching and the Structure for Motion (SfM) algorithms, with the aim of capturing and sharing information about the state of degradation (damp spots and crack patterns). This operation was supported by the use of the software AgiSoft Photoscan. The Dense cloud of PT02 (Fig. 89) has a number of point of 8.990.221, instead, that of the VS01, 8.297.531 (Fig. 90). The textured mesh of PT02 had 131.197 vertex, while that of VS01, 149,967.
Because of some obstacles during the survey process (i.e. floor covering accumulations of rubble), it was necessary to use manual instruments of polygonal creation, so as to interpolate the single vertexes of the perimeters of those areas difficult to reach. Furthermore, it was verified the correct orientation of the normal polygons of each element. The resulting mesh was exported as *.obj and inserted in a web viewer, Sketchfab® for being used in at the stage of informatization of the BIM model (E) as URL parameter. Also the point clouds have been inserted in a web viewer as Voxxlr®.

3.3.2.3 The 3D modelling and the information enrichment

The "as-built/as-damaged" HBIM has been mostly modelled from the output of (B) and (C) stages through a source-based or reality-approach. The architectural components were manually modelled through two different methods: parametric library objects (openings and related decorations, slabs, foundation micro piles, barrel vaults, crack, etc.) or solids, as stairs and vaults due to base on trapezoidal plans.
Whereas, some geometric primitives of vaults, openings and cracks have been traced as lines after importing the point clouds provided by the photogrammetric capture into the BIM software. The comparison of all the outputs of the Preliminary Knowledge and Data Collection (A) and the 3D survey (B) enhances the identification of previous transformations and interventions, the material-constructive characterization and decay mapping, such information to be included into the parametric model (E). This set of attributes is inherent to constructional and material features, description of

decay patterns, report and motivation of the previous interventions, useful to semantically enrich the model.

Fig. 91 The overlap of point cloud and 3D representation in BIM environment of Marchesale Palace of Laterza (Italy).

About 3D modelling methods used in this thesis we have already discussed in previous Sub-Section 3.1. Then in this paragraph will be described in general the methods used.

The HBIM model of the two cases studies has been constructed using source-based and reality based procedure in Autodesk® Revit®.

The Case 1 has been modelled using optimized point cloud as a metric reference importing it into modelling environment (*.rcp)(Fig. 91).

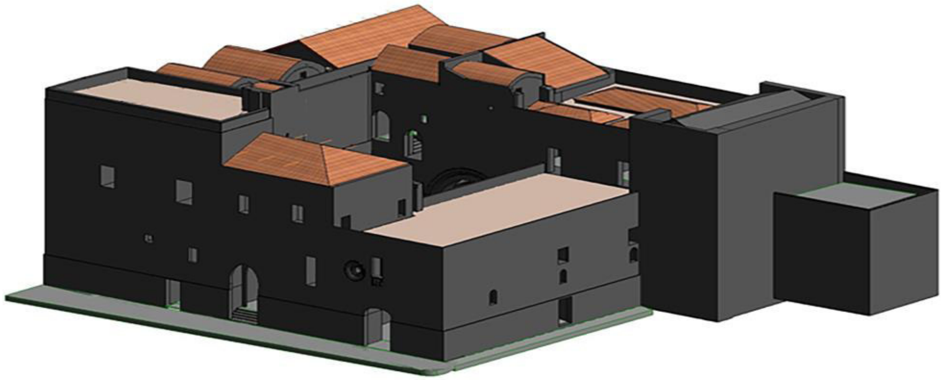

Fig. 92 HBIM model of the Marchesale Palace of Laterza, Italy

The building components (walls, vaults, doorways, windows and stair ramp, arched openings, frames) have been modelled as BIM parametric objects, mostly customized Fig. 92.

Fig. 93 Internal environment of the building which suffered the collapse of the vault a) and b) point cloud views, c) the old vault, d) the current roof.

The representation of the previous constructive phases has been realized through the source based procedure on the documentary sources collected in Sub-Sec 3.3.2.1. In Fig. 93 a) and b) show the internal view of the room where the barrel vault collapsed, c) the model performed from historical documentation, d) model performed from point-cloud

The 3D model of the Case 2 has been generated using source-based procedure for the whole construction except for the PT02 and VS01 for which the point cloud was available. The sources used were the 2D CAD drawings produced in (Sub-Sec.3.3.2.3) and technical repots of interventions (Petrignani & Camarchia, 1992)(Fabozzi, 2007)(Fig. 94).

The point cloud has been imported into the family editor (*.sat) and used as a metric reference for the graphic representation of the decay pattern, vaults, doorways, widows and stair ramp. The building components (arched openings, barrel vaults, rib vaults, groin vaults, frames) and decay patterns (cracks and damp paths) have been modelled as BIM parametric objects. The as-damaged model is also the result of the modelling and the data enrichment of damp and crack patterns shows the digital, parametric and computable representation of semi-parabolic cracks due to primary rotation and compared to the point cloud from which the BIM object has been generated.

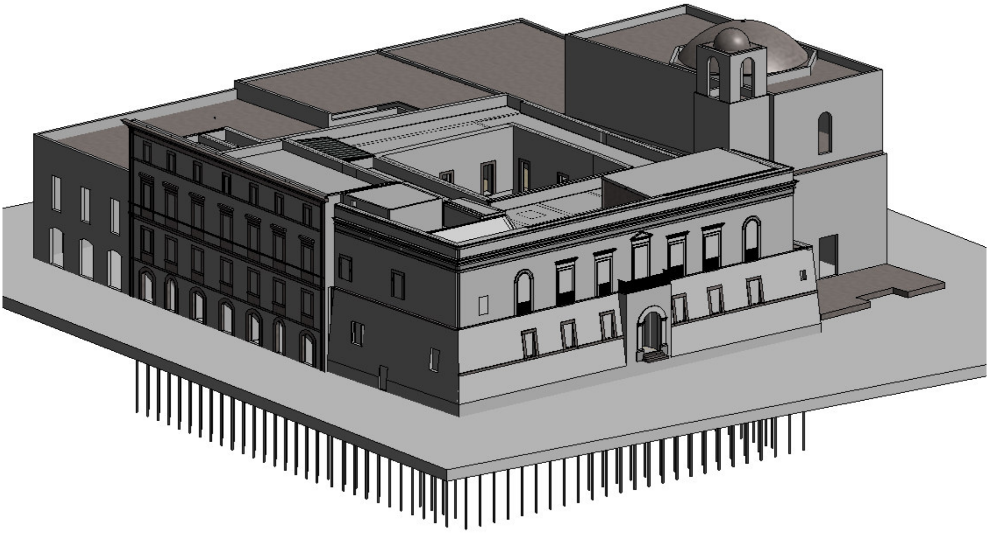

Fig. 94 HBIM model of the former Augustinian Monastery, Trani (Italy)

Fig. 95 PT07 As-damage HBIM model

Hence, it is possible to preserve the geometric complexity, as previously mentioned, given the limitation of parametric modelling to the realistic reproduction of irregular geometries and deformations, typical of a historical building, was chosen to link a hyperlink of the 3D object reconstruction - based on point cloud or mesh- to the HBIM model. Point cloud and mesh has been imported into the parametric object as URL of the employed BIM software Autodesk® Revit® Furthermore, the creation of the specific parametric object allows the insertion of geometric and descriptive attributes, derived from the analysis of information and data acquired during stage (A) and (B) of the process. This set of attributes is inherent to constructional and material features, residual performances, description of decay patterns, report and motivation of the previous interventions, useful to semantically enrich the model. After importing in Navisworks®, the parametric objects have been grouped in macro-categories divided by constructive epochs Specifically, for the case 1 has been created six groups: First construction unit 1393 (Unit 1); Building extension in 1545 (Unit 2); Building extension in 1749-1772 (Unit 3); Building extension in 1810 (Unit 4); Transformation in 1980–1985; Condition assessment 2020. The same has been done for the case 2: First construction unit 1530 (Unit 1); Building extension in 1640 (Unit 2); Building extension in 1754-1757 (Unit 3); Transformation in 1847-1969; 5. Intervention in 1992; and Intervention in 2007.

Information added to each group concerns technical properties of the building components and historical/analytical features, and organized in the categories, as shown in Table 22Table 23Table 24. The categories are i) constructive macro-elements, ii) previous interventions and iii) description of crack patterns, introducing parameters, their description and data type.

CONSTRUCTIVE MACRO-COMPONENTS		
Parameters	**Description**	**Data Type**
Construction phase	Year of constructive macro-component	NUMBER
Number of levels	Number of floors in the macro-component.	NUMBER
Maximum height at the eaves	Dimension expressed in meters.	NUMBER
Minimum height at the eaves	Dimension expressed in meters.	NUMBER
Average covered surface	Dimension expressed in square meters.	NUMBER
Volume	Dimension expressed in cubic meters.	NUMBER
Number of rooms	Number of rooms that composes the constructive nucleus.	NUMBER
Use	Use of the rooms that composes the constructive nucleus.	TEXT
Horizontal structural systems	Constructive system of horizontal structural systems (technical typology of vault, slab, etc.).	TEXT
Vertical structural systems	Constructive system of vertical structures (wall).	TEXT
Typology of structural system	Description of structural system (load-bearing masonry, reinforced concrete beams and columns).	TEXT
Roof	Typology of roof.	TEXT
State of conservation	Comments about the state of conservation based on visual inspection.	TEXT
Last use	Indication of the last designated use of the building	TEXT

CP X.N.	Crack Pattern (CP), description of morphology of a crack patterns (N) related to the constructive nucleus (X=1,2,3).	TEXT
Visual appearance	Description about the visual appearance of crack patterns.	TEXT
Settlement X.N.	General description of the settlement related to CP.X.N .	TEXT
Causes settlement X.N.	Description of the causes of settlement X.N	TEXT
Scaffolding	Typological and material description of scaffolding in the constructive nucleus.	TEXT
Incurred interventions	List of incurred interventions to constructive nucleus.	TEXT
Intervention (Year)	Description of the intervention.	TEXT
3D reconstruction	Link to 3D reconstruction model	URL

Table 22 Parameters about data of first construction and building extension

PREVIOUS INTERVENTIONS		
Parameters	**Description**	**Data Type**
Year of intervention	The year of construction of the nucleus.	NUMBER
Accessibility by inspection	Possibility of inspection of the intervention.	TEXT
Typology of intervention	Description about typology of intervention.	TEXT
State of conservation	Comments about the state of conservation based on visual inspection.	TEXT
Settlement prior intervention	Description of Settlement X.N related to CP.X.N.	TEXT
Causes of intervention	Description of the motivation for Settlement X.N.	TEXT
Description of intervention	Description of intervention (phases, materials, constructive techniques).	TEXT
Piles foundation system	Material and dimensional composition of piles foundation.	TEXT
Source of file	Indication about source of files and information.	TEXT
3D reconstruction	Link to 3D reconstruction data model	URL

Table 23 Parameters about data of interventions and transformations

DESCRIPTION OF CRACK PATTERNS		
Parameters	**Description**	**Data Type**
Encoding host	Code of constructive element where the cracking is identified.	TEXT
Crack pattern typology	Typology of the crack pattern.	TEXT
Settlement	Description of settlement.	TEXT
Cause of settlement	Description of the causes of settlement.	TEXT
Crack length	Dimension computed along the vertical axis, orthogonal to the floor.	TEXT
Crack upper cusp dimension	Dimension computed along the horizontal axis towards the vertical direction of the wall.	NUMBER
Crack lower cusp dimension	Dimension computed along the horizontal axis towards the vertical direction of the wall.	NUMBER
Crack skirt dimension	Dimension computed along the horizontal axis towards the vertical direction of the wall.	NUMBER
Crack description	Morphological description of the crack (vertical, horizontal, parabolic shape, etc.).	TEXT
Crack progression	Indication about the progress of the cracking.	TEXT
Edges profile	Indication of visual appearance of edges profile (sharp edges, rounded edges).	TEXT
Monitoring system	Indication about monitoring activities (optic fibres, strain gauges, etc.).	TEXT
3D reconstruction	Link to 3D reconstruction data model	URL

Table 24 Parameters about crack patterns (only Case 2)

3.3.2.4 Results and discussion

The previous phases are propaedeutic to the Information Management and the 4D-HBIM simulation, applying the methodology above descripted in Sub-Sec.3.3.1 with the aim of querying the databases for supporting the conservation process.

The data management concerns the creation of an Information System integrating the three-dimensional model and external databases via ODBC tools (Open DataBase Connectivity). The Navisworks® Manage software has been used for the management of the "as-is/as-damaged" BIM model because it supports the control of database and the data management via Structured Query Language (SQL).
The BIM model has been exported as *.nwd from Autodesk® Revit® to Navisworks® Manage. Specifically tables were created for each categories, as described in Sub-Sec. 3.3.2.3, then, each macrogroup has been matched to the categories of properties. The 3D photo-reconstruction models have been linked to the HBIM model as URL parameter due to provide the actual knowledge about the geometries, the decay condition and any decorated surfaces for documentation, structural monitoring and analysis of technological building systems. Specifically, tables related for each macro-groups have been created for each category for including properties. Then, the SQL Language permits consulting information within the information system through i) the selection of the interested building constructional group in the model and opening the related properties table (Fig. 96-98) or ii) employing the conditional query operations to filter categories and properties, consequently comparing corresponding values (Fig. 99).

Transformation	**Category**	**Properties**
Unit X	Analysis of the conservation state "year"	Tab 22
Intervention	Intervention "year"	Tab 23
Current decay state	Analysis of the conservation state"year"	Tab 24

Table 25 Correlation among constructive evolution, category of transformation/interventions and tables of properties.

The difference between the two methods stands in the type and the quantity of properties. The first permits the view of all the information related to an object or to a group, the second one helps the filtering of the required properties per each category and the comparison of the values for specific analysis (i.e. diagnosis of a settlement, construction phase, etc.).

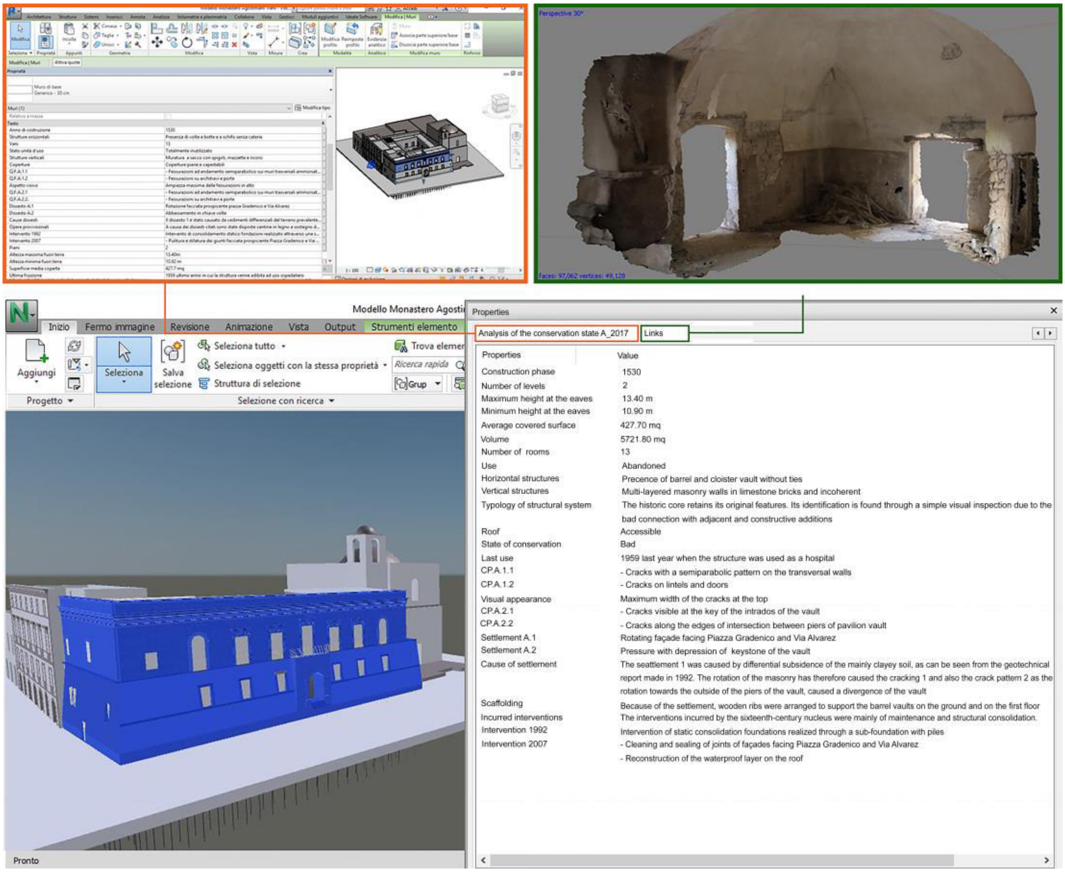

Fig. 96 Correspondence between selected constructional group in the model and the related properties table (Bruno et al., 2019b)

For example, in the first method (Fig. 96), selecting a BIM object in the Unit 1 elements the software opens the property table on the category " Analysis of the conservation state_2017", reporting geometry information, construction techniques, interventions and transformations, crack patterns and settlements analysed in the year 2017 (properties in Table 22). In Fig. 97 the table shows the properties relatives to the age 1393. This operation can be executed for each element belonging to the next transformations and interventions. In Fig. 98 selecting crack pattern the software shows all properties (described in Table 24).

The second method consists in the conceptual the inverse process than the first, due to the high-lighted of the geometric element starts from the selection the property.

Therefore, the query operations permit the filtering of multiple data to be compared; the comparison of the detected settlings in each construction unit, the morphology of the cracks, and the motivation of the consolidation intervention.

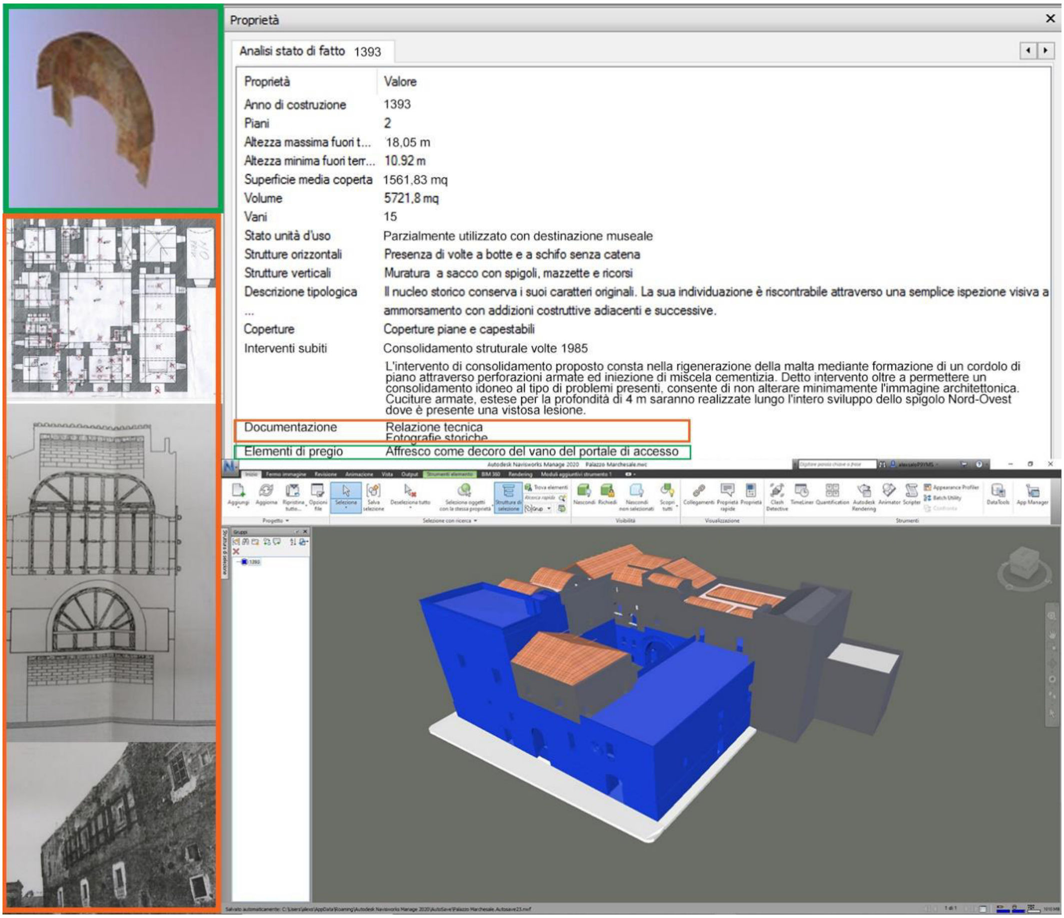

Fig. 97 Correspondence between selected constructional group in the model and the related properties table (Verdoscia et al., 2020b)

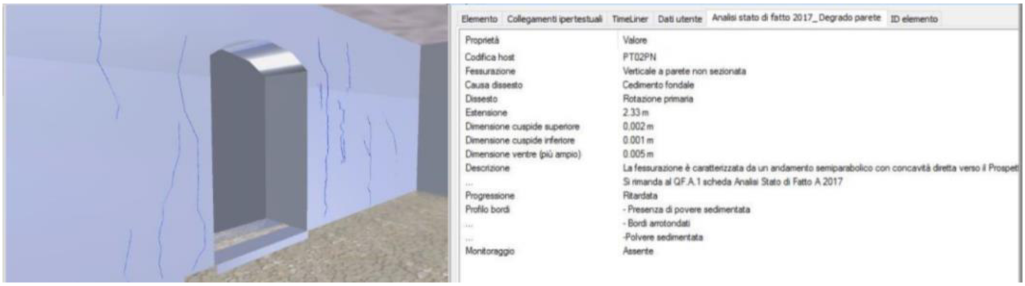

Fig. 98 Correspondence between selected constructional group in the model and the related properties

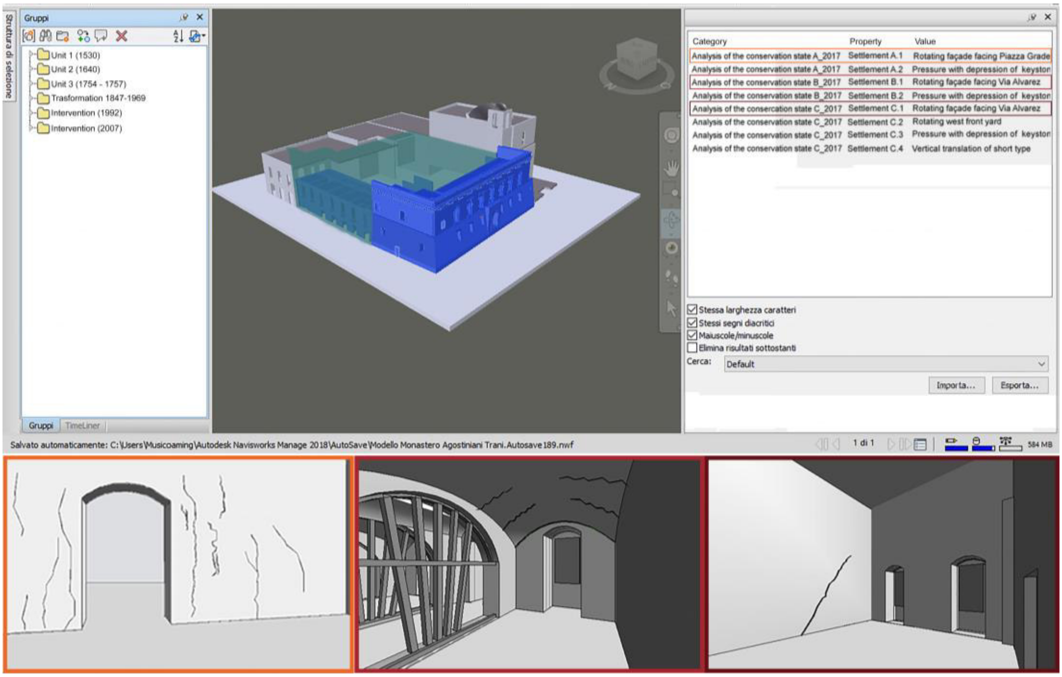

Fig. 99 On the top Selection of categories, property to be analysed, query and property value of the tree units. Bottom the cracking pattern of three rooms of the building, two on the ground floor (left) Unit 1 and (centre) Unit 2, and one on the first floor (right) Unit 3.

For example, in Fig. 99, the query of the database, underlines the presence of the same settlement in the three construction units.

From the Preliminary Knowledge and Data Collection (A) a constructive evolution timeline has been elaborated (Fig. 100).The correlation of the years in which occurred the first construction and subsequent transformations or interventions to each macrogroups permits the 4D-HBIM simulation in order to dynamically show the entire building life cycle to the actors of the conservation process (Fig. 101Fig. 102). The problem in allocating the temporal parameter is the limitation that Navisworks® starts from 1753; thus, an ideal year has been assigned to each element, respecting the chronological order of the events. The simulation allows an overview of the current conservation state, the constructive evolution and it is a support for diagnostic operations of the causes of decay and settlements.

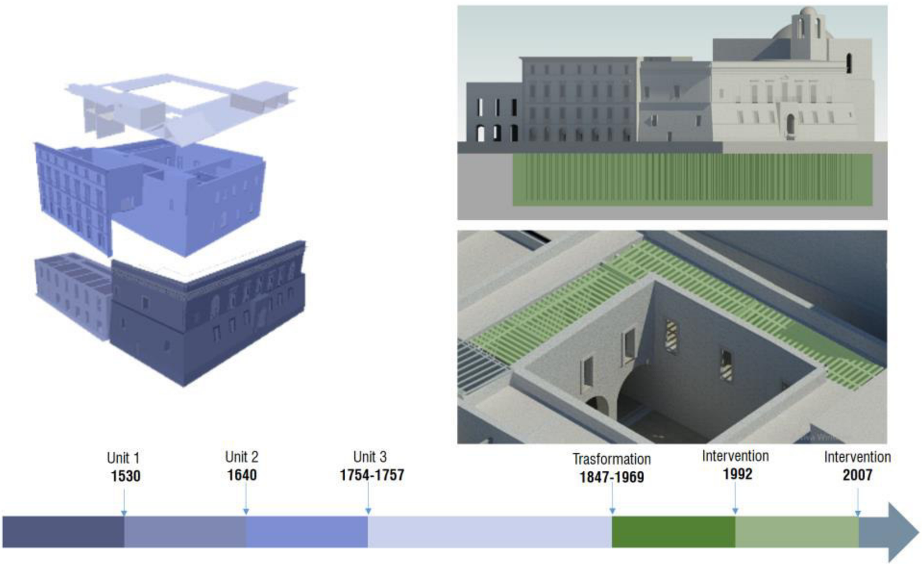

Fig. 100 Example of constructive evolution time line (Case 2)

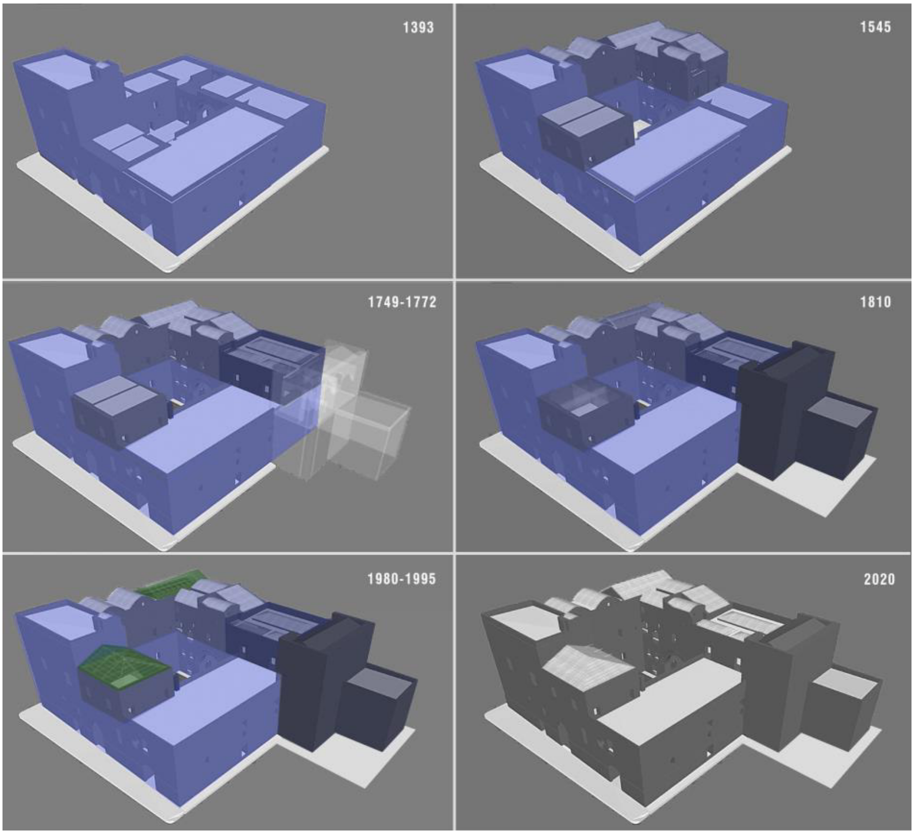

Fig. 101 4D simulation of Marchesale Palace in Navisworks®

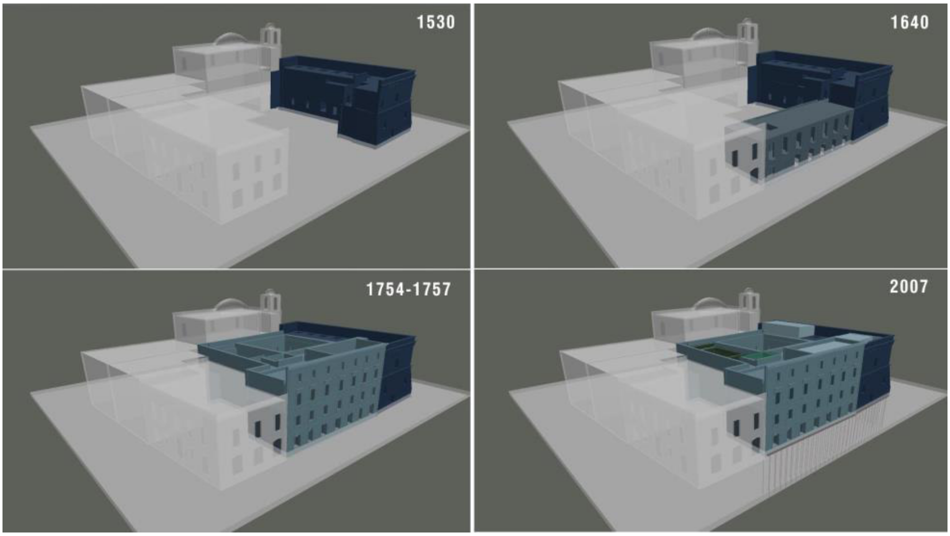

Fig. 102 4D simulation of Augustinian Monastery in Navisworks®

As results, the research deals with the significance of the research in 4D reconstruction as the integration of 3D models and databases proposing the 4D-HBIM, a methodology for integrating the static representation of historic building supporting the documentation and the analysis with the aim of supporting decision for refurbishment and restoration and recognising the correct diagnosis of the causes on which to intervene, without further compromising the building.

Firstly, the 3D representation of geometry and constructive evolution about historic building solves the limitations of traditional practices threatened by the fragmentation of the knowledge system. In this contest, necessary is the combination of source-based and reality-based modelling approach because the current state of the historic building is often the product of a lot of transformation activities documented in archives and no longer visible. However, the use of digital survey techniques speeds up the reality modelling phase guaranteeing more accuracy of 3D model and data extracted.

Furthermore, the 4D-HBIM overcomes the issues of traditional practices in i) investing a lot of time in the retrieval of documents, the survey of current building condition, ii) coordinating of the figures involved in the process and iii) consulting separate paper and digital documents about the geometric asset and incremental knowledge about the building that leads to errors.

The approach utilizes semi-automatic procedures based on the integration of the 3D model and structured databases and the inserted data/information sets can be compared with query operations. The databases are organized according to the historical flow via time parameter, useful for the study and analysis of the past and the prevention of possible risks in the future. Finally, the navigation of the building history and state of conservation could be immediately managed thanks to the hierarchization of the construction elements featured by relational databases. The digital managing has the benefit of facilitating a comparison of graphical and no-graphical information; for example, the direct connection of the instabilities detected within the building nucleuses, the morphology of the cracks and the related causes conducts to the identification of the consolidation interventions.

3.3.3 CONCLUSIONS AND FUTURE DEVELOPMENTS

This research proposes the 4D-HBIM system, an innovative methodology for managing knowledge about historic buildings assembling an interoperable workflow of existing commercial BIM tools. The connection of the HBIM model with external databases makes the historical evolution more comprehensible to all the users. The implementation of programs with query languages allows feasible access of data in the database. The SQL (Structured Query Language) is a common programming tool used by relational databases as the BIM ones for searching the required information. An advantage of this methodology lies in the assembly of easy-to-use software products with simple scripting for databases. The effectiveness of the method stands in the organization of the BIM model in groups of BIM objects corresponding to each identified constructive phases-each one associated to a timeline—and the structuration of the related knowledge in order to facilitate the query and analysis for conservation activities. In particular, the properties are associated with each parametric group about each temporal phase. Firstly, the categories collect the data/information about i) the analysis of the state of conservation, as executed per each constructive unit, ii) previous consolidation interventions and iii) the current decay patterns.

Then, the properties are defined as alpha-numerical parameters per each category, assigning a description and a data type. Such a system, characterized by an easy user-interface, can automatically produce the 4D-HBIM simulation that consists of the reproduction of the entire building life cycle and the query of properties.

The benefit of the Information Management is the support in identifying settling causes via database queries, consequently suggesting adequate interventions.

Thus, the 4D-HBIM system will support public and private actors such as building managers, planners, construction companies, researchers and users in the refurbishment process from the knowledge phase to the conservative interventions/maintenance and in the management of funding according to the current building conservation conditions.

This methodology has been tested on a case study and it can be applied on several historic buildings. The 3D survey (B) and 3D modelling and information enrichment (D) steps can be planned and performed with other methods according to the environmental conditions and morphological features of the building itself. The modelling step can be refined with Quality Assessment method (Sub-Sec. 2.3.2) in order to achieve a rigorous HBIM model.

Nevertheless, remaining within the main research objective, the link between the parametric model and 3D photo-reconstructed model (point-cloud and texturized mesh) allows to gain an accurate understanding of three-dimensional geometry and surfaces.

Then it would also be possible to integrate the outputs of (D)-Semantic data extraction-both in terms of segmented point cloud that of quantitative data extracted at this stage(Sub-Sec. 3.2). The integration of (D) can perform also the automatization of the recognition and the modelling of different constructive elements and decay patterns starting in order to reinforce the entire HBIM methodology.

Moreover, this process provides an interesting framework for planning medium- to long-term conservation strategies for architecture marked by complex and diachronic development.

A disadvantage of the methodology is the manual process of entering data into the database. A possible challenge to face will be the automation or the facilitation of the phase of insertion and fruition of the data through a dedicated tool, exploiting tested plugins or searches based on Visual Program Languages (VPL) as Dynamo or Grasshopper.

FINAL REMARKS

In the first part of the thesis, a critical review of the existing literature has been allowed the highlighting of the gaps and evaluate the development of a methodological process to support the documentary activity of historical buildings. Although not fully exhaustive, this study reported the most popular approaches suitable for the heritage community. The HBIM approach has been identified as the most suitable to meet the objectives of the research project.

HBIM is emerging as the most potentially efficient methodology for the preservation of historical artefact because it allows the collection within a single model of the volumetric and geometric characteristics of a building with multi-category information (material characterisation, performance levels, construction systems, etc.) through the use of three-dimensional model parameters that can be updated, shared and modified at any stage of the construction process, ensuring more effective control of the entire life cycle. In the specific case of historic buildings, it provides for the possibility of overcoming the difficulties linked to the fragmentation of relevant and archival data, facilitating their use through the use of computer procedures that facilitate interoperability between technicians and the integration of modelling and visualisation methods, limiting uncertainties in the reconstruction of knowledge and in the evaluation of the state of places.

The construction of the BIM model cannot ignore the complexity of the composition and the variety of the state of preservation of the products, so in the research work has been necessary to deepen the issues related to digital survey (laser-scanner and photogrammetric), the enrichment of models through the automatic extraction of geometric and colourimetric data of reverse engineering products (orthophoto, UV maps, point cloud, and mesh) using segmentation techniques based on Machine Learning algorithms (supervised and unsupervised), the management of document data by developing methods based on RDBMS (Relational Database Management System) and temporal simulations.

The construction of the BIM model cannot disregard due to the compositional complexity and variety of the state of preservation of historic buildings, cannot be separated from the integration of the BIM approach with other methodologies. The analysed methods have been divided into five macrocategories: digital survey, data segmentation, modelling approaches, semantic enrichment and 4D simulation.

From this analysis it emerged the possibility to implement the workflow that leads to the elaboration of a BIM model. First, reverse engineering products have been integrated into the parametric models, thus it was possible to obtain a representation at three different levels of detail useful with the purpose of preservation and reproduction of the artefact as a faithful facsimile of the real architecture. The model obtained has been become the base for subsequent processing.

Through Machine Learning proposed approaches, the raw 3D data of the digital survey have been segmented using the colourimetric and geometric properties. The advantage of the implemented methodologies consists, in the automation first of the segmentation process so far largely manual, and then in the extraction of qualitative and quantitative data.

The management of the 3D survey products, the segmentation and the preliminary knowledge and data has been carried connecting the HBIM model with external databases. Thanks to the interoperability underlying the BIM approach, importing the 3D model into programs with query languages has been allowed the feasible access of data in the related database for searching and analysing the required information.

The integration of the time factor as a parameter can be a valuable starting point for the analysis of the current state of conservation of the building and to carry out future structural surveys and mapping of degradation, the necessary basis for safeguard and maintenance program.

The interdisciplinary and collaborative approach in the application of BIM to cultural heritage objects was essential in the cognitive processes explored.
The achieved objectives allow to open new horizons of investigation and deepening in terms of reuse of the data for valorisation, conservation and interoperability. The models of architectures investigated, informed and informative, semantically structured and aware, do not dissolve all the issues, but they have shown themselves as valuable tools for deep knowledge and management of the goods themselves, data collectors able to make advances and evolutions in the purpose, now more and more widespread, to arrive at a more global view of the artefacts.

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ACRONYMS

2D - bi-dimension(al)

3D - three-dimension(al)data

4D – fourth dimension (time)

AH - Architectural Heritage

AI - Artificial Intelligence

AIM - Architectural Information Modelling

AH Architectural Heritage

BIM - Building Information Modelling

CAD - Computer-Aided Design

CH - Cultural Heritage

CIPA - International Committee for Architectural Photogrammetry

CRP - Close Range Photogrammetry

CRM - Conceptual Reference Model

GIS - Geographic Information System

HBIM - Historic/Heritage Building Information Modeling

HSV - Hue Saturation Value

HT - Hough Transform

ICCROM - International Centre for the Conservation and Restoration of Monuments

ICOMOS - International Council for Monuments and Sites

ICOM - International Council for Museums

ICP- Iterative Closest Point

ICT - Information and Communication Technologies

ISPRS - International Society for Photogrammetry & Remote Sensing

LiDAR - Light Detection and Ranging

ML - Machine learning

NURBS - non-Uniform Rational Basis-Spline

PNG - Portable Network Graphics

QA - Quality Assessment

RF - Random Forest

RANSAC - RANdom SAmple Consensus

RDBMS – Relational Database Management System

RGB - Red Green Blue

SDA - Surface Deviation Analysis

SQL - Structured Query Language

ToF - Time of Flight-

TLS - Terrestrial Laser Scanner

UIA - International Union of Architects

Weka - Waikato Environment for Knowledge Analysis

YCbCr - luma component, blue and red difference chroma components

YIQ - luma component, in-phase, quadrature

YUV - luma component, blue projection, red projection

VPL - Visual Programming Language

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KEY WORDS

Recupero edilizio
Rilievo 3D
Modellazione BIM
Modelli digitali
Simulazione 4D
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CAPACITÀ E COMPETENZE RELAZIONALI

Durante il periodo universitario e post lauream ho avuto la possibilità di constatare le mie capacità sia nel lavoro individuale che in team.
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La collaborazione intrapresa con il CONI Servizi SPA ha contribuito ad affinare le mie capacità organizzative. Essendo un lavoro svolto in totale autonomia, con obiettivi mensili suggeriti dai coordinatori, ho dovuto cercare di organizzarmi al meglio per raggiungerli.
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2. Il rilievo tridimensionale e la modellazione informativa per la tutela e la valorizzazione del patrimonio architettonico storico. IlPalazzo marchesale di Laterza.
   Laureando: A. Tucci , Relatore: prof. C. Verdoscia

3. Creazione e ottimizzazione di modelli tridimensionali basati su superfici mesh. Caso studio la scuola Corridoni di Bari
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   Laureanda: A. Cisaria Relatore: Prof. C. Verdoscia

5. Il laser scanner per il rilievo dei beni architettonici. la chiesa di santa Caterina D'alessandria a Conversano (BA)
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