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3D SURVEYING AND DATA MANAGEMENT TOWARDS THE REALIZATION OF A KNOWLEDGE SYSTEM FOR CULTURAL HERITAGE

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Summary

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Abstract

The research activities mainly involved the application of the Geomatic techniques in the Cultural Heritage field following the development of two main themes:

- The application of high precision surveying techniques for the restoration and the interpretation of high relevant monuments and archaeological finds
- The arrangement of 3D databases in view of a Building Information Modeling (BIM) approach, in a process which involves the generation and management of digital representations of physical and functional characteristics of historical buildings

These issues have been analysed through different study cases appropriately selected.

The first point was addressed presenting the survey of the Fountain of Neptune in Bologna for the generation of a high-fidelity 3D model of the monument. In this work, aimed to the restoration of the manufacture, both the geometrical and the radiometrical aspects were crucial. These issues required to integrate and merge each other different techniques and instruments (Photogrammetry, Laser Scanner, Light Structured Scanner, Total Station and so on) to obtain the desired result. The final product was the base of a 3D information system and it represented a shared tool where the different figures involved in the restoration activities shared their contribution in a multidisciplinary approach. This aspect represents an innovation for a restoration project of such a great monument, never done before.

The second point is referred to the Building Information Modeling (BIM) process, which involves the generation and management of a digital representation of physical and functional characteristics of buildings. The open challenge is the integration of the Geomatic field and the BIM for the existing and historical buildings, towards a so-called Historical Building Information Model (HBIM). A first application was conducted in the case study of the San Michele in Acerboli’s church in Santarcangelo di Romagna, Italy. The survey was performed by the integration of the classical and modern Geomatic techniques, and the entire point cloud representing the church was used for a first development of a HBIM model, where all the relevant information connected to the building could be stored and georeferenced, i.e. historical, materials, constructive techniques, etc. A second application regards the domus of Obellio Firmo in Pompeii, in which a multidisciplinary team composed by engineers, architects and archaeologists is trying to develop an HBIM approach useful for the management of the different and heterogeneous information connected to this unique situation. Also, in this case, the 3D survey was performed by the integration of the classical and modern Geomatic techniques. The main difficulties are connected to the historical stratification of materials both in elevation and in plan. An accurate historical analysis, currently in progress, with the contribution of the archaeologists, permitted the definitions of phases and the organization of a database of materials and constructive elements of the domus. The goal is to obtain a federate model able to manage the different aspects: the documental, the analytic and the reconstructive ones.

Introduction

The Cultural Heritage is gaining an increasing interest by the scientific community, especially for the documentation purposes, the different engineering analyses aimed to its preservation, the management of restoration activities and so on. The identification and the correct management of the Cultural Heritage represents a duty Italian context, which is rich of monuments and historic buildings and extremely exposed to risks at the same time. These aspects required a solid database in which different information could be stored, managed, shared and combined to guarantee the right choice for their preservation in the forward years.

Nowadays, the modern Geomatic techniques could fill this gap thanks to their ability to generate high-fidelity geometrical and radiometric digital 3D models. These models could be used for collecting the heterogeneous information in a structured way and represent the core of some information systems. A significant common element of the experiences carried out is the possibility to integrate the different techniques and methods, characterized by the generation of digital data of controllable quality. For the purposes of the 3D surveying, different technologies can be used according to the scale of the survey and the required level of detail: from laser scanning, with time of flight or triangulation methods, to structured light projection systems, to photogrammetry. Each technique finds case by case the best use and offers advantages and disadvantages: the best solution could be found with the synergies between each-other.

In the following chapters, we will discuss the basic aspects concerning the acquisition techniques and their use at different scales and for different purposes. In particular, three case studies will be presented.

The first case concerns the survey of the Fountain of Neptune in Bologna and the use of the resulting 3D model as the core of an information system aimed at the restoration activities. In fact, the survey techniques were the first step of a great project of the restoration of the monument, based and directly managed through a digital information system based on an open source code.

The second case regards the survey and the 3D modelling towards the development of an historical building information model (HBIM) of the ancient church of San Michele in Acerboli, located in Santarcangelo di Romagna. In this case, the modern Geomatic techniques can represent the first step to obtain the right 3D abstraction of the reality and a solid support to develop a BIM project. The commercial software Autodesk Revit 2017, a widely used tool in this field, was adopted. The case study represented the attempt to obtain a BIM-oriented simplified 3D geometry starting from the point cloud derived from a combined use of laser scanning and photogrammetry.

The last case study is referred to the first stages of an ambitious multidisciplinary project, involving different research areas of University of Bologna, towards a comprehensive information system for an important archaeological building, the Domus of Obellio Firmo in Pompeii. In this case the attempt is to provide a multiscale and very accurate 3D model of the structure, able to support a whole of activities through the development of the information structure deployed by a HBIM project.

1. The geomatic techniques for Cultural Heritage

The modern geomatic techniques are gaining more and more interest in the Cultural Heritage field and they are continuously improving the accuracy and the precision of the surveys to perfectly represent the 3D shape of the objects, such as a sculpture, an historical building or an archaeological find. The historical relevance of these objects requires some contactless survey techniques in order not to damage them.

In fact, the surveying of a Cultural Heritage always represents a challenge and it is frequently difficult to perform it with the conventional schemes and standardized methodologies. Every situation represents a unique case and frequently needs the integrations of several approaches and lot of experience to obtain the desired results in terms of accuracy and precision. The modern instruments can be easily adopted in the field of Cultural Heritage, but only some of them are suitable to solve the different problems, case by case.

A 3D survey represents the first step aimed to the realization of a 3D model able to digitally represent the reality and performed using the 3D active sensors. These sensors perform a non-destructive, rapid and precise digitisation of a visible shape in the form of the so-called point cloud. Among the wide panorama of the existing surveying techniques, this thesis focuses on the use of the scanner techniques and the close-range photogrammetry, which represents the best solutions for a contactless surveying.

1.1. The scanning techniques

There are many types of 3D scanners and each of them is the ideal for a peculiar situation. Some are ideal for a long-range scanning while others are better suited for a close-range scanning (Rinaudo, et al., 2007). The long-range scanners are represented by the so-called Terrestrial Laser Scanner (TLS) and they typically use a time of flight (TOF) or a phase-shift (PS) technology, while the short-range scanners use a laser triangulation or a structured-light technology.

1.1.1. The long-range scanners

Basing on the working principle, two main scanner categories can be identified for long-range surveys: Time of Flight (ToF) and the Phase Shift (PS). These instruments are typically used for surveying large objects by using a laser impulse emitted, reflected and finally received from the scanner. The measurement systems provide these aspects:

- TOF, Time of Flight: equipped with a clock measuring the time elapsed from the emission and the reception of the returning portion of a laser beam. It permits a directly definition of the point coordinates
- PS, Phase Shift: equipped with a receiver able to measures the displacement between the forward signal emitted by the instrument and the returning one reflected by the shape of the object. It permits an indirectly definition of the point coordinates

These scanners are also equipped with devices for measuring the vertical and horizontal angles of the laser beam emitted. However, if a traditional topographical survey permits to evaluate the spatial coordinates of some chosen points, the 3D scanners detect a huge number of points without making any choice of their quality. The result is a cloud of 3D points, the so-called point-cloud, where each point is expressed using spherical coordinates: the two known angles of the emitted laser beam and the distances between the shape and the instrument measured according to the mentioned ToF or PS principles. the coordinates are then supplied in cartesian form.

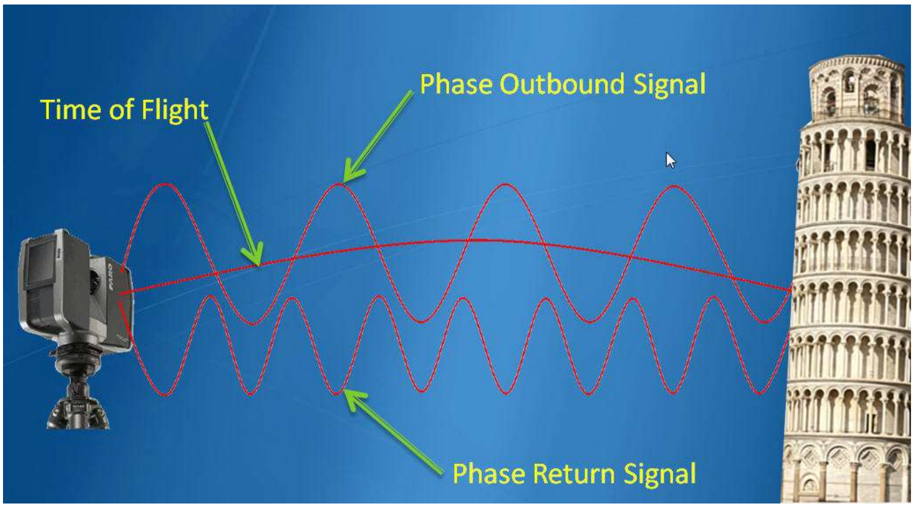


Figure 1. The comparison between the Tof and PS laser scanner

These families of instruments are more suitable for surveying large size objects and therefore inherent the architectural and territorial ambit. They need to be placed in several different positions from which it is possible to have only a limited view of the entire object and by using overlapped and common portions it is possible to align each other the different scans in a post-processing phase.

ToF, Time of Flight systems

These instruments measure the so-called time of flight of a short Laser impulse emitted by the scanner versus the object. This measure of the distance uses an analogue signal and this aspect sets limits, especially regarding the necessary threshold values to consider acceptable the returning signal. Some tools solve this problem using a digital encoder of signals.

From a structural point of view, these systems are equipped with a laser transmitting diode that generates a beam of infrared light and with a receiving diode, which pick up the returning beam and generates an electrical signal. The time elapsed from the impulse emitted to the one received is calculated by a clock with a stabilized quartz frequency, which sends the data to a microprocessor inside the instrument to calculate the distance. In fact, knowing the speed of light and the time elapsed between the emitted and received impulse it is possible to directly calculate the distance.

The accuracy regarding the distance measurement essentially depends on the accuracy of the flight time measurement, which however cannot be very high due to the presence of noise on the return signal. This problem is caused due to the diffusion by the impacting surface and the absorption of the radiation by the atmosphere during the flight time. The consequence is that the impulse detected by the sensor will have a lower intensity than the emitted one. According to this, the distance measurement is carried out only if the incoming signal has an intensity higher than a minimum threshold.

As mentioned, the measuring of the distances by the calculation of time of flight is also associated with the values of the horizontal and vertical angles of the emitted laser beam respect the instrument. These angles are perfectly known and mechanically controlled by movements imposed by the instrument. The result is a set of spherical coordinates, which, appropriately converted into Cartesian coordinates (X, Y, Z) represent the shape of an object.

$$\begin{aligned} X &= d\cos\alpha\sin\beta \\ Y &= d\sin\alpha\cos\beta \\ Z &= d\cos\alpha \end{aligned}$$

PS, Phase Shift systems

These instruments represent an evolution of the scanning techniques using the measurement of the time of flight, allowing to increase the precision and the speed of the measurement, although a lower measuring range.

Instead of emitting discrete laser pulses, these scanners emit a continuous wave (CW) used to modulate a signal, usually taking advantage of amplitude modulation (AM). The phase difference between the emitted wave and the reflected one is used to determine the distance and the relationship between the phase difference and the distance is expressed by the equation:

$$d = (n + \Psi) \cdot \frac{\lambda}{2}$$

where n is a whole number and ψ is related to the phase difference $\phi(0 \leq \phi \leq 2\pi)$ from the relationship $\Psi = \frac{\phi}{2\pi}$; ψ is a number between 0 and 1.

The problem lies in the fact that the whole number of n loops is not observable, causing an ambiguity in its definition. This problem could be solved simply adopting a wavelength λ such that $\frac{\lambda}{2} > d$ so that $n = 0$. For example, with a wavelength of 100 m it is possible to unambiguously measure distances up to 50 m.

It is important to notice that the measure of the phase shift is affected by an error depending on the distance. In this way the use of very large wavelengths can lead to an unacceptable error by limiting the maximum measurable distance without ambiguity. Therefore, to reduce that problem of ambiguity in distance, it is usually used a modulation of different frequencies to roughly identify the distance with a phase shift on a cycle or portion of cycle, and refine the information using progressively higher frequencies

1.1.2. The close-range scanners

The triangulation scanner systems base their working principle on the trigonometric properties of triangles. These instruments are composed by a signal emitter and the incident radiation on the object is partially absorbed, partially transmitted and partially reflected. The reflected radiation is focused by a lens in a flat sensor, rigidly constrained to the light source.

This configuration works if the known distance between the emitter and the sensor (the so-called "Baseline") and the distances between the instrument and the object are comparable. The consequence of this constructive limit is the possibility to survey only close objects, because high distances would clash with this limit (Guidi et al., 2010).

The type of sensor used to receive the portion of reflected radiation is normally a solid-state Charge-Coupled Device (CCD) sensor. This device is composed by a microchip with a web of semiconductor elements able to accumulate an electrical charge proportional to the intensity of the acquired electromagnetic radiation. The laser is a monochromatic light and is possible to mount in front of the CCD sensor a filter based on the laser emission frequency, therefore making the sensor not affected by light sources that could generate disturbs.

The kind of instruments based on this principle depending on the impulse emitted by the light source, which can be single spot laser, a pattern of structured light and so on. All of these are therefore part of the instruments that base their own measurement mode on the principle of triangulation. Their characteristics are different in terms of rapidity of the scans, in the level of precision, in the use limited to the small objects and in the close distances from the shape.

This work mainly focuses on the last one, the light structured scanner, which is an instrument able to project at the same time a set of patterns acquired by a digital camera, in according to the triangulation scheme of acquisition. Depending on the projection of the pattern and its codification, it is possible to two methods: the grey-code method and the Moiré technique.

Grey code method

The instrument projects a sequence of different black and white stripe images according to a coded sequence, which named Gray Code. The coding the projection of different patterns, a first one with a single transition and progressively to the last one with the maximum number of transitions than the instrument can simultaneously acquire and store. At each projection, the camera acquires the correspondent image that is registered and saved while the procedure is carried on.

As mentioned, these instruments based their functionality on the triangulation principles and in this condition, each point will appear in certain images of the gray coding sequence illuminated or not, according to its position in the 3D space. Analyzing these sequences, the values that the same point presents in the different images is associated to a value of 0 for detecting black and 1 for detecting white. The result is a sequence of binary codes giving us the necessary information to build the points of the 3D cloud.

Moiré technique

This technique consists in analysing the interferences generated by the superimposition of two similar patterns. The difference between the pattern is slight, however when they are superimposed, a third image is generated which represents the variation between them. The aim of the Moiré technique is to measure the frequency difference of the patterns by estimating the periodicity of this low frequency variation. The grey level will depend on the phase shift: the higher the shift, the whiter the colour. Being the phase shift related to the object shape, this also means a higher z elevation of the surface considered.

1.2. The image-based techniques

Photogrammetry is a technique used for the reconstruction of a 2D or a 3D model of an object starting from a set of photos taken from a camera placed in several different positions. The result is a 3D digital model representing the shape of the object and to do so, the operating principle consists in the estimating the coordinates of relevant points in a scene, such as those one indicating a geometrical or a chromatic discontinuity highlighted form the natural light in the scene. This aspect means that photogrammetry is a contactless and passive method.

The photogrammetric techniques changed according to the technological and digital developments. Starting from an analogical photogrammetry when the images were generated and processed on a photographic support and then developed to an analytical approach thanks to the advent of electronic computers, nowadays the photogrammetry has become digital and the images, acquired by digital cameras, are processed with a high level of automation by software adopting the more modern algorithms.

Moreover, depending on the field of application, one can refers to airborne or close-range photogrammetry: the first one refers to an acquisition system composed by a photo camera positioned on aircrafts (or drones) through which large portions of ground can be acquired. Instead, the latter one applies to relatively small objects whose photos are taken from short distance: this technique is mainly used for architectural surveys, industrial applications and Cultural Heritage.

1.2.1. Analytical Photogrammetry: basic concepts

A common picture taken with a camera can be considered as a central projection of the photographed object: the central perspective geometry links the object and the image space as Figure 2 shows:

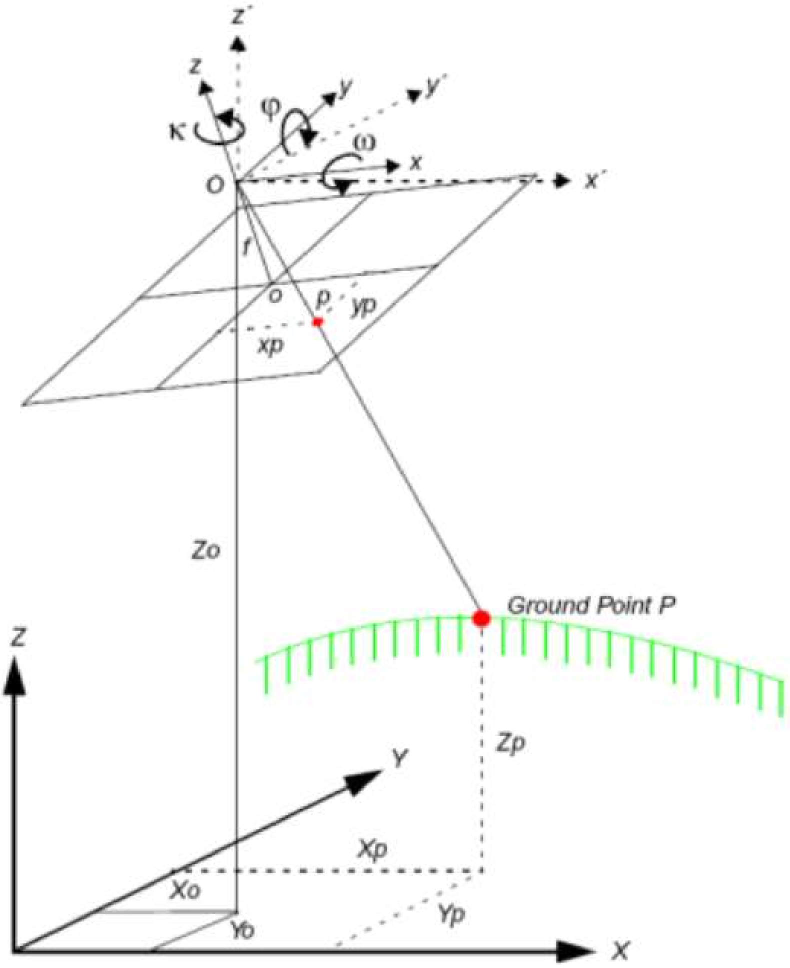


Figure 2. Central projection: relation between image and object points

The aim of the analytic photogrammetry is to relate the image to the real object through an analytical model. Once defined the 3D object reference system X, Y, Z and the 2D image reference system η, ξ, the collinearity equations allow one to pass from a point P' on the image space to point P in the object reference system. The collinearity equations, from image coordinates to object space, are:

$$X = X_0 + (Z - Z_0)\frac{r_{11}(x - x_0) + r_{12}(y - y_0) + r_{13}f}{r_{31}(x - x_0) + r_{32}(y - y_0) - r_{33}f}$$

$$Y = Y_0 + (Z - Z_0)\frac{r_{21}(x - x_0) + r_{22}(y - y_0) + r_{23}f}{r_{31}(x - x_0) + r_{32}(y - y_0) - r_{33}f}$$

The collinearity equations, from object coordinates to image space are:

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

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

The first equations show that, being Z at the right side of the equation, it is not possible to find a unique relation between image and object using just a single image. It is necessary to have at least two images of the same object to achieve the information about the Z coordinate. Furthermore, it is necessary to know the interior and the exterior orientation parameters. The interior orientation parameters are:

- η_0, ξ_0, coordinates of reperes;
- c, focal length;
- parameters of lens distortion.

The exterior orientation parameters are:

- X_0 Y_0 Z_0, projection centre coordinates;
- ω, φ, κ, angle of rotation of matrix R.

The interior orientation parameters are generally constant values provided by the manufacturer, while the exterior ones are usually estimated through topographic methods

1.2.2. Digital Photogrammetry

The digital photogrammetry applications have been rapidly increasing in the last few decades due to two main aspects:

- the high-performance digital cameras, being more and more affordable and user-friendly, have become wide-spread;
- the development of dedicated software for digital image processing have made this technology suitable for many applications.

This new approach gives the possibility to automate the traditional processing steps and making all the process faster. One of the most used approach is the Structure from Motion, which does not require the knowledge of the camera calibration parameters and its position during the acquisition phase. The 3D model is reconstructed starting from a high number of photos with a certain degree of superimposition and applying algorithms, deriving from the computer vision, that automatically solve both internal and external orientation of the photos.

The position of the camera and the scene are reconstructed at the same time through the automated identification of known geometrical features located on several images. Furthermore, the reconstructed scene is either oriented in space or scaled: it has its own orientation, which however, if needed, can be converted in global one through a geo-referencing procedure. In this way, the time required to get the results become shorter than the traditional photogrammetric approach.

Since digital photogrammetry uses 2D digital images measurements to recover 3D object information, the main characteristics of digital images and their acquisition must be specified.

Digital images characteristics

A digital image is a matrix composed by n x m elements called pixels, which contains radiometric information varying with space. The principle behind a digital image acquisition is the discretization of a continuous entity (a natural scene) with the purpose of representing it through a discrete function. This process, called digitizing, quantifies the radiometric content of the selected space variable and assign it to each pixel. The following image schematizes the digital image generation.

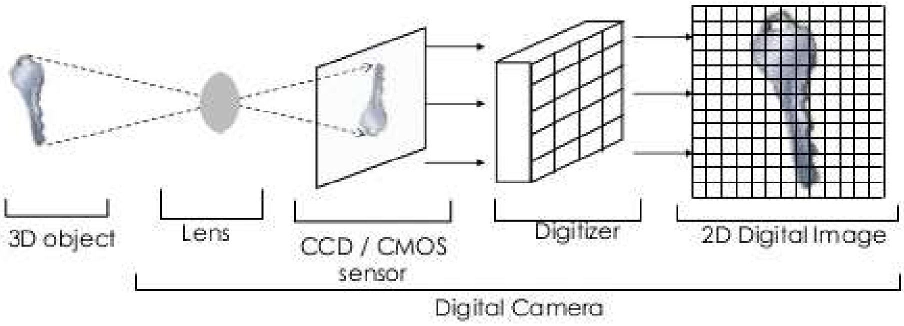


Figure 3. Image formation, from real object to discrete 2D image

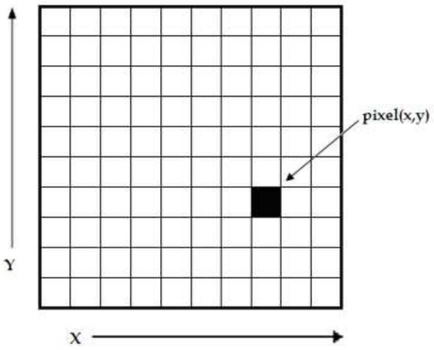


Figure 4. Pixel array

Radiometric resolution

The first operation that contribute to the digital image formation is the sampling and it is related to the radiometric resolution. The acquisition of a digital image starts with the transformation of the light in an electric signal through a sensor; then follows the conversion of this signal in an integer number (digitizer) and its memorization in the corresponding pixel. Depending on how many radiance levels are represented, the number of bits that measure the information of each pixel will vary: if only two values (0, black and 1, white) are possible, one will work with 1 bit; if the radiance levels are 256, the images will be in 8 bit (1byte) (grey scale or in colour palette).

Figure 5. The example of 3 different radiometric resolution of the same image

Spatial resolution

The second operation is the quantization and is related to the concept of spatial resolution. It represents the relation between the image area and the pixel one and influences the level of detail that one can reach within the image. If the pixel size is small in the object space, the matrix representing the image will be characterized by a high number of rows and column, thus will have a high spatial resolution.

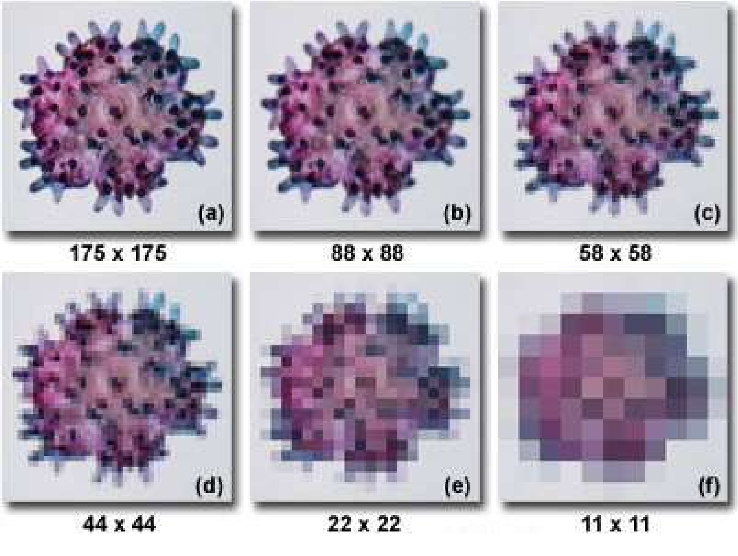


Figure 6. Spatial resolution of a digital image and number of columns and rows of each matrix; a) 175 x 175 resolution, the highest; b) 88 x 88 resolution; c) 58 x 58 resolution; d) 44 x 44 resolution; e) 22 x 22 resolution; f) 11 x 11 resolution the lowest. Decreasing the resolution, the image becomes less and less detailed

Digital camera sensors

The sensors are elements installed in the electronic chip of a digital camera and they are composed by a line or a 2D matrix of photo-diodes able to convert light in electric charge. The two main types of sensor are:

- Charged Coupled Device, CCD
- Complementary Metal Oxide Semiconductor, CMOS

Figure 7. Example of real CCD (on the right) and CMOS (on the left) sensors

The difference between them consists in the method used for the conversion and the transfer of the electric signal: in a CCD sensor, each raw of charged pixel is sequentially transferred to a register before A/D conversion takes place. A CMOS, instead, converts the charge inside each pixel and the chip directly transfers the digital number.

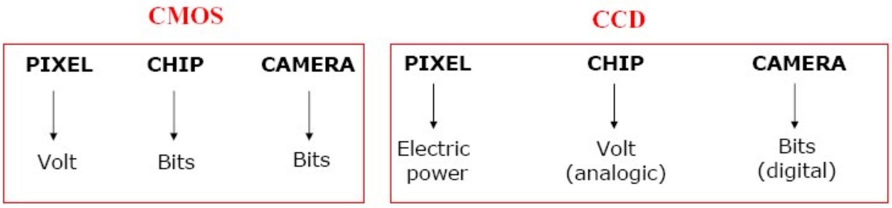


Figure 8. Digital signal conversion and transferring in CMOS and CCD sensors

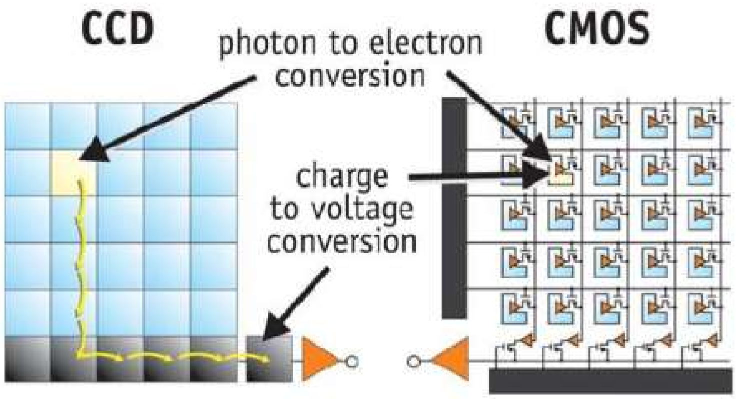


Figure 9. The CCD and CMOS sensor working principle

Colour Filter Array

In order to obtain coloured images, a filter is normally placed over each pixel: the CFA (Colour Filter Array) decomposes the incident light in its three components (Red-Green-Blue) and let only one component to reach the pixel;

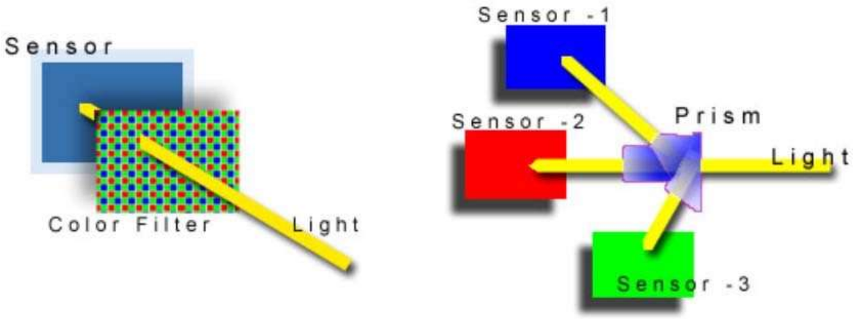


Figure 10. Schematization of CFA working principle

then this component is "measured" and the other two are calculated with an interpolation procedure. With this method, each pixel has a colour information expressed in percentage of Red, Green and Blue.

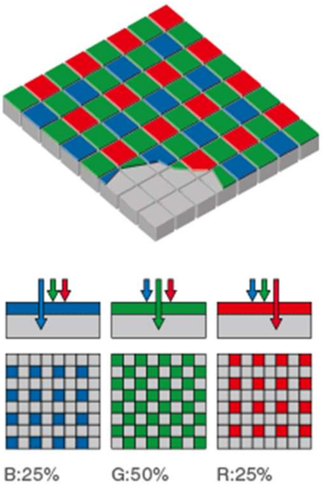


Figure 11. CFA operating principle (Bayer filter)

2. The knowledge systems for Cultural Heritage

The communities need to conserve, identify and properly manage its own Cultural Heritage, often susceptible to transformations due to the time, anthropologic factors or damages caused by natural events, such as earthquake, floods and so on. For these reasons, it is important to provide a knowledge system of Cultural Heritage, enhancing existing databases, making them visible to general public, making them interoperate in a flexible way through the construction of shared information platforms useful to improve the conscious level about them, both for the audience and both for the technicians involved in preservation projects.

For these reasons, Cultural Heritage is extensively documented, also for the benefit of future generations. Geomatic techniques, when integrated each other, can provide dedicated methodologies able to detect and survey the characteristics of such complicated structures. In this way, 3D geometric models of monuments can be created and enriched with a wide range of information, resulting by the high accuracy of the techniques now available.

Furthermore, not only the geometrical aspects but also some other kinds of information are required to guarantee and plan the right choices in terms of preservation of a monument. About a monument or a moveable heritage, it is also essential to know the materials of which is composed, as they may allow to date not only its creation, but also the subsequent modifications made over time. Moreover, it is important to define its ‘health status’ in to understand the degree and causes of decay phenomena.

Al last, a manufact is almost always composed by some other kind of aspects, not appropriately tangible, including its meaning and its purpose at the time of its creation, its history, and so on.

All these heterogeneous information (geometry, material, meaning, history, status of preservation, changes, etc.) can be now stored and shared by using some common digital tools, in which the digital 3D models generated by the geomatic techniques represent a true core of a knowledge system for Cultural Heritage.

In the following paragraphs are shown two different ways to obtain these kinds of intents. A first one, mainly based on web platforms for a several kinds of monument and manufacts, and a second one mainly focused on a building dimension and represented by the Building Information Modeling (BIM).

2.1. Web based platform for Cultural Heritage

The requirements to make the mentioned data accessible to many users, most of which are unfamiliar with the software and tools specifically adopted by the technicians involved in the processes of maintenance or restoration, brought to the development of various user-friendly interface to the data. Moreover, the recently needs for the dissemination of knowledge on Web have grown up (Scianna et al., 2018). The resulting Web pages could contain forms and tools for data input and editing directly managed by the users. Nevertheless, the new achievements in computer science have allowed people to easily access to this online information using different kind of devices, such as tablets and smartphones.

The use of a digital representation on these devices allows to create immersive 3D models explorable by the users with different possibilities: past or future reconstructions, impossible to explore in the real world (Eve, 2012) (Marques et al 2017). For these reasons, the application and development of specific technologies for the creation of 3D Cultural Heritage representations and virtual reconstructions is a fundamental research field. Merging the virtual representation and Cultural Heritage comes the so-called term Virtual Heritage (VH) (Roussou, 2002). The virtualisation of heritage consists of the digitalisation of the Cultural Heritage to simulate and recreate it with the help of computer graphic technology (Tan et al., 2009)

In the following paragraphs will be discussed WebGIS experiences and some tools for the creation of Web interactive presentations of high-resolution 3D models, oriented to the Cultural Heritage field.

2.1.1. GIS and WebGIS for Cultural Heritage

As known, a Geographic Information Systems (GIS) is a tool for collection, management and analysis of geospatial data, georeferenced in a same coordinate system. The digitization of historical data and the development of Information and Communication Technology (ICT) based methodologies related to the Cultural Heritage have become highly relevant and the use of GIS is significantly growing, with the aim of collecting, analysing and managing heterogeneous data in a spatial context.

GIS and geoinformation mapping allow to obtain new products able to include new historical information in the processing of historical archive sources, merging maps and text materials in a readable form for the users. It is also possible to maximize the management of the information, storing the attributes in a unique database, archiving also the data related to planned actions. Using GIS-technologies applied to the study of cultural heritage was formed as an interdisciplinary field of research.

The technology has also evolved from classical desktop GIS to WebGIS. The use of these tools is very diffused, due to its immediate and impressive representation of the reality. These technologies have been applied to Virtual Heritage 3D reconstructions, to improve its fruition, achieving interesting results in this way. This GIS oriented to 3D models also gives complementary text and multimedia information on the history, architectural features (i.e. old maps acquired in a digital form and archive sources), based on querying of semantic information.

The literature review brings several projects made with the aim to create a customized geographic information system to maintain and manage.

An example is referred to the archiving system and documentation Web-based related to an application in Castelfranco Veneto (TV, Italy) (Guarnieri et al., 2016).

Figure 12. Aerial view of Villa Bolasco and its park

In this case, the purpose of the authors was to manage multi-sources and multi-time data related to a Cultural Heritage site. The geodatabase is made up of historical information, documents, descriptions of artistic features of building and its park, in the form of text and pictures. The authors also adopted floorplans, sections and views of the outer façades of the building extracted by a 3D model deriving from a TLS survey. The top-view images of the building complex were collected by an Unmanned Aerial Vehicle (UAV).

nome: 004a.JPG

autore: Guarnieri Alberto, Cirgeo

descrizione: foto prima dell intervento di restauro

data: 2013-02-07

Figure 13. Screenshot of the web pages of the WebGIS

This geodatabase was developed by a Database Management System (DBMS) PostgreSQL and PostGIS in the spatial environment, and exported on WebGIS platform (Figure 13).

Although, not available via web, interesting case is related to the big Arc of entrance to the Vittorio Emanuele II Gallery of Milan (MI, Italy), shown in Figure 14, in which both the project documentation of an object and the object itself are Cultural Heritage (Bitelli et al, 2018).

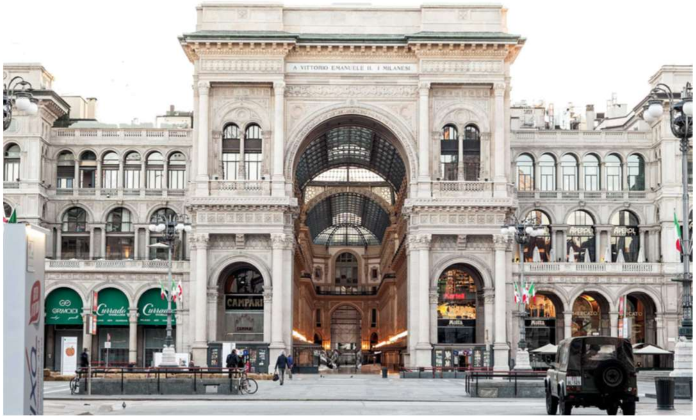


Figure 14. The big Arc of entrance to the Vittorio Emanuele II Gallery of Milan

The project documents are today kept at the “Museum-Archive Giuseppe Mengoni” of Fontanelice. In this study the authors tested the utilization of geomatic techniques, specifically the photogrammetry and GIS, for managing the whole information related to the architectural project in a geospatial environment.

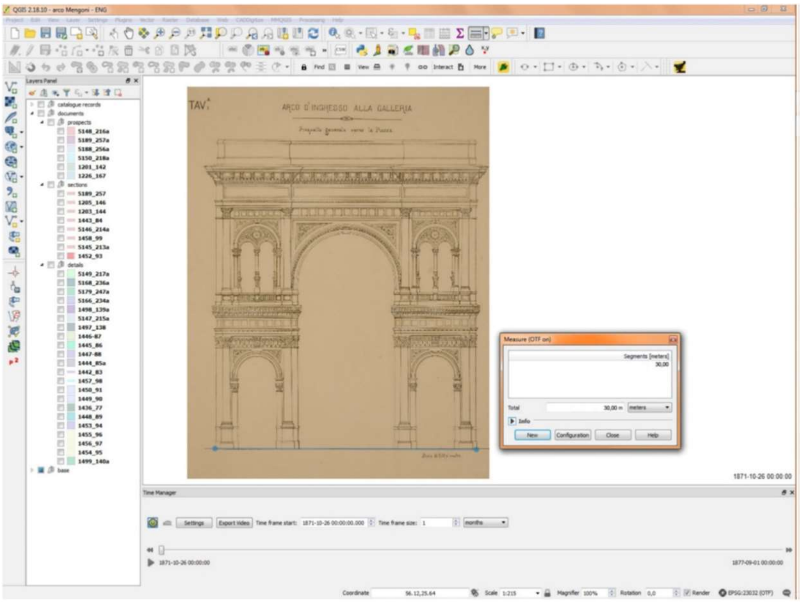


Figure 15. Screenshot of the GIS developed by the authors

Regarding the second aspect, the authors developed an innovative tool able to allow intuitive and immediate searches among the archive documents and the catalogue records. The tool permits an innovative reading of the big Arc, in each step of its project phases.

The use of a GIS for the management of those kind data, which are not properly geographical, is justified by the authors by the data organization and the tools of measurement, search and analysis available on a GIS platform. They structured the GIS according the real object developing a tool which is visual, intuitive and immediate, because selecting a vector polygon (e.g. referred to an architectural element) allows high resolution metrical consultation of the inherent digital document (this way avoiding material consultation, which can further deteriorate the delicate analogue document), with access to the archival references.

This information system therefore permits a spatio-temporal exploitation and exploration of the whole project process performed by the architect Giuseppe Mengoni and his atelier.

2.1.2. Web-based platform for Cultural Heritage

The delivery of 3D Cultural Heritage models for interactive consultation using web sites started to be supported with a considerable delay than some other digital media such as text, images, videos and so on. First approaches proposed for publishing and visualizing 3D data on the web had the disadvantage to consider only the visualization of the 3D data, requiring specific tool developed as a plugin for the web browsers and requiring to be installed by the users. The Cultural Heritage community needed tools developed in a most user-friendly approach, mainly because potential users are commonly not ICT experts.

The introducing of the Web-based Graphics Library (WebGL) standard in 2009 (Khronos Group, 2009) was a fundamental change and it represent the latest component of the OpenGL system, modelled as a JavaScript Application Programming Interface (API) and it provides a specification on how to render 3D data that web browsers should implement.

Figure 16. The WebGL logo

Thanks to WebGL, modern web browsers can natively render 3D models directly using the features of the 3D graphics hardware, without needing additional plug-ins or extensions. It’s important to notice that developing an application that uses WebGL is not easy and it requires a considerable confidence in graphics programming. So, WebGL is not itself a solution to the requirements of the Cultural Heritage community but it represents the core for the development of several interesting tools or resources. WebGL brought to the development of different approaches for the management of the 3D content on web and some of these approaches produced more sophisticated libraries (Behr et al, 2009) rather than commercial services developed to support the easy publication and visualization of 3D content.

Nowadays, a widely used commercial platform is Sketchfab, which represent a sort of standard about the 3D content publishing on web.

Sketchfab

Figure 17. The Sketchfab logo

Sketchfab provides a 3D model viewer based on WebGL enabling the users to move all around a 3D scene using the mouse or a touch-based device. In addition to static 3D models, the viewer can also play and control interactive 3D animations and enable the Virtual Reality (VR) mode to make the model viewable in the VR headsets devices.

This tool allows users to insert the data on a specific 3D data file and upload it on the web platform, sharing and embedding it on various external web sites or social network. All the processing and conversions are automatically performed on the Sketchfab platform and users can choose to make their 3D model files available for download under Creative Commons License.

The main limitation of this platform consists in the lack of flexibility caused by the impossibility to configure or modify the Sketchfab viewer to support the specific Cultural Heritage needs. Moreover, it supports only a mono-resolution model and uses a lossy compression method to optimize the download transmission times, which it causes drastically simplification of the original 3D digital model of the Cultural Heritage

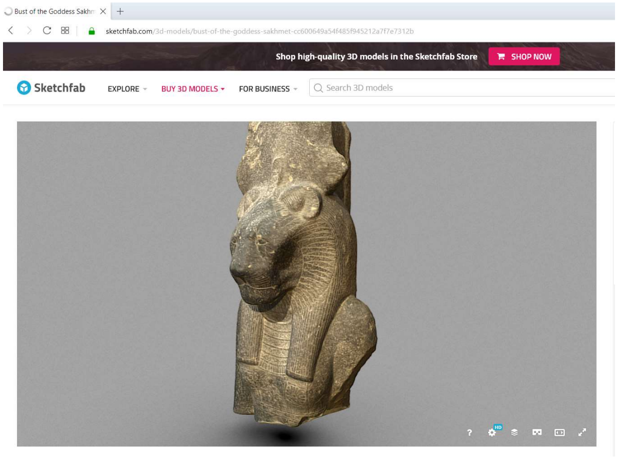


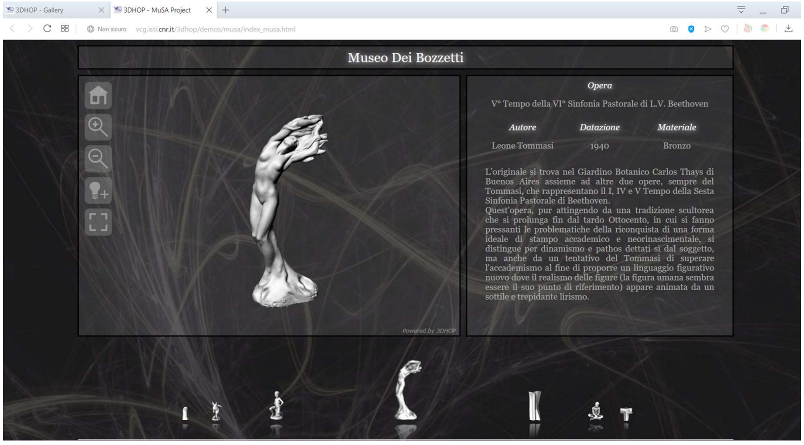
Figure 18. A snapshot of a 3D model published on the Sketchfab website

Another example is represented by the 3D Heritage Online Presenter 3DHOP (Potenziani et al., 2015), which is a platform specifically designed to support the Cultural Heritage community. 3DHOP has been released as open source software (GPL licence) in April 2014 and is based on the WebGL subset of the HyperText Markup Language HTML5 and thus it works without the need of plugins on most modern browsers and on all platforms.

3DHOP
3D Heritage Online Presenter

Figure 19. The 3DHop logo

The developers designed 3DHOP to be a user-friendly tool, especially for people not having a background in web development and without requiring a solid knowledge in Computer Graphic (CG) programming. This tool simplifies the creation of interactive visualization webpages and enables to display high-resolution 3D models. Moreover, the 3D resources can be deeply connected with the rest of the webpage elements. One of the most interesting characteristics of the 3DHOP framework consist in its facility to work with extremely complex 3D geometries, using a streaming-friendly multiresolution. It has been designed to work with web environments.



Museo Dei Bozzetti

Opera

V° Tempo della VI° Sinfonia Pastorale di L.V. Beethoven

Autore	*Datazione*	*Materiale*
Leone Tommasi	1940	Bronzo

L'originale si trova nel Giardino Botanico Carlos Thays di Buenos Aires assieme ad altre due opere, sempre del Tommasi, che rappresentano il I, IV e V Tempo della Sesta Sinfonia Pastorale di Beethoven.
Quest'opera, pur attingendo da una tradizione scultorea che si prolunga fin dal tardo Ottocento, in cui si fanno pressanti le problematiche della riconquista di una forma ideale di stampo accademico e neorinascimentale, si distingue per dinamismo e pathos dettati sì dal soggetto, ma anche da un tentativo del Tommasi di superare l'accademismo al fine di proporre un linguaggio figurativo nuovo dove il realismo delle figure (la figura umana sembra essere il suo punto di riferimento) appare animata da un sottile e trepidante lirismo.

Figure 20. A snapshot of a 3D model published on the 3DHop repository

Over the years, the core engine of the viewer has been upgraded several times to reach the best balance between rendering and streaming performances. These improvements and developments permit to 3DHOP to easily handle in a light multiresolution compressed format both high-resolution meshes and point clouds (over tens millions of triangles/vertices).

An example of how 3DHop works it will be show in the Paragraph 3.1 where a case study regarding the Fountain of Neptune will be discussed and in which 3dHop where adopted for development of a digital system of knowledge over all the restoration activities of the monument.

2.2. Building Information Modeling (BIM)

In the last decades, a quick development in the Information Technology (IT) has taken place and the Architecture, Engineering and Construction (AEC) sector has been massively affected by it. The CAD tools focused on architectural design started to spread in the AEC professional practices beginning from the 80’s of the last century, replacing traditional paper drawings with the digital ones. During the years, this digital revolution has gained more and more importance and made several steps ahead because of the IT tools evolved from a sort of digital drawing boards to a complete design framework based on enhanced parametric objects, combined to originate whole buildings within a virtual environment.

An object is not only a geometric representation of an entity, as in the CAD systems, but it’s a data collector with specific meanings. These objects provide a useful abstract computer representation of the physical world, in fact a wall as an object represents an actual wall in the physical world and a door as a digital object represents a real door and so on. This graphical correspondence with the reality is the foundation for the Building Information Modeling (BIM), a coordinated, consistent and always up to date working process supported by software tools, continuously improved to reach higher quality, reliability, optimized scheduling, errors and costs reduction together with avoidance of any possible project misinterpretation. In fact, the Building Information Modeling should be considered a process, rather than a technology or a worst just only a software, which instead should be a support for that process.

It is a 3D digital representation that connects all the available information to each 3D object of the model. As mentioned, while a CAD is essentially a tool that allows creating plans, sections, etc., but still formed by purely geometrical elements, a BIM model has all its elements linked to a database containing all the related metadata. The BIM models are composed of parametric objects, i.e. virtual building components that are identified by modifiable parameters, such as dimensions. These virtual objects may also contain other types of data, such as material information

Understanding the meaning of a parametric object helps to better understand the BIM concept and how it differs from traditional 2D and 3D drawing. An ordinary wall in any 2D CAD is drawn with two parallel lines, which indicate the thickness of the masonry and the same wall in a 3D CAD is designed through a solid parallelepiped. In both cases we have limited ourselves to describe just the form of the object and we do not have any information about its quality, (composition and quantification of materials) or on its own properties, such as supports, joints, thicknesses, developments and so on.

If all these aspects can be easily applied for the new buildings, which BIM is mainly referred, an open challenge concerns the application of all these approaches to the existing ones. This challenge is also harder when we talk about Cultural Heritage and historical buildings. In fact, these objects were often manipulated during the centuries, with demolitions, reconstructions and collected, layer after layer, dissimilar styles. Furthermore, also their maintenance status and deformation are to be considered and managed.

The conservation of ancient buildings, mainly due to their high relevant heritage evidence, is frequently a critical point in the Italian context. In fact, recent events, such as the earthquake involving the centre of Italy, made clear the need of a capillary system of knowledge for the management of these aspects and for an efficient development of restoration and conservation activities. The international scientific community introduced the concept of HBIM (Historical Building Information Modeling). Originally, the term HBIM was used as "a novel prototype library of parametric objects, based on historic architectural data, in addition to a mapping system for plotting the library objects onto laser scan survey data".

2.2.1. The BIM definition

The main BIM concept was introduced by Professor Charles Eastman at the Georgia Tech School of Architecture in late 1970, when Eastman claimed that drawings for construction were inefficient due to their limitation to visualize the buildings and, at the same time, the drawings were not updated. He also illustrated a Building Description System (BDS) obtained through the aggregation of many 3D graphic elements that can contain geometric information but also materials, etc.

"Contractors of large projects may find this representation advantageous for scheduling and materials ordering".

In a part of the '74 publication, we read:

"Much of the design, construction, and building costs come from using drawings as a way to report building records".

Nowadays we can consider BIM with a double meaning, where the M is able to represent both a Modeling and both a Model. BIM as Building Information Modelling is a process for storing, managing, combining and creating information on a construction project across the project lifecycle itself. The BIM as Building Information Model is the core of this process, representing a model able to collect information assembled collaboratively in a multidisciplinary approach and updated at every key stages of a project. The goal is to enables those who interact with the building to optimize and share their actions to all the figure involved in the project.

It is important to highlight that BIM is not a specific software. A software is only the technological core of BIM, but that represents only a small part of the whole system. The main aspects of BIM consist of 3D design, intelligent models and information management, such as components including synchronous collaboration, coordinated work practices and a cultural or institutional framework in which BIM is incorporated in processes and business plan.

2.2.2. The BIM methodology

The BIM methodology involves different aspects for the project management through a single 3D digital model to reduce the times of the design, the production and therefore the costs. It also requires a new way of coordinating the different technicians involved to improve the quality of the results.

In the early stages, where the project evolves and is being generated, the BIM methodology helps us to easily extract floors and sections from a single 3D model. This model is the germ of the project and thanks to the various displays, it allows the understanding of the different proposals by the customer and by our own team, and all that in real time.

Because of the importance of the project's implementation on its place and its adaptation to the environment, is valuable the information we can get about the energy evaluation of the building. In this way from the initial phases comparatives of different sustainable solutions are generated, allowing us to select the most appropriate from the conceptual phase. For this, we use the BIM model to study the optimum orientation of the rooms, the amount of solar radiation and lower environmental impact (6D). We may, if necessary, export the model to specific tools that complement the information obtained from the native model.

The coordination of the design team is gaining relevance also in the intermediate stages and this aspect needs to be managed till the start of the project to let modify the different design elements by each team involved. Therefore, the BIM model enables various design teams to simultaneously design different parts of the project without getting interference by each other.

Figure 21. BIM methodology: the information sharing during the building lifecycle

During the most advanced stages of the design, the use of open standards allows the interoperability inside the process, becoming an essential aspect for the traceability of actions and the responsibilities of each participant. Firstly, the export to the Industry Foundation Class (IFC) format of the architectural model allows engineers to import into their software to model and analyse for evaluation and approval by the project coordinator. Furthermore, the BIM Collaboration Format (BCF) file sharing enables the transmission of comments and observations as well as tracking the modifications to the project that facilitates its traceability. The IFC files are also used to federate or integrate the different partial models of the project and check the degree of collisions between them. By using verification tools, it is possible to detect in advance the possible anomalies that may cause conflict later in work, and thus avoiding more costly changes during the execution of the work.

Some unique elements require special attention during the development of the projects, and they can be designed and managed thanks to the use of parametric tools. These tools are used to develop façades and unique elements in the interior design phase using interoperable formats.

The use of BIM methodology guarantees the correct coordination between the 3D model, the 2D planes exported to various formats. Furthermore, exporting the yet mentioned IFC file model is also possible to measure and budgeting programs (5D) and simulation, planning and construction management (4D) to complete the information that we can extract from the model. Once the project is built, the BIM model can still be used to carry out the comprehensive management of services and building maintenance (7D).

2.2.3. The Maturity Levels of BIM

It is possible to describe the transition process from a simple CAD to a BIM and clarify the achieved level of development concerning to it. The

British Standards Institution (BSI) introduced in 2013 the concept of Maturity Model to describe the maturity levels in the use of BIM.

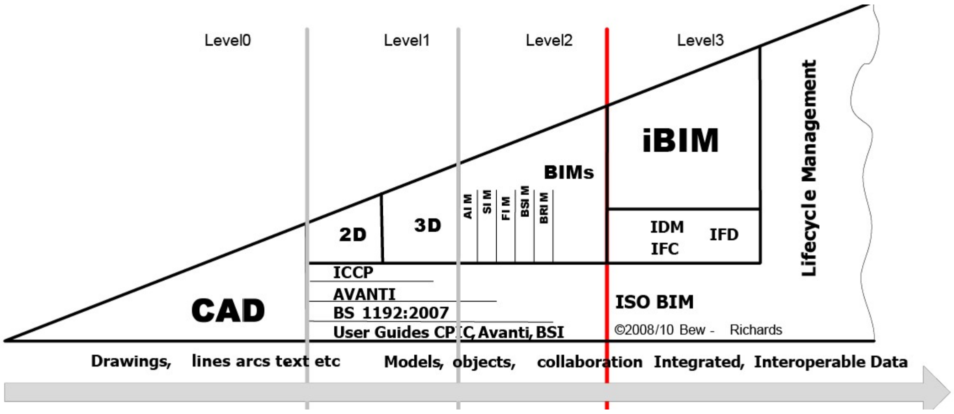


Figure 22. The UK BIM Maturity Model (Bew, Richards, 2008)

These levels (often described as "Maturity levels") of application and collaboration are based on the use and share of files and on the databases management. These classifying of maturity, defined by the Government of the United Kingdom, is composed by 4 levels, from 0 to 3 to classify the type of technical and collaborative process related to the adoption of BIM systems.

- Level 0 - This level means no BIM adoption: design documents are produced only by 2D CAD drawing and the outputs are supplied in paper or electronic version;
- Level 1 - At this level, the CAD begins to be managed with the increasing introduction of spatial coordination functions, structures and standardized formats. It could be useful imagine that the BIM Level 1 includes a mixture of 3D about the design phase and 2D regarding the documentation and the production information. In this level, the models are not yet shared among all the team members;
- Level 2 - In this case, all the members involved use their own 3D CAD models, but they are not necessarily working on a single shared model. The collaboration just consists in the exchanging of the information between the different members using a common

file format that allows any organization to combine the used data with them, making the BIM model “federated”. In fact, this level consists in a 3D environment with attached data created by models of different disciplines and even if they are assembled in a unique federated model, they don’t lose their identity. The data can also include information about the scheduling program (4d) and the costs (5d);

- Level 3 - The latter level represents the level in which a full and complete cooperation between all the disciplines is gained and where unique shared design model is used. It is important to highlight that this model must by in accord to the IFC standards. The 3rd level manages the information about the lifecycle project (6d), and the model represent the unique model in use by all the team members aimed to a complete control of the whole building.

The Level 3 introduces the fundamental concept of interoperability, i.e. the ability of a system to exchange data and information with other systems or programs, which means that can "dialogue" between software with a high reliability, reducing errors and maximizing resources. The concept is expressed in the "Patrick MacLeamy Curve", expressed during the AIA Conference and shown in Figure 23.

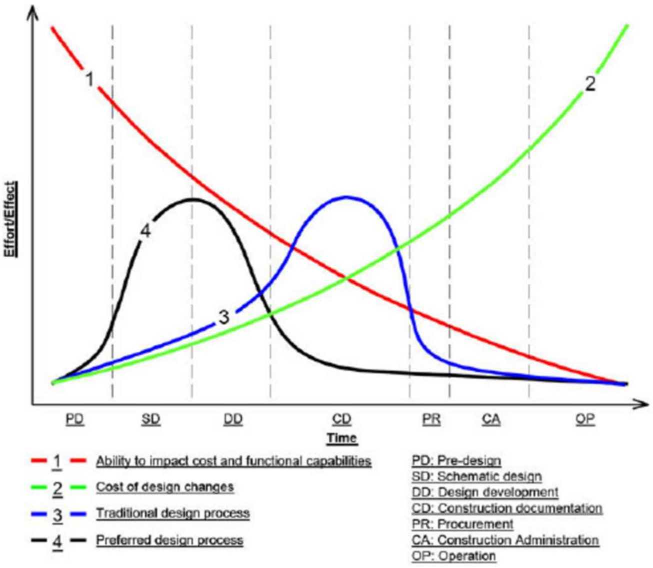


Figure 23. The MacLeamy Curve

The graph shows the bell curve of the traditional design process with the peak of efforts and resources at the construction phase centre and shows how the BIM moves this peak at the end of the preliminary design phase. It also shows that the design changing is easier and less expensive in the early phase of the process. Therefore, the interoperability is the essential requirement for many projects and to let the BIM used as a methodology and not just as a simplified Building Information Model. The possibility of exchange the Information in a clear way and using technical standards is required by the ordinary use of different software, and the user need to be sure that no information could be lost or manipulated or damaged. The Association BuilgingSmart developed the program OpenBIM, which represents a collaborative approach from the design phase to the building exercise and it is based on standard and open workflows.

The standard used in Open BIM is the yet mentioned IFC, which is an open source and free format registered From ISO and follows the requirements ISO 16739:2016. The main characteristics of this standard are the small size of the file, the same 3D content of the original file and the ability to transmit to other BIM platforms the additional information about the inserted objects without needing any further operation.

2.2.4. The Level of Development LOD

The acronym LOD is sometimes interpreted as Level of Detail rather than Level of Development. The Level of Detail is a measure of the amount of information provided and due to this, it is just a quantitative measure. Instead, the Level of Development is the degree to which the element’s geometry and attached information has been thought and it express a qualitative indication, the level which the team members may rely on the information when they are using the model. The LOD Specification utilizes the basic LOD definitions developed by the AIA for the AIA G202-2013 Building Information Modeling Protocol Form and it defines and illustrates characteristics of model elements of different building systems at different Levels of Development.

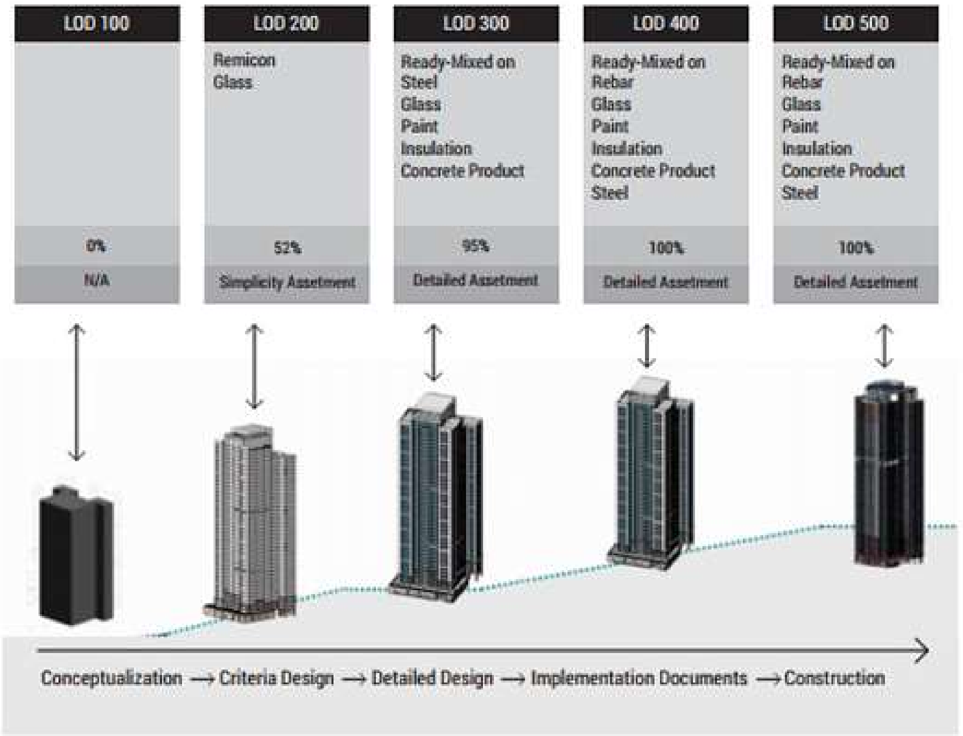


Figure 24. The Level of Development LoD

As shown in Figure 24, the different LOD are classified in:

- LOD 100: The Model Element may be graphically represented in the Model with a symbol or other generic representation but does not satisfy the requirements for LOD 200. Information related to the Model Element (i.e. cost per square foot, tonnage of HVAC, etc.) can be derived from other Model Elements;
- LOD 200: The Model Element is graphically represented within the Model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element;
- LOD 300: The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element;
- LOD 350: The Model Element is graphically represented within the Model as a specific system, object, or assembly in terms of quantity,

size, orientation, and interfaces with other building systems. Non-graphic information may also be attached to the Model Element;

- LOD 400: The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information. Non-graphic information may also be attached to the Model Element;
- LOD 500: The Model Element is a field verified representation (i.e., as built) in terms of size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the Model Elements.

2.2.5. Interoperability

As seen, the Building Information Model represents the core for the integration and the exchange, in a unified way, of the information among the project stakeholders to a project using a digital 3D model as a platform on which convey this intent. It is remarkable the fact that all the different software and platform store information in their native formats. In order to make the information available to project stakeholders, there is the need to obtain an easy and accurate data exchange.

Interoperability represents the ability of different systems and organizations to work together (interoperate) and is a fundamental requirement in the BIM approach. There are different methodologies and systems to led to an effective exchange of data between the software applications, such as the exchange file formats developed by individual proprietary software i.e. DXF (Data eXchange Format), standards and open-specification data models like gbXML (an eXtensible Markup Language scheme developed by Green Building Studio), IFC (Industry Foundation Classes), Web Services, deployed for distributed databases ICT (Information and Communication Technology), project model servers, and semantic Web applications.

These data exchange formats have developed over the years, as shown below in Table 1:

EXCHANGE DATA MODELS IN A BIM FLOW	
First generation	• STEP (ISO, 1992) • COMBINE (Augenbroe, 1992) • ICADS (Pohi and Reps, 1988) • ARMILLA (Gauchel et al., 1992) • IBOM (Sanvido, 1992) Mainly exchange of geometries and mathematics.
Second generation	• Hierarchical models (Bedell and Kohler, 1993) • KNODES (Rutherford, 1993) Information dedicated to the energy/thermal exchange, Heating Ventilation and Air Conditioning (HVAC) simulation, lighting design, building life-cycle analysis and building plan checking.
Third generation	• Industry Foundation Classes (IFC, 2006) • Green Building XML (gbXML, 2007) Complete information about the whole building, semantically organized according to precise schemes

Table 1. Exchange data models in a BIM flow

Industry Foundation Class (IFC)

Industry Foundation Class (IFC) is a neutral and open specification for object-based data models developed by buildingSMART to facilitate interoperability in the building industry. Version 2x3 is in common use for exchange of BIM information by many BIM applications. Version 4 was released for implementation in 2013 (2016 Version 4 Add2).

Figure 25. The IFC logo

It is a neutral format of exchange, not controlled by a single vendor and it is represented by an object-based plain text file format, currently in the process of becoming the official International Standard ISO 16739;

As shown in Figure 26, the IFC is a based entity-relationship model consisting of several hundred entities organized into an object-based inheritance hierarchy:

The highest level is represented by the domain layer, which contains entity definitions for concepts specific to individual domains such as architecture, structural engineering, facilities management and so on.

The shared layer comprises entity categories that are commonly used and shared between multiple building construction and facilities management applications (i.e. shared building elements scheme has entity definition for a beam, column, wall, door, etc).

The core layer consists in the basic structure, the fundamental relationships and the common concepts, which are necessary for the subsequent specific definitions of the different disciplines. In particular, the two extension schemes define process and control related concepts, such as task, procedure, work schedule, performance history, work approval. The product extension defines abstract building components, such as space, site, building, building element, annotation. The kernel defines the core concepts, such as actor, group, process, product and relationship.

The resource layer represents the basic properties, which cannot exist independently and requires the existing in relationship to other elements, such as geometry, material, quantity, measurement, data and time, costs, actors, roles and so on.

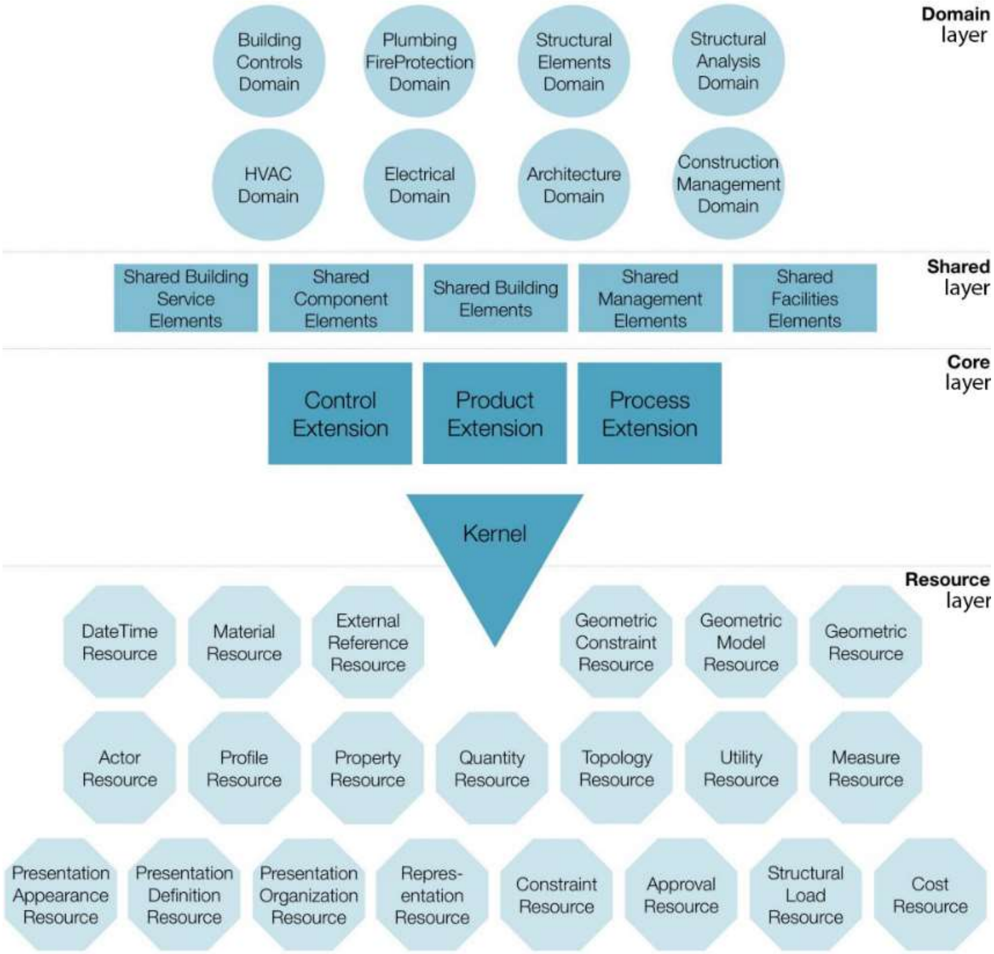


Figure 26. IFC schematic organization (BuildingSMART)

All the objects are called entities and located in a common base, the IfcRoot, which contains the information about who generated the entities, the related information and the story of the entities itself. Successively, all the entities are composed by three categories: firstly, the objects (IfcObject); secondly, the properties (IfcProperty); al last the relationship between the objects (IfcRelationship)

Green Building XML (gbXML)

Green Building XML (gbXML) is an XML schema developed by Green Building Studio, Inc. with the support of the California Energy

Commission Public Interest Energy Research (PIER) Program, and the California Utilities (Pacific Gas and Electric Company, Southern California EDISON and Sempra Energy Utility)to facilitate the transfer of building information stored in CAD building information models, enabling integrated interoperability between building design models and a wide variety of energy analysis tools. The current release is the Release 6.01 on 2015.

Figure 27. The gbXML logo

It mainly consists in an XML non-proprietary exchange format based, persistent, and verifiable file format for the storage and transmission of text and data. gbXML is written in the computing language XML and is written in accordance with rules specified in the latest gbXML Schema Definition (XSD). This is a definition document that specifies all the mandatory and optional XML elements that can be contained, within a gbXML file, to describe a building.

This language allows the exchanging data about the geometry and the information regarding thermal ad emission aspects, fire properties, energy efficiency, HVAC, water use, lighting and controls, ventilation requirements and everything else regarding the Life Cycle Analysis (LCA) until demolition and the disposal of rubble. In Figure 28 an example of a gbXML structure.

- gbXML
  - Campus
    - Location
      - Name
      - Latitude
      - Longitude
    - Building
      - Area
      - BuildingStorey
      - Space
        - Name
        - Area
        - Volume
        - PlanarGeometry
        - ShellGeometry
        - CADObjectID
        - SpaceBoundary
    - Surface
      - Name
      - AdjacentSpaceID
      - RectanguarGeometry
        - Opening
      - PlanarGeometry
        - Opening
      - CADBjectID
  - DocumentHistory

```
<gbXML>
   <Campus>
      <Surface id="su1" surfaceType="ExteriorWall">
         <AdjacentSpaceId spaceIdRef="sp1" />
            <RectangularGeometry>
            <Azimuth>0</Azimuth>
               <CartesianPoint>
                     <Coordinate>2224</Coordinate>
                     <Coordinate>1529.75</Coordinate>
                     <Coordinate>4</Coordinate>
               </CartesianPoint> <Tilt>90</Tilt>
            <Height>96</Height>
            <Width>42.81</Width>
            </RectangularGeometry>
         <PlanarGeometry>
         <PolyLoop>
               <CartesianPoint>
                     <Coordinate>2224</Coordinate>
                     <Coordinate>1529.75</Coordinate>
                     <Coordinate>4</Coordinate>
               </CartesianPoint>
         </PolyLoop>
         </PlanarGeometry>
         </Surface>
      </Campus>
</gbXML>
```

Figure 28. On the left: a generic gbXML example; on the right: how gbXML represent a simple wall

2.2.6. HBIM

As mentioned, BIM is getting more and more influence in the AEC sector to collect and integrate each other several kinds of information. Therefore, it’s easy to understand the power of this approach to generate a shared knowledge system able to involve at the same time all the technical figures involved during the whole lifecycle of the building. In fact, BIM is a digital representation of a building, which includes a shared database of all the aspects and information concerning a building, such as the geometrical and material issues, the time scheduling, the maintenance and so on until the demolition phase.

If these aspects can be easily applied for new buildings, an open challenge concerns the application of this approach to the existing ones.

This challenge is also harder when we talk about Cultural Heritage and historical buildings. In fact, these objects were often manipulated during the centuries, with demolitions, reconstructions and collected, layer after layer, dissimilar styles. Furthermore, also their maintenance status and deformation are to be considered and managed.

The conservation of ancient buildings, mainly due to their high relevant heritage evidence, is frequently a critical point in the Italian context. In fact, recent events, such as the earthquake involving the centre of Italy, made clear the need of a capillary knowledge system for the management of these aspects and for an efficient development of the restoration and conservation activities (Oreni et al., 2014). The international scientific community introduced the concept of HBIM (Historical Building Information Modeling). Originally, the term HBIM was used as "a novel prototype library of parametric objects, based on historic architectural data, in addition to a mapping system for plotting the library objects onto laser scan survey data" (Murphy et al., 2013).

The terms HBIM indicates a technical process of geometric modelling and information management. The existing buildings could be accurately surveyed using a TLS and the resulting point cloud is compared to the objects stored in a software library until the similarity is satisfactory. This process aims to abstract the geometries to obtain models to associate data for documentation or for numerical simulations. Therefore, the terms HBIM does not mean to apply the BIM to an existing building but to apply a method to get a simplified model of it from the surveyed data.

It clearly emerges the need to have some geometrical and radiometric data to support the modelling phase of the process, and some modern Geomatic techniques can offer a solid support for this purpose. Terrestrial Laser Scanner and multi-view Structure from Motion techniques can for example generate high-fidelity point clouds, which represent the monument inspected (Remondino, 2011; Chiabrando et al., 2016). The modern Geomatic techniques can represent the first step to obtain the right 3D abstraction of the reality and a solid support to develop a BIM model (Dore & Murphy, 2012).

These data represent the start of a subsequent modelling phase of the both geometrical and semantical information, which they will generate the final model. The process is in opposite with the traditional flowchart of the development of a BIM for a new building and it can be shown in the flowchart proposed by (Bruno, 2018) that easily shows the succession of the steps:

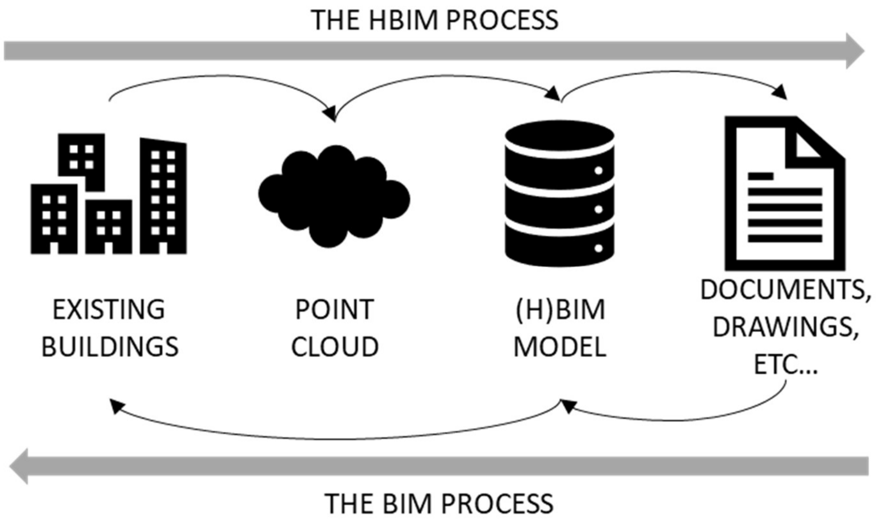


Figure 29. The Comparison between the BIM process for new buildings and for existing ones

Nowadays, there are different consolidated techniques available in each of these fields, but in order to analyse historical assets, not all the methodologies are suitable. Particularly, there are several issues to be considered, such as the accuracy and reliability of the survey, the fidelity of the model to the reality, the time and historical data management and so on.

To correctly document an historical building, a preliminary phase of study in which building characteristics are analysed and in which the BIM final purposes are set up, is crucial. The geometrical survey and the historical and archival researches must be carried out to gain the basic knowledge of the building past and to lacking some incomplete and information deriving from just one of them. For this reason, the building is always document of itself and can be deeply known through accurate spatial, geometrical, material and structural analyses.

2. Case Studies

In the field of Cultural Heritage, the knowledge system and the management tools represent crucial aspects for their valorisation, preservation and maintenance for the future. The case studies shown in the following paragraphs focus the attention on these aspects at different level and scale. The common aspects of these three works are represented by the extremely high level of detail of the data acquired by the geomatic techniques and the multidisciplinary collaboration of different experts involved for their specific aspects. In particular:

Paragraph 3.1 will show the case study of the Fountain of Neptune, located in Bologna, Italy. This work was mainly focused to the whole restoration of the monument and the management of the hydraulic system. One of the key elements of this work was the creation of an information system developed ad hoc to permit, in an innovative, efficient and user-friendly way, the collection, sharing, management and analysis of all the information and data related to diagnostics and restoration actions. The core of the information system is a very detailed 3D model of the monument, realized by using the integration of the most modern geomatic techniques to obtain a textured 3D model characterized by a sub-millimetre precision level in the geometric description and a high perceptive fidelity of colour reproduction (Girelli et al, 2019).

Paragraph 3.2 will show the case study of the San Michele in Acerboli's church, located in Santarcangelo di Romagna, Italy. This church, dated about the 6th century A.D., represents a high relevant Romanic building of the high Medieval period. The building presents an irregular square plan with a different length of the lateral brick walls and a consequential oblique one in correspondence of the apse. Nevertheless, the different lengths of the lateral brick walls are balanced thanks to the irregular spaces between the windows. Different changes occurred during the centuries, such as the closing of the seven main doors and the building of the bell tower, in the 11th century A.D., which is nowadays the main entrance of the church. Moreover, an integrated survey was realized, covering the exterior and the interior. The final 3D model represents a valid support not only for documentation, but also to maintain and manage in an integrate approach the available knowledge of this Cultural Heritage site, developing a HBIM system in which all the mentioned historical, geometrical, material matters are collected.

Paragraph 3.3 will show the case of the Domus of Obellio Firmo, located in Pompeii, Italy. This work shows the very first results of a multidisciplinary activity, particularly focused on one side to the management of different multiscale 3D models and to the other side to the specific characteristics required for an HBIM in order to be a support for the archaeological fields. This work is still in progress, as it is a long-term collaboration between the various stakeholders and its development exceeds the time of the PhD course.

3.1. The Fountain of Neptune

The Fountain of Neptune is one of the most emblematic monuments of Bologna. The manufacture was directly committed by the deputy papal legate, Bishop Pier Donato Cesi, as an expression of the munificence of Pope Pius IV towards the city. The project and the realization of the fountain were assigned to the collaboration of the architect and painter Tommaso Laureti from Palermo and to the Flemish sculptor Jean de Boulogne of Douai called Giambologna, which between 1563 and 1567 realized one of the most spectacular examples of existing renaissance fountains.

Figure 30. The Fountain of Neptune in Bologna

The concept of the fountain was a symmetrical structure, in which several bronze sculptural groups (dolphins, sirens, lion heads, shells, heraldic coats of arms, cherts and winds) adorn a castle made of Istrian stone and at its top the statue of the god of the waters, Neptune. It is an extraordinary complex for the dimensions (only the statue of Neptune is 3.35 meters high), for quality of details, for engineering aspects, hydraulic systems and solutions to guarantee the perfect operation. Anyway, the high level of degrade of the mountain required an intense and complete restoration activity.

Figure 31. The high level of degrade of the monument

The restoration project of such a great monument required an innovative approach, in which a 3D digital model represented the core for an information system useful for the management and sharing of the different kind of data collected and elaborated by the different specialist involved in this activity. This approach gives the possibility to map, document and store every single information and activity conducted on the manufacture and to easily refer and recover them by a direct link to its position in the digital space of the model. Therefore, a 3D model of a such uncommon precision, especially for an object of this size, is a solid support for a great amount of activities such as documentation purposes, restoration support and so on.

The goal was the achieving of a 3D surface, the so-called mesh, characterized by an average length of the triangles around 0.5 mm. The model was also associated with the actual colour of the real physical surface and georeferenced according to the official cartography of the Bologna municipality. Considering the size and complexity of the object and the extremely stringent requirements about the geometric accuracy, the radiometric fidelity as well as the morphological and material characteristics of the different parts, it has been chosen to adopt different techniques integrated each other: a Tof laser scanner, structured light scanners, digital photogrammetry. The choices related to the instruments and operative modalities were also influenced by the need to work with very small deadlines and in a complex logistical context.

3.1.1. Acquisition report

A first survey, concerning the fountain, its underground and the square, was performed before the effective restoration project using the ToF laser scanner Riegl VZ400. This survey generated a point cloud of the whole mentioned part of the manufacture with about few millimeters' precision and enriching also the point cloud with the radiometric information. The point cloud counts about 140 million of points, characterized by an average spacing of 5 mm.

Firstly, the survey of the tunnels underground, in which the technological part of the fountain is located until the sixteenth century, represented the most critical part, both for the reduced spaces that required a remarkable number of scan-station (15), both for the difficulty alignment of this scans with the local reference system of the ground part. The only link between these two parts, the underground and the ground ones, is represented by a small manhole just in front of the fountain. For this problem, a specific topographical approach has been designed: the definition of a local reference system and its subsequent insert into the official municipal cartographic system by using a high precise total station to accurately define the verticality of the survey and for the next alignment of all the different scans. The final 3D model of this first survey was essential for the second part of the activity: it was the base on which georeferencing the next high precise survey and the support for the different analysis carried out by the University of Bologna, such as the structural and the hydraulically ones.

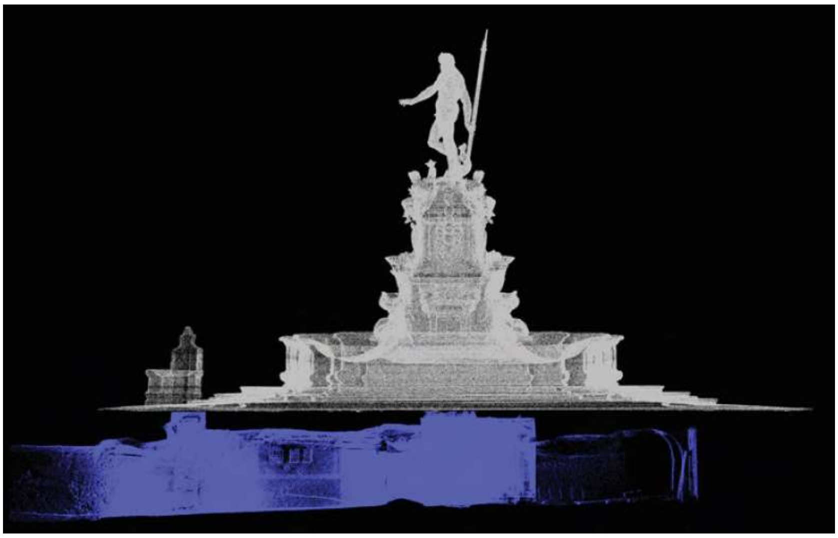


Figure 32. the point cloud resulting from the first survey activities

The second survey, aimed to the generation of the yet mentioned 3D model of the fountain with a very high geometrical precision and a very high radiometric fidelity, was conducted during the months of January ed April 2016. This activity required a virtual breakdown of the object into portions and defined by its morphological features and materials, according to the Istituto Superiore per la Conservazione e il Restauro (ISCR).

It was necessary to treat the stair, the basement, the inside of the tank, the castle and the Neptune adopting different approaches and working for single parts. This choice was also linked to technical reasons concerning the management of the great amount of the digital data acquired during this phase and concerning the problems related to the different material and superficial characteristics. Nevertheless, the atmospheric conditions conditioned the activity, limiting the useful working of work because the of the need to operate with dry surfaces for a better result (Girelli et al., 2019).

The survey of the stairs required a photogrammetric approach, using for the acquisition a camera DSLR Full frame Canon 6D and for the elaboration of data the modern Structure from Motion approach, originally developed in the Computer Vision environment. This solution allows the generation of an accurate 3D digital model starting from photographs, also convergent, acquired from different points of view and with a good overlap. The large number of images was also radiometrically corrected using a 24 elements Color-Checker acquired for every day, in every atmospherically condition and in the different working hours, to consider the light changing even in the same day.

The steps started from a first phase of alignment and generation of a 3D sparse point cloud, then densified and converted into a surface (Mesh) also Textured With the calibrated colours. The models have been scaled due to redundant and precise distances, directly measured on the stairs. The single 3D portions had merged each other, following a shared scheme of agreed elements, to supply the Consiglio Nazionale delle Ricerche - Istituto di Scienza e Tecnologie dell'Informazione (CNR-ISTI) to assembly the information system. It’s remarkable how some aspects, such as the high level of detail required, the morphology of the object, required a large photographic set (about 1500 images) with a small field of view. All these matters represented critical aspects for algorithm adopted by the software in use. Further problems were due by the direct sunlight reflected by the shiny surfaces of the steps (these led to choose the working days when the object was predominantly in shade), water and objects on the surfaces. These difficulties required a careful elaboration process and the necessity to control the semi-automatic procedure and to operate an appropriate masking of the images. Also, a manual insertion of numerous Tie Point was necessary. Finally, the final Mesh also required an appropriate manual editing to correct the residual anomalies.

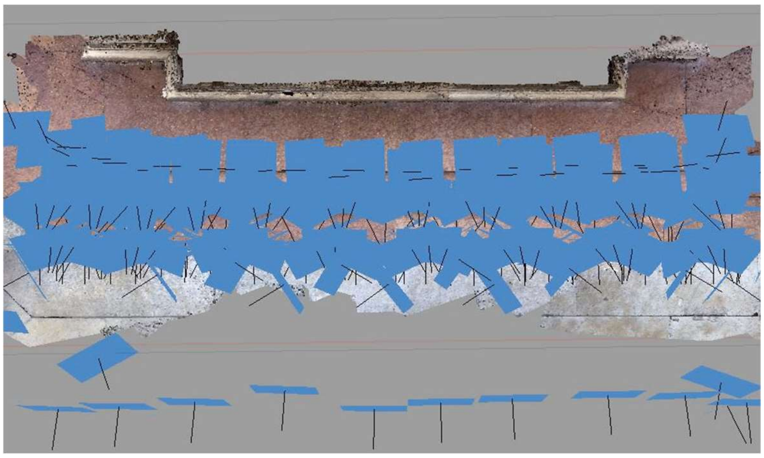


Figure 33. the photogrammetric acquisition for a part of the stairs

For the basement, the castle and the bronze sculpture of Neptune, the survey was conducted by using a structured light 3D scanner. The two instruments adopted (both produced by Artec) have an intrinsic precision of a tenth of a millimeter in the coordinates of the points and this also allows the direct generation of a mesh enriched with the radiometric information. All of these meshes were processed to delete some outliers and fill the small holes before proceeding to the aligning phase, the merging in a single model and the final texturing. As mentioned, every single mesh was referenced on the 3D model obtained by the first survey. Among the problems encountered, it is important to mention the huge amount of data (as an example, the only south side of the basement is about 8 Gb), which required parallel processing and Hardware and Software resources.

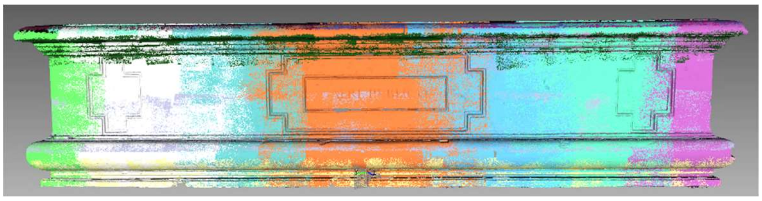


Figure 34. The resulting 3D model of the basement acquired with a light-structured scanner (the colours refer to different datasets)

Figure 35. A close view of the digital model. On the left the mesh in false colour; on the right the texturized one.

The complete and final simplified model, assembled by CNR-ISTI, consists in a mesh of more than 600 million of triangles, representing an incredible goal.

Figure 36. the final 3D model georeferenced using the model of the first survey

3.1.2. The application development and the data management

The application, representing a sort of information system, was developed for this specific case, involving its different potential users yet in the design phase. The goal was the creation of a user-friendly tool aimed to manage two different issues: firstly, managing the documentation process as an analytical process of studying and producing a considerable amount of different data (texts, images, photographs, diagnostic results, graphs, etc.); secondly, managing the restoration as a complex process based on the interaction of different professions (chemists, physicists, biologists, hydraulic engineers, structural experts, Geomatic, restorers, historians of art and architecture, informatics, documentarians, economists and so on)

There are many previous experiences of digital documentation of the restoration process, which used canonical databases, 2d GIS systems (such as SICAR, widely used in the activities coordinated by the Ministero per i Beni e le Attività Culturali MiBACT) or 2d computerized design systems (such as the AutoCAD system, recently used by the ISCR aimed to mapping the state of conservation of the Colosseum in Rome). An innovative approach was the using of the 3D model as an operative tool able to be modified and constantly enriched of new information. This tool consists in vast and ordinate database of spatial information and properties of the 3D model allow both the visual representation of the characteristics of the shape and the collector of information, allowing the integration of the different data into a simple visual form. The 3D model, by an easy and intuitive interface, let the linking of the information to its real context and the semantical integration of the 3D objects with heterogeneous data aimed to specific scopes.

In this case, the use of these 3D methodologies of referencing and access to data represented a great opportunity to redesign the functionalities and the architecture of the documentation system. A goal was the design of an easy interface able to be directly used by the operators of the restoration for a direct access to the system, to the storage functions and to the data analysis, without the intermediary of an expert operator. The main goal is the usage of this digital platform as a unified reference of information not only for today's conservation project but also for the entire lifecycle of the manufacture, including the knowledge system, fruition, communication and management. To meet this requirement, the digital platform has been designed by the ISTI-CNR as an easy tool usable in a web browser, to permit a cooperatively usage directly on site and at a distance, using normal laptops and even limited Internet connections.

Firstly, it was necessary to consider an appropriate virtual division of the global model to provide also access for levels and components (Figure 37): a hypogeal part (i.e. the underground service spaces, not shown in Figure 38) and six levels above ground where the monument was divided. The latter are: the basement stairs (L0); the basement (L1), divided into four portions according to their main orientation, the lower part of the Castellum (L2) with its basins and bronzes; the medium part of the Castellum (L3), the upper part of the castellum (L4), and finally the statue of the Neptune (L5).

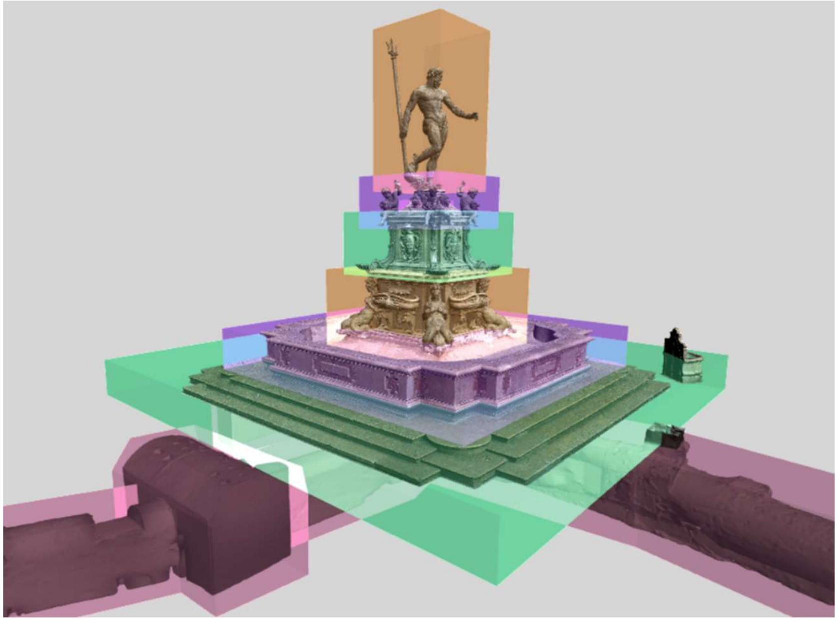


Figure 37. The final 3D model and the digital division of the model

Figure 38. The divided part of the model. From left to right: the underground, L0, L1, L2, L3, L4 and L5 parts

This logical subdivision has an obviously impact on the organization of the 3D data: alongside the overall complete model, all the single mentioned levels and individual components have been made independent. This allows the user to decide to work only on one level or on one of its components, and the system loads the corresponding 3D sub-model (reducing the time of data transmission and optimizing the performance in view).

The information system was created as a web application, using HTML5 for the creation of the graphical interface and the WEBGL library for the management and visualization of 3D data. The system interface provides a prevailing access through navigation of 3D models, both in data entry and navigation and inspection. For this reason, it is vitally important that the system guarantees the download times of 3D models and visualization suitable for a context of interactive use and on medium-range machines. To this end, all 3D models have been converted into Nexus multiresolution format developed by ISTI-CNR. The information system uses several basic technologies (3D data streaming, view-dependent visualization, 3D data compression) that are part of the open-source web visualization platform 3Dhop, always developed by ISTI-CNR.

Therefore, the information system has been designed, organized and implemented with the aims of:

- Guaranteeing a digital archiving of the types of data relating to the monument, from the previous restoration actions to the current ones;
- Allowing a 3D navigation of the model, both to remotely analyse to have access to the indexed data;

- Providing some easy tools to create links between the different elements of the documentation (texts, PDF documents, scientific analysis reports, images, graphs, drawings) and the part of the object which they refer to guarantee their easy search and visualization, and their insertion into the database must be as transparent as possible to the operator;
- Supporting the drawn of technical issues directly on model (points, polylines or regions and associated metadata).

The management of all these aspects in a collaborative multiuser way has been ensured by an access management system that provides differentiated accounts (read-only or modification/data entry).

3.1.3. Results and feedback from the usage of the tool

One of the main characteristics of this tool is the integration of the documentation capabilities required by all the specialists and operators involved in the restoration process. The usage showed a high level of user satisfaction by the possibilities to directly work on the 3D space, uploading and viewing content and information also in the pipeline, with different types of devices and different level of connectivity (Apollonio et al., 2017). The usage of the tool highlighted:

- The possibility to interactively visualize certain areas, such as those impossible to see in a normal frontal view proposed by a simple photo;
- The georeferenced mapping, which has been extremely useful for a precise recording, allows to define certain and for the possibility to directly link it to the result of the diagnostic investigation);
- The management of the decomposition into elements, which facilitates the mapping phase and allowed a quick placement in the whole and close context.

Figure 39. The degradation map directly performed on the statue of Neptune

Figure 40. The degradation map directly performed on the basement

A second category of features, identified as distinctive, involved data integration:

- multiple functionalities and heterogeneous documental materials connected in a single box (textual, photo and graphic documentation);
- the possibility of visualizing the graphical mappings together with any notes and photo;
- the facility of data acquisition and archiving and their direct and simple correlation.

In addition, most users showed no difficulty in the process of consulting and searching information and in the data entry; for both the phases, the end users highlighted the easy way of use the graphical interface.

3.1.4. Discussion

The information system created for the restoration project of the Fountain of Neptune in Bologna is characterized by a massive 3D approach, which was possible by the consolidation of the Geomatic techniques for Cultural Heritage, the efficient management of the high-resolution models and finally the technologies for the 3D graphics on web. It is the first case of a restoration of a such complexity (and its great amount of data) managed in real time on a web-based 3D system. This approach, thanks to the digital and informatic development, could be extended for other cases, becoming a widely used process in the field of restoration for documentation of great restoration projects and for smaller interventions, being relevant to preserve along the time the information and the knowledge acquired.

3.2. The San Michele in Acerboli's Church

This chapter shows the case study of the San Michele in Acerboli's church, located in Santarcangelo di Romagna (RN), Italy. This Church, dated about the 6th century A.D., represents a high relevant Romanic building of the high Medieval period. The building presents an irregular square plan with a different length of the lateral brick walls and a consequential oblique one in correspondence of the apse. Nevertheless, the different lengths of the lateral brick walls are balanced thanks to the irregular spaces between the windows. Different changes occurred during the centuries, such as the closing of the seven main doors and the building of the bell tower, in the 11th century A.D., which is nowadays the main entrance of the Church.

Figure 41. The church of San Michele in Acerboli

An integrated survey was realized, covering the exterior and the interior. The final 3D model represents a valid support not only for documentation, but also to maintain and manage in an integrate approach the available knowledge of this Cultural Heritage site, developing a HBIM system in which all the mentioned historical, geometrical, material matters are collected. In fact, the HBIM is a sort of shared information-collector, where the different aspects concerning an historical building could be stored.

The work presents the main problems and the procedure followed and developed to achieve and manage the final product, that could certainly be a valid support for the future maintenance and restoration activity of the Church.

3.2.1. Acquisition report

The survey of the whole church was conducted with an integrated approach, in which a classical topographic survey with a Total Station has supported modern Geomatic techniques, such as the Terrestrial Laser Scanner (TLS) and the multi-view Structure from Motion (SfM).

Firstly, through a survey by total station, performed with a Leica TS30, the 3D coordinates of some artificial targets, placed externally and internally the church, were calculated. This choice permitted the establishment of a unique local reference system for the whole building model, with Z axis along the vertical. Furthermore, it allowed an easy and robust subsequent registration of all the point clouds, generated by TLS and SfM.

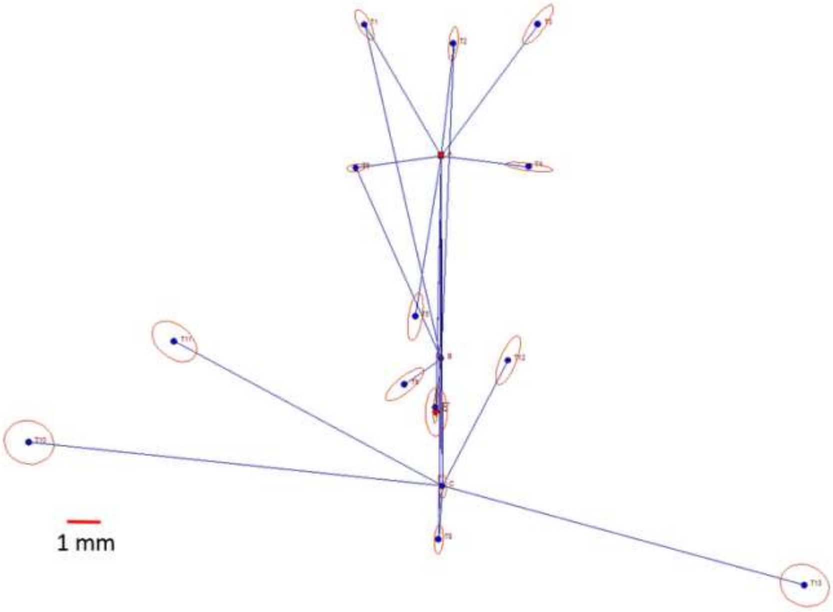


Figure 42. The result of the adjustment of the total station survey (95% probability ellipses): the network was established considering the logistical constraints and the need of a quick survey

The RIEGL VZ400 instrument, equipped with the calibrated digital camera Nikon D90 for the RGB information, performed the TLS survey of the external and internal portions of the church. To cover the whole monument, 51 point-clouds were acquired from 12 scan positions for the exterior and 12 for the interior of the church, distributed as shown in Figure 43. From some points of view, it was necessary to tilt the instrumental axis at various inclinations, to survey the highest parts of the building as ceiling and vaults.

All the scans were aligned by using the high reflectance targets acquired with the total station survey, obtaining a unique point cloud characterized by 3-4 mm density.

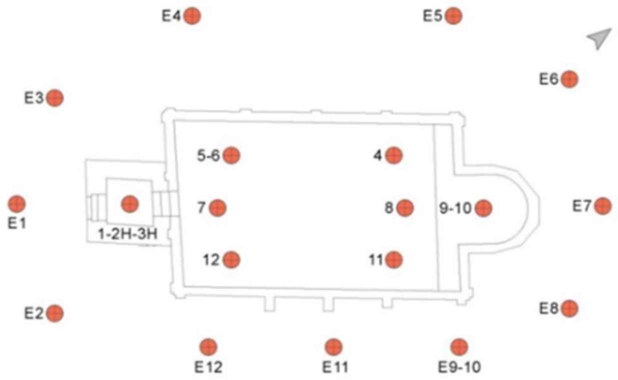


Figure 43. The TLS acquisition scheme; red dots indicate the scan positions

Figure 44. The laser scanner with horizontal inclination of the instrumental axis in the church entrance hall

The SfM survey, useful to reconstruct the roof of the church, has been conducted by using a DSLR full-frame camera Canon EOS 6D, and an extendable telescopic tripod, able to grow up till to 13 metres (Figure 45). A considerable number of images (209), variously oriented, were acquired to obtain a complete model of the roof.

The photogrammetric reconstruction process was conducted with the commercial software Photoscan, from Agisoft. The same targets used during the total station and TLS surveys were adopted to georeference the final 3D model.

Figure 45. The photogrammetric survey of the church roof: a) and b) equipment used for the images acquisition, c) reconstruction of exterior orientation after the image alignment phase in the SfM processing

The two models obtained with the TLS and SfM surveys have been aligned and merged in a commercial software for the processing of 3D data; the integration of the techniques permitted to fill the lacks present in the single products.

The result of all the surveys is a complete, high dense and accurate point cloud representing the church's geometry. The final model counts about 87 million of points for the exterior and 80 million of points for the interior. Overall, the spacing between points is varying between 2 and 4 millimetres.

Figure 46. Different views of the final point cloud of the exterior of the church

Due to some problems with the light conditions inside the building, it was decided to artificially colour the internal point cloud with a grey scale, by using the Portion de Ciel Visible (PCV) plugin in the CloudCompare software. This plugin calculates the illumination of a point cloud as if the light was coming from a theoretical hemisphere or sphere around the object, allowing to emphasize the geometrical discontinuities (Figure 47).

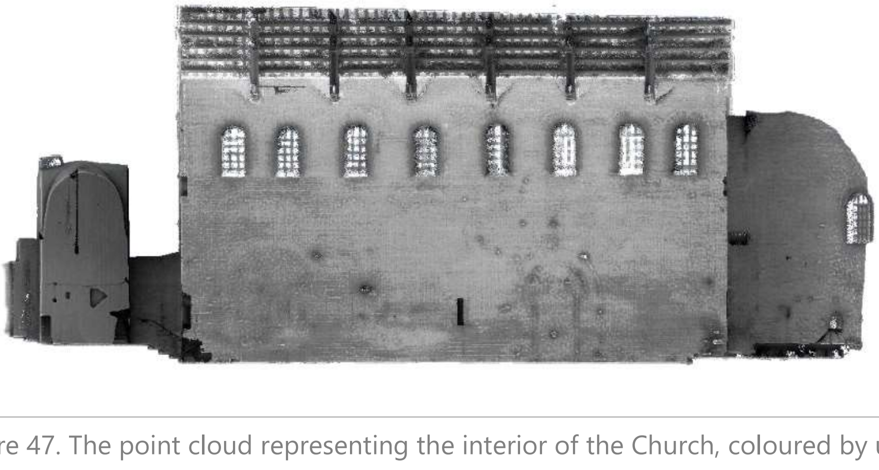


Figure 47. The point cloud representing the interior of the Church, coloured by using the PCV algorithm

The 3D point cloud, accurately reproducing the building geometry, permits to analyse it in every detail and characteristic, also noting the irregularities. In the case study, the model highlights an irregular plan with a non-perpendicular angle between the walls and a great deformation occurred at the East façade. The last was used to evaluate the reliability of the HBIM model.

3.2.2. From the point cloud to an HBIM model

The complete point cloud representing the San Michele in Acerboli's church was finally used for a first development of a HBIM model, where all the relevant information connected to the building (historical, materials, constructive techniques, etc.) could be stored and georeferenced. The commercial software Autodesk Revit 2017 was adopted for this purpose.

The final goal was the efficiency evaluation of the tools directly offered by the software to develop an HBIM of such an irregular brick wall monument, and to compare it with the point clouds acquired. It is important to notice how the modelling of this kind of buildings presents many difficulties, mainly concerning the great vertical and horizontal irregularities involving the structure.

In fact, a BIM developed in a preliminary design phase does not need to consider these aspects and these irregularities. It is possible to represent its portions with some approximate and idealized entities, such as regular walls, roofs, plants and so on. Anyway, these considerations are not applicable in a modeling phase concerning an existing building as irregular as the San Michele's church. Therefore, the challenge was to achieve a satisfying geometrical representation of this church, focusing its evaluation on the east façade, which presents a great deviation from the ideal vertical plan.

As known, there are many commercial and few free plug-ins (Garagnani & Manfredini, 2013) able to work with the point cloud in Revit and to extract features. In this case, we tried to develop an accurate and a high-fidelity model by using the tools offered by the software only and in the fewest possible steps (Quattrini, 2015). To do so, we firstly needed to reduce the point cloud to easily manage the great amount of data. We decided to decimate the complete point cloud adopting 1 cm as spacing between the points. This reduced point cloud was successively imported in the software Autodesk Recap and converted in the .rcp format for the importing in Revit.

Finally, the modeling phase in Revit started, mainly using the mass modeling tool to generate the masses able to represent the geometry of the building with all its irregularities. The use of this tool, normally adopted during a preliminary and conceptual design phase, is a fast way to draw the volumes representing the church, on which directly apply all the families.

This procedure was conducted in the mass modeling environment inside Revit. In this environment, we directly and manually drew on the point cloud the main reference lines able to correctly represent the church. Focusing on the nave, in Figure 48 is shown the mass representing this part of the church.

Figure 48. The mass of the nave

Starting from this mass, the transition between the generical mass trough the building model was possible converting its faces into the components, the so-called Revit families, such as the walls, the floors and the roofs. This step was performed using both the parametric elements already in the Revit internal library and some external families imported into the model. Moreover, the most complex elements, such as the pilasters and the buttresses, were directly modelled in place by using the B-Rep operations, such as extrusion and so on, to obtain a high-fidelity geometrical representation.

It is also important to notice and highlight how, in a genuine BIM approach, the volumes and the floor areas of the masses are also able to be automatically extracted, put into abacuses and immediately updated after every model modification.

Figure 49. The East façade of the Church

Finally, the result was the entire HBIM, developed in the Revit environment, of the whole church. As said, this model takes in account all the irregularities involving the structure.

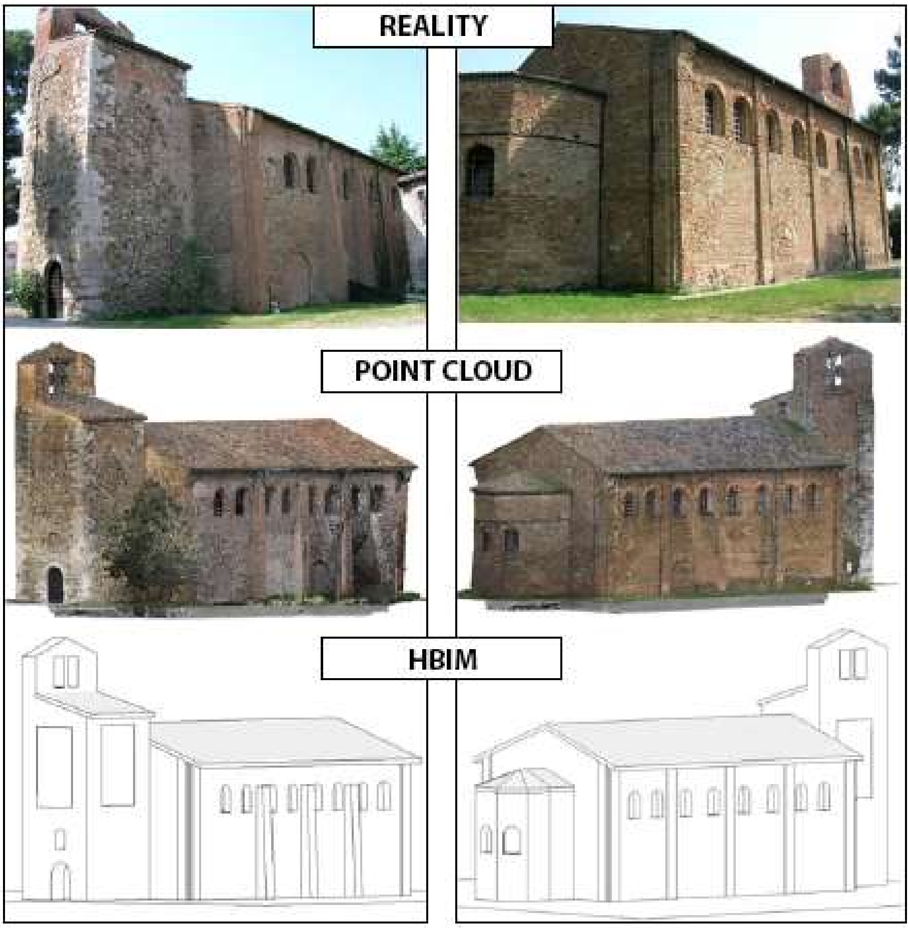


Figure 50. The distinct phases: from the reality to an HBIM, through a point cloud resulting from the 3D integrated survey

3.2.3. Results and evaluation

The evaluation of the model was mainly conducted on the most not-vertical façade of the building, the eastern one (Figure 51). For this portion were compared the point cloud, considered like a reference, and the HBIM model. Furthermore, a second comparison was realized between the same point cloud and a simplified HBIM, which did not consider the irregularities of the structure and presents simple vertical walls.

This part was conducted using the mentioned CloudCompare open source software, exporting the mesh of HBIM façades from Revit in .obj format.

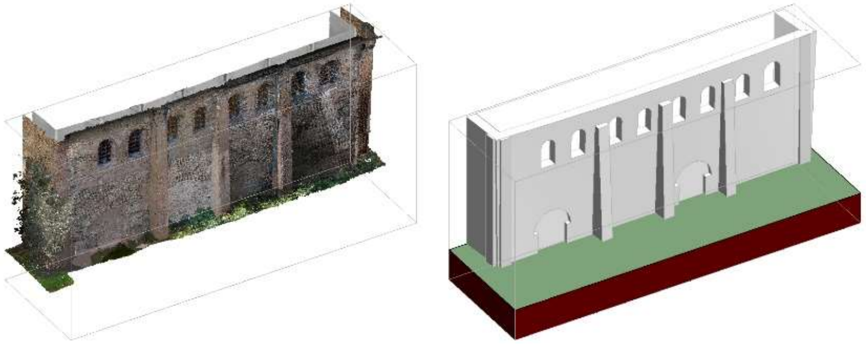


Figure 51. The portion of the point cloud and the portion of the HBIM considered

The first comparison, the one between the point cloud (about 3 million points) and the HBIM, shows the quality of this model, well representing the real condition of the façade. The Figure 52, visually presenting the difference between the two datasets, clearly permits to assume this model as a good and reliable representation of the façade. There are only some dissimilarities in correspondence of some architectonical peculiarities. One of these peculiarities refers, for example, to a brick adornment in correspondence of the left buttresses, presenting a local high deviation highlighted from the red colour in Figure 52.

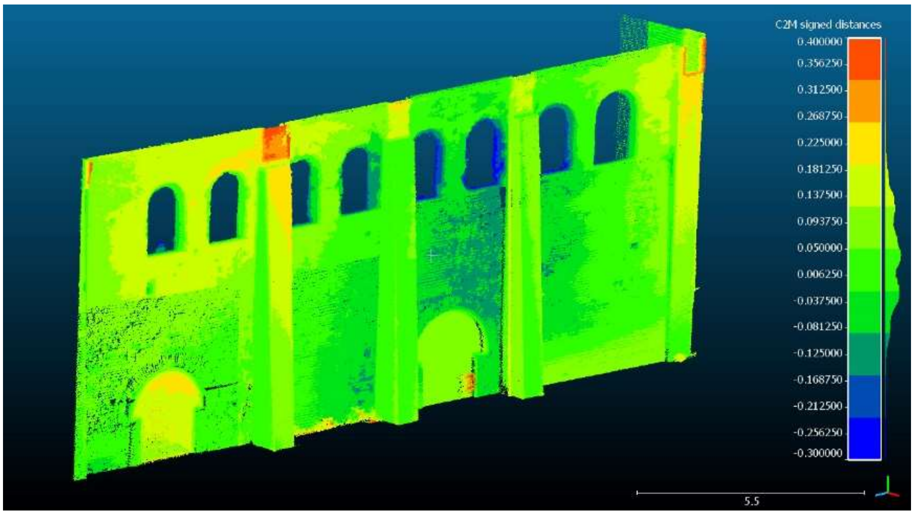


Figure 52. The first comparison: the HBIM façade versus the point cloud

The development of an external and exhaustive library useful for these objects will permit to manage and represent these architectural peculiarities in an effortless and speedy way and to obtain better results.

One of the main difficulties on the management of this façade concerned the presence of a double curvature in the wall. This aspect causes much more difficulties mainly to insert the so-called Revit families.

At last, an additional analysis permitted to show the average distance between the two entities (Figure 53). This value, about 6 cm, is a satisfying result that confirm the good similarity gained with this kind of approach.

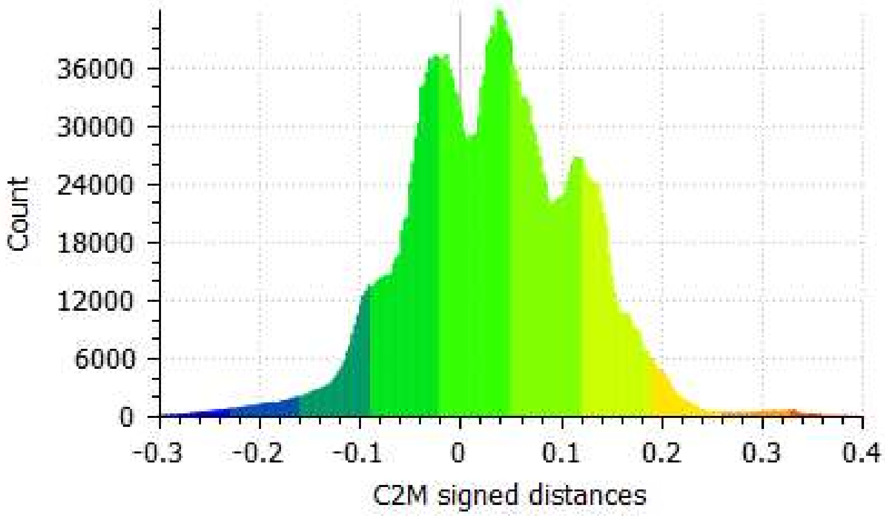


Figure 53. The distances between the point cloud and the mesh in the first comparison, expressed in m

Contrary of what shown before, the second comparison between an ideal vertical wall and the point cloud (Figure 54) highlighted the evident deviation of the top of the wall from a vertical plane. This considerable deviation reaches also values in the order of 30 to 45 cm, evidencing the importance of a knowledge system able to highlight these and the historical matters. In fact, these aspects and the historical problems could be represented and considered as an information collector, such as an HBIM, to start forward-looking preserving activities for the safety of these kinds of Cultural Heritage.

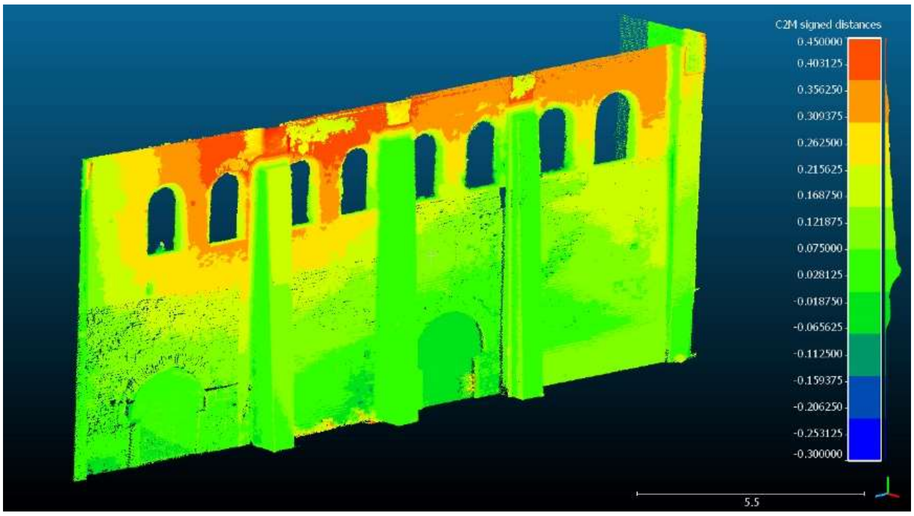


Figure 54. The second comparison: a vertical façade versus the point cloud.

Nevertheless, also the average distance (Figure 54), estimated in the order of 15 cm, allows considering this kind of deviation not acceptable for a reasonable representation of the façade.

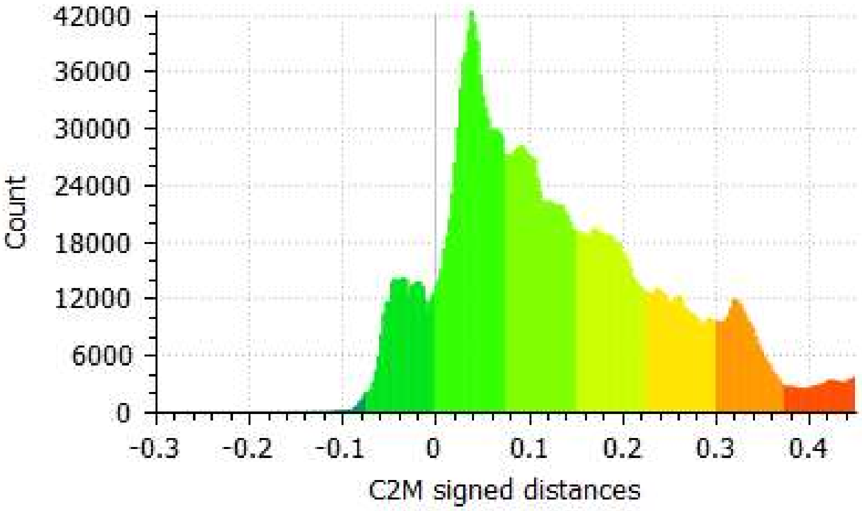


Figure 55. The distances between the point cloud and the mesh in the second comparison, expressed in m

3.2.4. Discussion

This case study shows the capability of the modern geomatic techniques to integrate each other and to obtain some 3D models useful for the development of an HBIM of an ancient Cultural Heritage building.

For this purpose, the procedure adopted for the development of the San Michele in Acerboli’s church HBIM was shown and described. This product aimed at supporting the correct geometrical representation and the historical knowledge management for the architectural heritage conservation processes.

In fact, a collector of both the geometric and the historical information represents nowadays a useful instrument for all the operators involved in the management of these assets. Nevertheless, this contribute tries also to offer a review to an effortless way to generate an irregular model of an ancient building in a widely used BIM software, such as Autodesk Revit, starting from 3D surveys data.

3.3. The domus of Obellio Firmo in Pompeii

The ancient town of Pompeii (Figure 56) is one of the most important archaeological sites in the world and its beauty needs to be preserved and protected. The town is a UNESCO World Heritage Site since 1997 and represents the first place in the ranking of the most visited archaeological sites in Italy, counting millions of visitors every year. This unique place, almost due to the perfect state of preservation, requires many studies, projects and activities to preserve its status.

Figure 56. A panoramic view of the ancient town of Pompeii

The University of Bologna, in a collaborative and multidisciplinary approach which involves the Dipartimento di Storia Culture Civiltà (DISCI) and the Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali (DICAM), conducted many of these activities, such as numerous surveys and excavations. An example concerns the survey of the "Insula del Centenario" performed for the project "Progetto Vesuviana" or the activities conducted on the "Lotto 3", which includes the regions III, IV, V and IX for the "Piano della Conoscenza del Grande Progetto Pompeii", financed by the European Union and Italy. The "Lotto 3" is characterized by the presence of buildings of relevance and high monumental impact, as the Houses of the Nozze d'Argento, Marco Lucrezio Frontone, Marco Lucrezio Stabia and Obellio Firmo.

A new project started in 2016 in agreement with the Soprintendenza Speciale per i Beni Archeologici di Pompei Ercolano Stabia, aimed at the documentation, preservation and enhancement of the House of Obellio Firmo (Figure 57), which is in the Northern sector of the ancient town. This is one of the oldest domus in Pompeii, built during the pre-Roman Age for a local important family.

Figure 57. A panoramic view of the House of Obellio Firmo

The building is a big residential complex, in which the façade occupies the entire short side of the urban block and is articulated on two atria and a peristyle. The first atrium, with Corinthian columns in tuff, was monumental and enriched by a fine marble decor aimed at underlined the aristocratic status of the owner. The second atrium, smaller and with Doric columns, was surrounded by residential and service rooms.

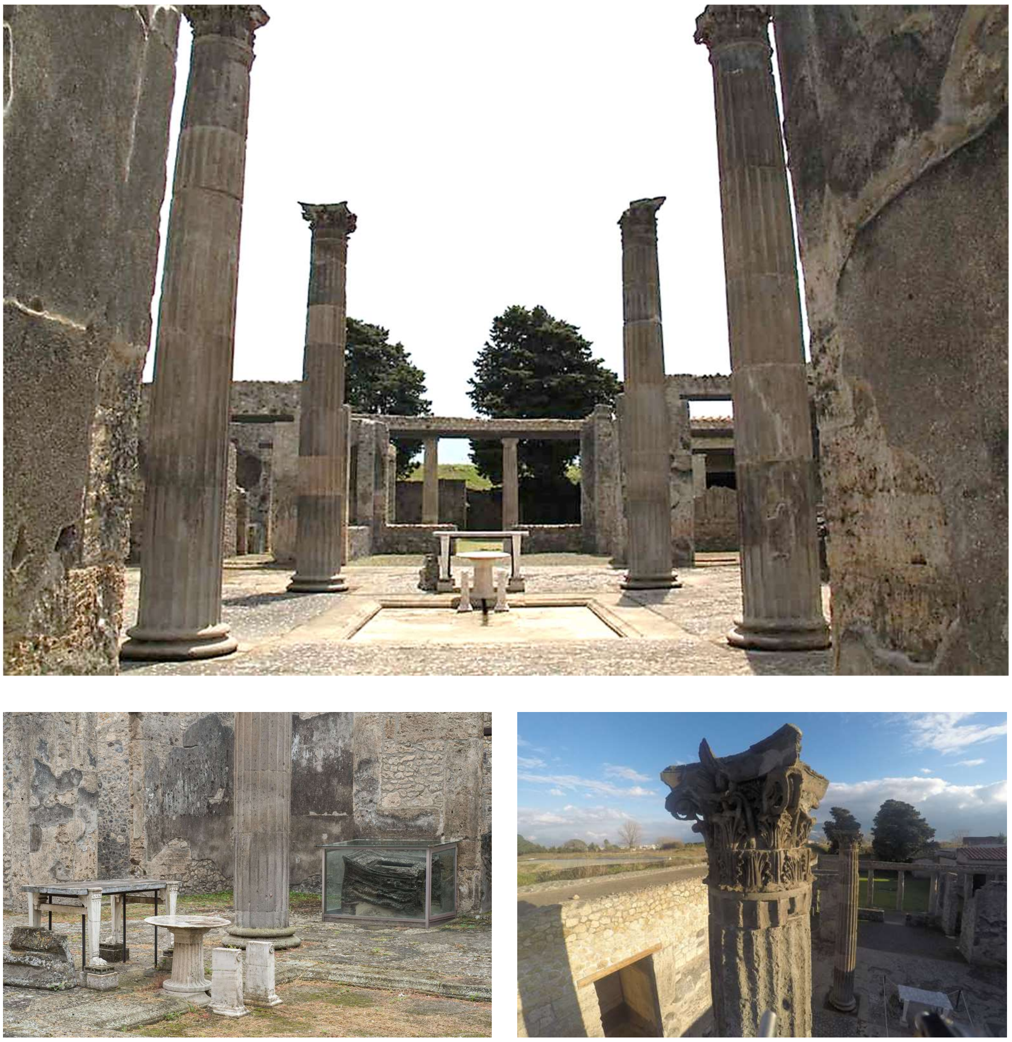


Figure 58. The inside of the House of Obellio Firmo: the first atrium, a detail of some furniture and a GoPro image from the top of a rod

Figure 59. The inside of the House of Obellio Firmo: the second atrium

The activities required an accurate analysis of the house, which was supported by the modern geomatic techniques, such as scanning and photogrammetry methods to generate a geometrically and radiometrically accurate 3D model of the whole building. Furthermore, not only the house but also some furniture where digitalized with a very high level of detail (Figure 60). This approach permitted a virtual reconstruction of the original asset of the furnishing and their location in the domus. Those amounts of data also require a process able to store, manage and share them. For the building scale the answer is represented by the BIM process applied for the Cultural Heritage.

Figure 60. The survey activities on the furniture

The 3D model obtained represents the basis for the parametric model, which is now at its very first stages and in a future development will constitute a complete HBIM project. The disposal of a 3D digital model is fundamental to organise all the information, and to perform different analyses.

The application of a BIM approach to this site, based on an accurate 3D model, offers numerous opportunities to optimize a number of activities related to this important complex, achieving different results:

- to get and maintain an accurate level of knowledge for the management and monitoring of the site;
- to support the archaeological studies by objective elements not directly available today;
- to quickly evaluate costs for any future interventions;
- to perform the right choices in terms of restoration planning
- to perform the simulation of catastrophic events
- to support further promotion and scientific activities.

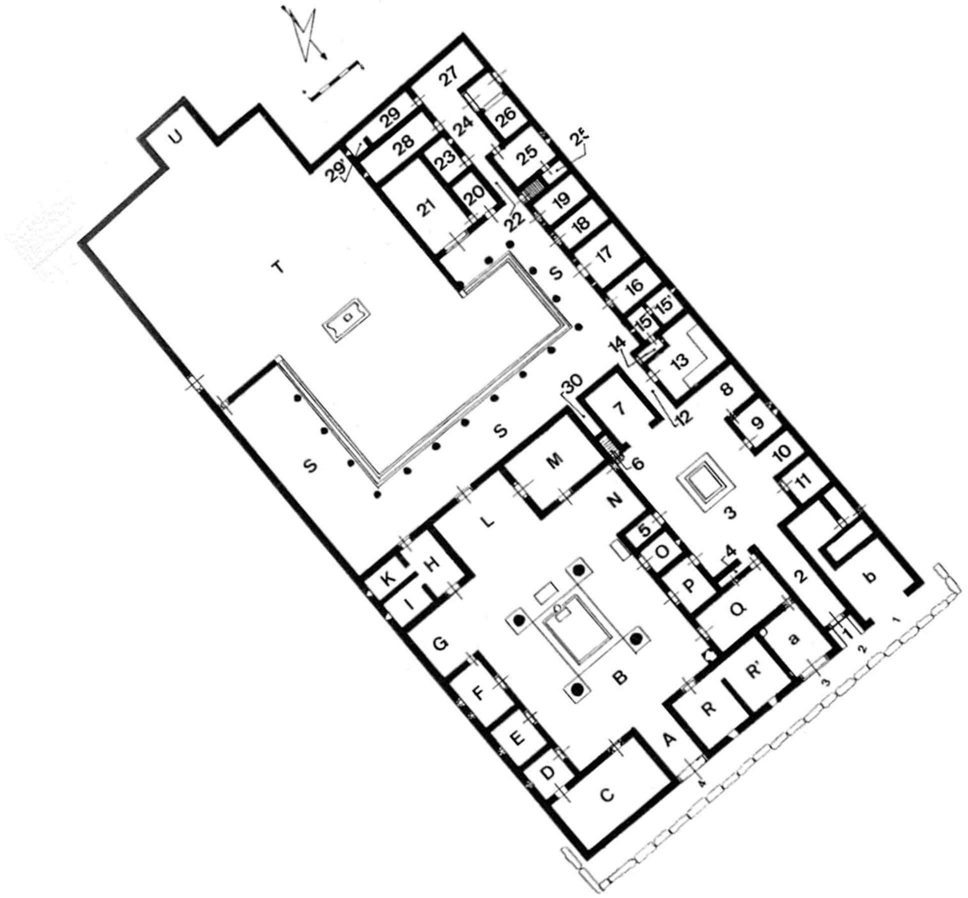


Figure 61. The planimetry of the domus

In recent years, this comprehensive approach and these aspects are gaining more and more importance and it must be highlighted that there are no conventional schemes or procedure and each situation must be considered individually, especially in this case for the great historical relevance of the object.

3.3.1. Acquisition report

The survey activities were conducted on two different scales: the first one, mainly conducted by the DISCI, regards the building, while the second one, conducted by the DICAM, regards the detailed survey of some furniture.

The survey of the building was performed by the DISCI in 2016 by using a Leica Scanstation P30 laser scanner, able to perform a 3D data acquisition of a high quality (3 mm at 50 m on the three point coordinates), low range noise, survey-grade dual-axis compensation and High Dynamic Range (HDR) imaging. This instrument led to a highly detailed 3D colour point clouds mapped in realistic clarity (Figure 62).

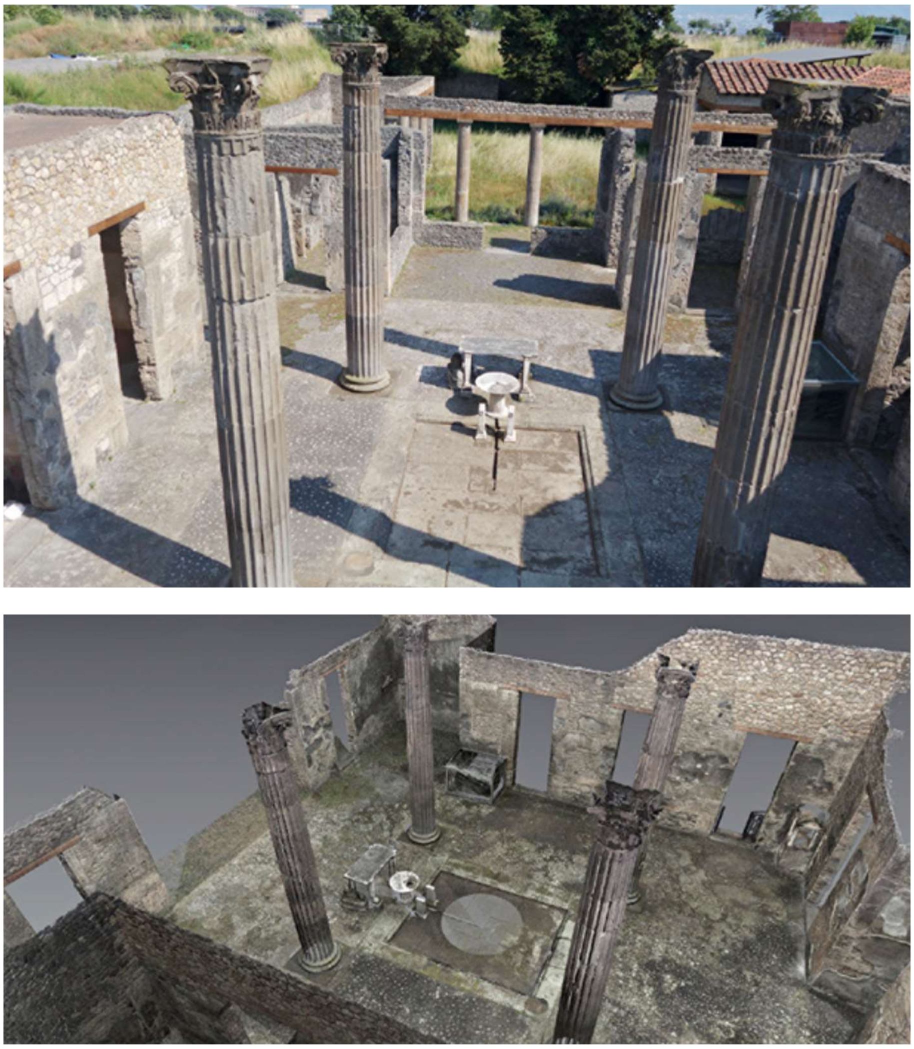


Figure 62. The House of Obellio Firmo, panoramic view and the 3D point cloud (Silani et al., 2017)

Figure 63. Visualization of the 3D model for the atrium by the PCV shading method

Figure 64. The final point cloud of the whole domus

The new laser scanner survey generated a detailed documentation in 1:50 scale, regarding the planimetry, the sections and the prospects. It was also performed a further photogrammetric documentation by means of panoramic and full-frame Digital Single-Lens Reflex (DSLR) cameras, both for the colouring of the point-clouds and for the extraction of the high-resolution orthophotos to be applied to the 3D model. The obtained dataset has been essential for the surface modelling of the entire building. This new survey permits to document the recent restoring interventions performed during the "Grande Progetto Pompeii" and to compare the present structure's conditions to those recorded in a previous surveying activity of 2015 (Silani et al., 2017).

A parallel survey was conducted by the DICAM and aimed to augment the detail level for the documentation of certain small objects inside the House of Obellio Firmo. The main elements of the furniture located in the Domus, such as the Lararium, the Tabula Vasaria, the Trapezofori and the Monopodio have been measured having recourse to a structured light projection scanner, able to reach a sub-millimetric accuracy (0.1 mm nominal instrument precision) and an exact geometric reconstruction of the surface shape.

Furthermore, it was surveyed a small sculpture of a Satiro, currently preserved in the warehouses of the National Archaeological Museum of Naples (MANN) and in the past placed on the top of the Tabula Vasaria (Figure 65). This choice was conducted for the purpose of a virtual reconstruction of the original placement of this statue inside the Domus.

Figure 65. Image of 1937 showing the Satiro statue currently conserved at the MANN Museum

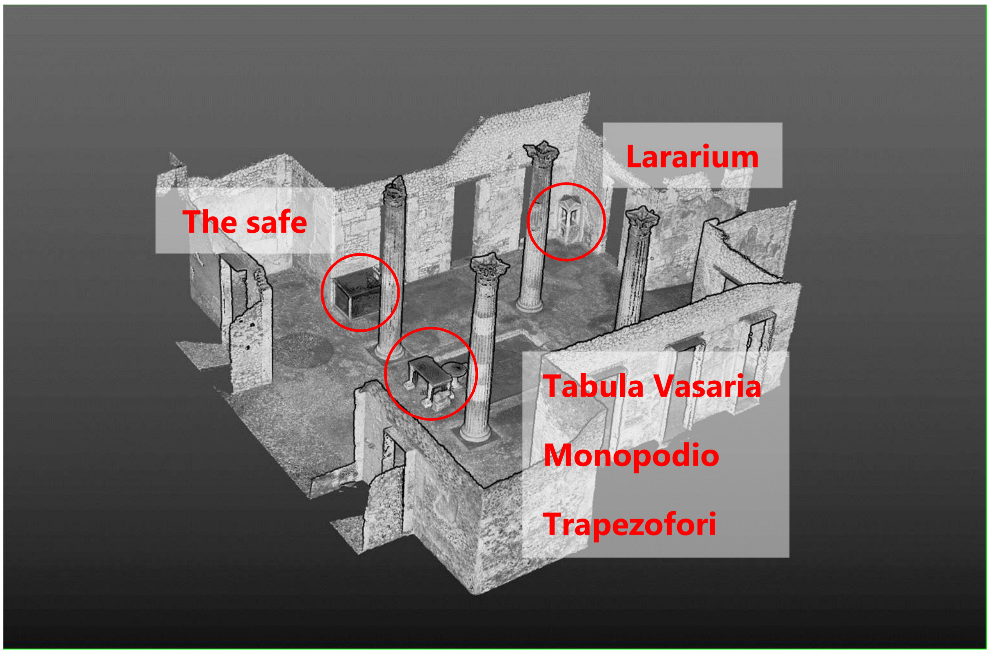


Figure 66. The Atrium and the location of the furniture

Figure 67. From the left to the right: firstly, the Lararium; secondly, the Trapezofori, the Monopodio and the Tabula Vasaria; at last, the safe

Figure 68. A detail of the safe's surface

Figure 69. The Satiro, currently located at the MANN

For the survey of this furniture of the domus, the instruments in use were the structured light scanner Artec3D MHT, Artec Spider and two different digital cameras, the Canon EOS 6D and the Panasonic Lumix DMC-TZ60.

Figure 70. The instruments for the survey of the furniture. From the left to the right: Artec MHT, Artec Spider, Canon EOS 6D and Panasonic Lumix DMC-TZ60

After an accurate evaluation of the different circumstances concerning the surveying phase, it was chosen to digitally acquire the Lararium and the Tabula Vasaria using the integration between the scanning, performed by the structured light scanner MHT, and the digital photogrammetric techniques.

The photogrammetric survey was performed to integrate the scanner surveys due to some difficulties in the acquisition phase, especially for the table of the Tabula Vasaria. The main reasons concern its flat geometry combined to the atmospheric conditions: the marble directly illuminated by the sun made almost impossible the use of the structured light scanner.

The Monopodio and the Trapezofori, being of the same materials and presenting the same reflectance problems yet mentioned, have been detected only by photogrammetry.

Finally, for the Satiro located at the MANN it was necessary to adopt an integrated approach of both the structured light scanner Artec Spider and the digital photogrammetric techniques.

The total amount of data acquired is reported in the following Table 2:

Object	Scans	Photos
Larario	59	102
Tabula Vasaria	37	79
Monopodio	/	92
Trapezofori	/	51
Safe	/	603
Satiro	33	124

Table 2. The acquired data of the furnishing

The full-scale deepened documentation of the house also includes a detailed geophysical mapping of all the open accessible domestic spaces, systematically employing the ground penetrating radar (GPR) technique. The survey was characterized by an extremely high-resolution data recording, which was achievable using a system equipped with a 600 MHz antenna. This high-resolution Ground Penetrating Radar (GPR) mapping covers all the largest open spaces of the building, including both the atria, the peristilium, the garden of the peristilium, as well as many others smaller service and domestic rooms (Figure 71). This mapping highlights some buried infrastructures, such as pipelines and tanks, and the data collected in the garden. In the garden, the geophysical survey shows the foundation walls, which are probably referable to the earlier divisions of the house (Silani et al., 2017).

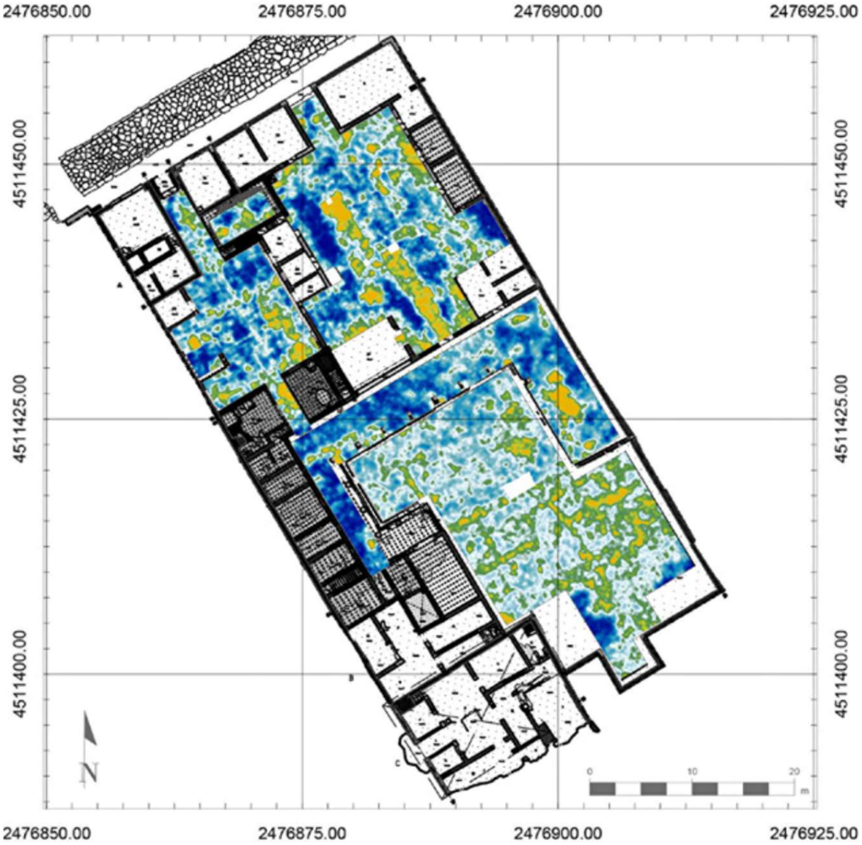


Figure 71. GPR of the domus (Silani et al., 2017)

3.3.2. The reconstruction of the furniture

As said, the main difficulties during the digital reconstruction phase of the furniture were due to the reflectance of certain materials. This aspect was not so critical for the Larario which was easily surveyed by the light structured scanner. Anyway, the geometrical characteristics and the range of the scanner generated some lacking part of the object, especially the inside of the niche (Figure 72).

Figure 72. The Larario: the detail of a lacking part inside the niche

To cover these parts, it was also necessary a photogrammetric survey and choosing to acquire not only the lacking part but the entire object. For the photogrammetric reconstruction, a high number of targets were placed all around the object, also used to scale the digital model by the measurement of a redundant number of distances.

Figure 73. The Photogrammetric survey, from the left to the right: the placement of the targets on the object, the spare cloud and the 3D mesh (without the RGB information) in that stage

Both the techniques generated a 3D mesh enriched by the radiometric information and the integration of these results of the two surveys permitted the generation of the complete and highly accurate 3D model of the whole Larario (Figure 74).

Figure 74. The complete digital 3D model of the Larario, resulting by the integration of scanning and photogrammetric techniques

A similar approach conducted for the Larario were adopted also for the Tabula Vasaria. Anyway, contrary to the Larario, the Tabula Vasaria required a massive integration between the light structured scanner and the photogrammetric survey. The sunny day, combined to the reflectance of the marble which the object is composed, made almost impossible scanning the portions directly lightening by the sun. During the survey activities, it was tried to artificially shadow the portion that were scanned but it wasn’t enough to obtain a complete model. The photogrammetric survey was so necessary and conducted in this case only for the top of the table, impossible acquired by the scanning survey.

Also in this case, both the techniques generated a 3D mesh enriched by the radiometric information and the integration of these results permitted the generation of the complete and highly accurate 3D model of the whole Tabula Vasaria (Figure 75).

Figure 75. The reconstruction of the Tabula Vasaria: the light structured scanner without the top, the top of the table generated by the photogrammetric reconstruction and the final complete
3D model of the Tabula Vasaria

For the Monodopio and the Trapezofori it was chosen to only perform a photogrammetric survey, due to the almost impossibility to scan them for the mentioned sunny conditions and the physical characteristics of marble. For these kinds of surveys, the acquisition and the reconstruction phase were conducted in a classical way. As for the previous cases, also for these objects the targets were used to align and scale the final digital 3D models. The results are shown in the Figure 76 below:

Figure 76: The digital 3D models reconstructed by a photogrammetric approach. From the left to the right: the Monopodio and the Trapezofori

A photogrammetric approach was also adopted for the safe; in this case, due to logistical constraints, a specific acquisition method was applied, acquiring a lot of images at a very close distance (in the order of 15 cm).

Figure 77. The digital 3D model of the safe

At last, the survey of the Satiro located at the MANN was conducted according to the same procedure adopted for the Larario and the Tabula Vasaria. The structured light scanner was used for the complete survey of the statue. Anyway, both the problems seen for the Larario and the Tabula Vasaria, the geometry and the material reflectance, caused lacking portions in the digital 3D model. It has been necessary a photogrammetric survey to acquire and digitally reconstruct, case by case, the missing parts and obtain the complete model shown in Figure 78.

Figure 78. The digital 3D model of the Satiro

All these surveys were finally aligned on the georeferenced point cloud of the entire Domus, in order to have a multiscale representation that can constitute an excellent documentation of the atrium. Starting from this multiscale 3D model it is possible to obtain accurate metric information and it will be possible to support Virtual or Augmented Reality explorations of the site.

The result is shown in Figure 79, which shows a comparison between the real atrium and the digital reconstruction.

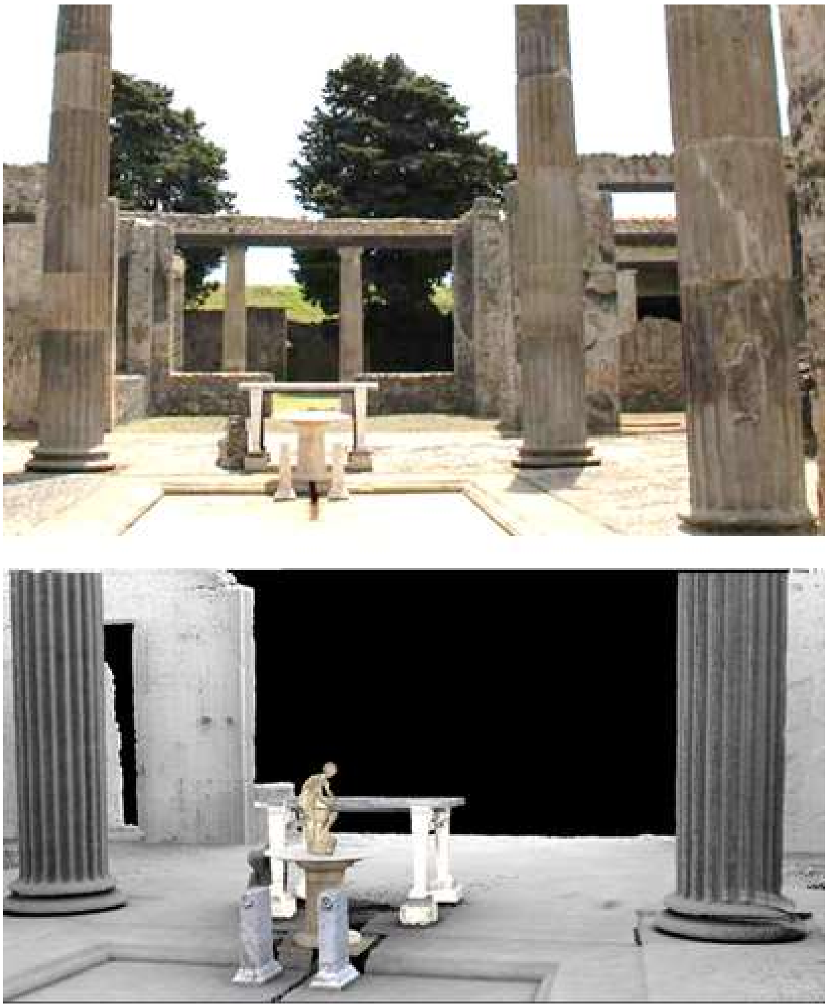


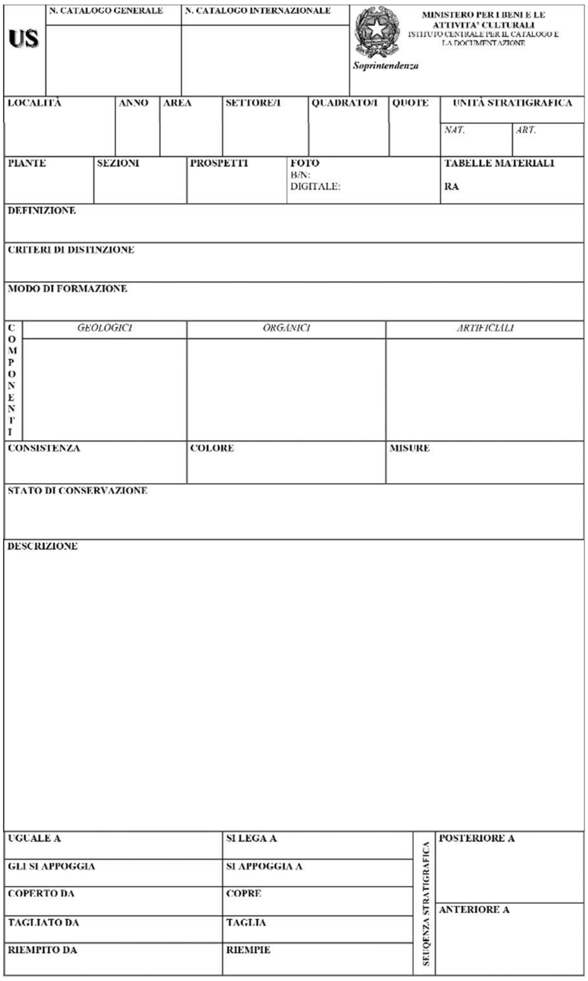
Figure 79. The virtual reconstruction of the forniture
(Tabula Vasaria, Monopodio with the Satiro, Trapezofori,)

3.3.3. The development of an HBIM

The results achieved from the surveying phase permit to gain many information about the building, such as the analysis of the standing walls, in terms of structural stratigraphy, building techniques and materials.

This combined work has been supporting in a worthwhile way the archaeological reconstruction and interpretation of the house’s history, regarding its first genesis as well as to its main development phases during the centuries. To reach this goal, the management and sharing of the amount of information, related to both the out-of-ground elevated structures and the subsoil, will be organized within a comprehensive 3D model and within a BIM.

The very first step has been a sort of interview with the archaeologists, in order to clearly understand how an HBIM of this Domus in Pompeii could be useful for their work. From that analysis emerged that the archaeologists are currently using some tables directly given by the Ministero per i Beni e Le Attività Culturali (MiBACT) to archive some parameters (Figure 80).



US

N. CATALOGO GENERALE

N. CATALOGO INTERNAZIONALE

MINISTERO PER I BENI E LE
ATTIVITA' CULTURALI
ISTITUTO CENTRALE PER IL CATALOGO E
LA DOCUMENTAZIONE

Soprintendenza

LOCALITÀ

ANNO

AREA

SETTORE/I

QUADRATO/I

QUOTE

UNITÀ STRATIGRAFICA

NAT.

ART.

PIANTE

SEZIONI

PROSPETTI

FOTO
B/N:
DIGITALE:

TABELLE MATERIALI
RA

DEFINIZIONE

CRITERI DI DISTINZIONE

MODO DI FORMAZIONE

COMPONENTI

GEOLOGICI

ORGANICI

ARTIFICIALI

CONSISTENZA

COLORE

MISURE

STATO DI CONSERVAZIONE

DESCRIZIONE

UGUALE A

SI LEGA A

GLI SI APPOGGIA

SI APPOGGIA A

COPERTO DA

COPRE

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SEUQENZA STRATIGRAFICA

POSTERIORE A

ANTERIORE A

Figure 80. An example of a table provided by the MiBACT for archaeological analysis.

The most important parameters concern the building types and the way in which they merge and relate each other. These aspects are extremely important for the archaeologists, because they permit to obtain a preliminary historical and chronological reconstruction of the manufact. Some rules can be established following simple assumptions: i.e. if a wall lie at the bottom in respect to another, it means that is probably the older one, and if a wall lie on an another the first one is more recent than the second one.

Nowadays, these procedures are manually done by the archaeologists. An HBIM, correctly set and developed with the consciousness of these request, could give an important and useful feedback to the archaeological analyses and assumptions. In fact, once set all the parameters concerning the building elements (i.e. walls, floors, their stratigraphy, their historical phase and so on), it is possible to obtain also a sort of clash detection, especially in terms of historical reconstruction, to validate the assumptions done by the archaeologists.

Nevertheless, the archaeologists require to HBIM to visualize in an immediate and intuitive manner the techniques and chronology associated to the building typologies adopted in the house.

A further very interesting and challenging aspect is referred to static assumptions and analysis to digitally reconstruct the missing portions of the domus, such as floors and roofs. This part needs to be supported by a deep consciousness of the materials, their original characteristics and the construction techniques and skills adopted at the time. Thanks to the interoperability treated at the paragraph 2.2.5, it is possible to let the model communicate with third-party software to perform structural analyses and, also in this case, understand and validate if the supposed reconstructions are in accord to the structural capacity of the elements. Obviously, it is interesting to perform these analyses for each historical phase, highlighting the changes in a sort of timeline of structural changing.

The parametric model able to support the above mentioned aims, and other that are in a definition phase, is at its very first stages and, as mentioned, the intent is to make an ordinate collector of the information able to manage the scheduling and the time phases, both about the past and the future, especially concerning the maintenance aspects. For this case, it will be used a federate approach, which it consists (as mentioned at paragraph 2.2.3) in a model of linked but distinct component models, drawings derived from the models, texts, and other data sources that do not lose their identity or integrity by being so linked, so that a change to one component model in a federated model does not create a change in another component model in that federated model. The federate model in development for this case, it will be composed by four different models:

- POINT CLOUD MODEL: it consists in a layer effectively composed by the point cloud model, useful for obtaining some geometric or radiometric information;
- DOCUMENTAL MODEL: it is a derived model, in which it is possible to attach the information (such as documents, datasheets, tabs, figure and so on) to all the components. It is directly linked to the semantic of the objects;
- ANALITIC MODEL: it represents a model able to support analysis on it, otherwise impossible to perform just on the point cloud. This model uses the information inserted in the second model;
- RECONSTRUCTIVE MODEL: this model let to virtually reconstruct the building on the base of its actual form and on the base of the historical research and the obtained information. This model could also manage the high detailed digital model of the furniture.

The main problems about this part of the work regard the management of all the different phases and the management of the different stratigraphic overlays of the structures (both horizontally and vertically). Also, the terrain configuration requires a considerable attention because of its different level during the centuries. This aspect, in a BIM model developed to manage also the different chronological phases, requires an accurate preliminary study and a very clear view of the overlaying, which all the elements considered has suffered.

A first step was the segmentation of the point cloud to extract the terrain model of the actual configuration (Figure 81) and to analyse the evolution of the area during the centuries, according to the information given by the archaeologists involved. This part is a crucial part, especially for the relationship between the ground and the vertical structures, such as the wall, the columns and so on.

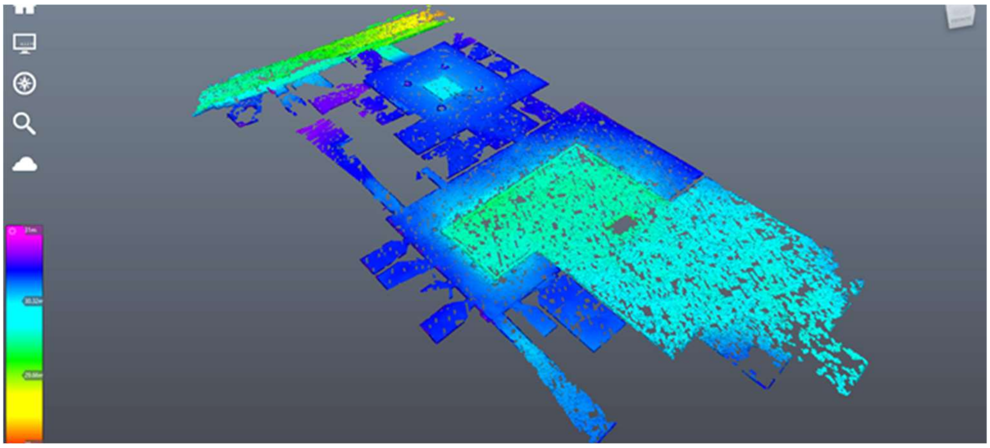
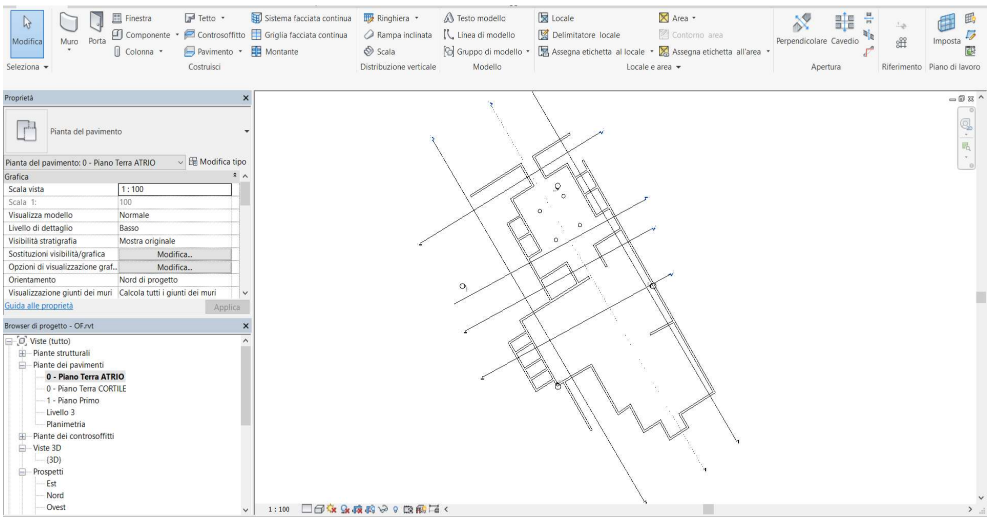


Figure 81. The terrain model and the highlighting of the elevation using a false colour scheme

Also, a very first BIM model has been developed, mainly representing just the geometry of the domus and yet enriched by the stratigraphic information about the actual configuration.



Pianta del pavimento

Pianta del pavimento: 0 - Piano Terra ATRIO

Grafica	
Scala vista	1 : 100
Scala 1:	100
Visualizza modello	Normale
Livello di dettaglio	Basso
Visibilità stratigrafia	Mostra originale
Sostituzioni visibilità/grafica	Modifica...
Opzioni di visualizzazione graf...	Modifica...
Orientamento	Nord di progetto
Visualizzazione giunti dei muri	Calcola tutti i giunti dei muri

Figure 82. The planimetric view of the HBIM

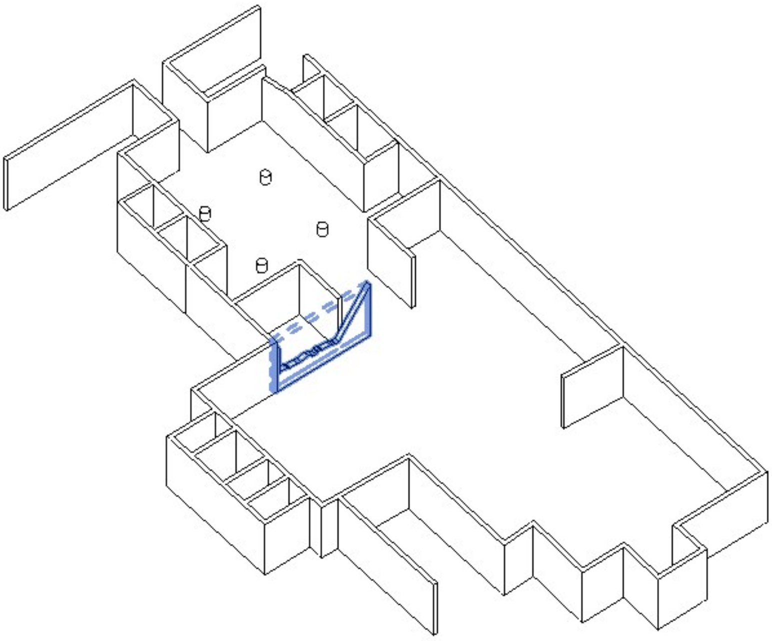


Figure 83. 3D view of the first stages of the HBIM model

Some elements, such as the door and the columns have been modelled as parametric objects. The parametrization of different elements could be useful for further analysis and interpretation. It is possible to automatically extract some information about the geometrical relationship between the different elements. This aspect, remarkable for the interpretation purposes and for the dating of single parts of the Domus, could also help both the archaeologists and the restorers for the future activity of maintenance and restoration.

3.3.4. Closing note

It is not correct talking about conclusions for this last case. The vastity and the relevance of the object, together with the hard challenge of the development of an HBIM of the domus, requires more time to complete this work, which is at its first stages and in a continuous development by the multidisciplinary team involved, formed by archaeologists, architects and engineers. This multidisciplinary approach and this requirement of a common language between the different ambits give more relevance and interest to BIM for the Cultural Heritage communication, preservation and maintenance.

4. Conclusions

In this thesis, it was discussed the relevance of the Cultural Heritage and the increasing interest by the scientific community for this theme, especially for the management of the information. For this purpose, a relevant role is played by the geomatic techniques aimed to the generation of accurate 3D models, which represent a beginning and a continue for the different kind of analysis performed on the acquired data. In fact, the correct management of the information represent a crucial issue for the Cultural Heritage, and it requires a solid support for their organization.

It has been shown the potentiality of the 3D model to represent a support and a core of a solid databases in which the different information could be stored, managed, shared and combined to guarantee the right choice for the preservation of objects at different scales.

Firstly, the Fountain of Neptune represent a clear example of the capability of the 3D model to be used all along the lifecycle of a great monument: since the information collecting, trough the restoration activity and not only the preservation of the monument itself but also of all the information and activity conducted.

Secondly, the case of San Michele in Acerboli Church moves to another scale, passing from a great monument to a building. This example showed the possibility to start from the 3D data acquired to a HBIM model able to collect the different kind of information and to accurately represent the peculiarity and the geometrical anomalies of an ancient Church, also for structural analysis.

Finally, the case of the House of Obellio Firmo in Pompeii is a case, yet in progress, which represent a mixture of both the previous situations. In this case, several survey activities have been performed, both for the digital reconstruction of the domus (with some further investigations by geophysical methods) and for the digital reconstruction of the related furniture. These two activities, aimed to different scopes, were obviously conducted by different approaches due to the different scale of the object considered and the final analysis to develop on it. The preliminary results achieved by the combined analysis on the model, integrated with the analysis of the standing walls, in terms of structural stratigraphy, building techniques and materials, supported the archaeological reconstruction and interpretation of the house's history, regarding its historical phases and development during the centuries (Silani et al, 2017). The final intent is the management and sharing of the amount of information, organized in a comprehensive Building Information Model (BIM), which is still in the developing phase.

In the complex and evolving relationship between the Cultural Heritage, the Information management, the data acquisition process and the technological development of the instruments, Geomatics increasingly play a key role as a discipline able to drive a modern multidisciplinary approach.

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Bibliography

1. Apollonio, F. I., Gaiani, M., Basilissi, W. & Rivaroli, L.: "Photogrammetry driven tools to support the restoration of open-air bronze surfaces of sculptures: an integrated solution starting from the experience of the Neptune Fountain in Bologna", ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2/W3, pp. 47–54. https://doi.org/10.5194/isprs-archives-XLII-2-W3-47-2017, 2017.
2. Apollonio, F.I., Basilissi, V., Bitelli, G., Callieri, M., Catalano, D., Dellepiane, M., Gaiani, M., Ponchio, F., Rizzo, F., Rubino, A.R. & Scopigno R.: "Il restauro della fontana del Nettuno a Bologna. Un sistema 3D Web per la documentazione e la gestione dei dati", Archeomatica, VIII-4, pp. 30-34, 2017.
3. Augenbroe, G.: *"Integrated building performance evaluation in early design stages. Building and Environment"*, 27(2), pp.149-161, 1992.
4. Benedetti, B., Giyani, M. & Guzzo P.G.: "Scientific knowledge and information representations in historical technical archives of archaeological sites: Pompeii as a case study", Responsibilities and opportunities in architectural conservation conference proceedings, pp. 275-290, 2008.
5. Balletti, C., Guerra, F., Scocca, V. & Gottardi C.: "3D integrated methodologies for the documentation and the virtual reconstruction of an archaeological site", The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 40(5/W4), pp. 215-222, 2015.

6. Barazzetti, L., Banfi, F., Brumana, R. & Previtali, M.: "Creation of parametric BIM objects from point clouds using NURBS". The Photogrammetric Record, 30(152), pp. 339–362, 2015.
7. Barazzetti, L., Banfi, F., Brumana, R., Gusmeroli, G., Oreni, D., Previtali, M., Roncoroni, F. & Schiantarelli, G.: "BIM from laser clouds and finite element analysis: combining structural analysis and geometric complexity", International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 40(5/W4), pp. 345–350, 2015.
8. Bedell, J. and Kohler, N.: *"CAAD Future"*, pp. 423-435, 1993.
9. Behr, J., Eschler, P., Jung, Y., Zöllner, M.: "*3DOM: A DOM-based HTML5/X3D integration model*", Proceedings of the 14th International Conference on 3D Web Technology pp. 127–135, http://doi.org/10.1145/1559764.1559784, 2009.
10. Bew, M., Richards, M.: *"Bew-Richards BIM Maturity Model"*, 2008.
11. Bitelli, G., Balletti, C., Brumana, R., Barazzetti, L., D'Urso, M.G., Rinaudo, F. & Tucci G.: "*Metric Documentation of Cultural Heritage: Research Directions from the Italian GAMHer Project*", The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-2/W5, pp. 83-90, doi:10.5194/isprs-archives-XLII-2-W5-83-2017, 2017.
12. Bitelli, G., Borgatti, L., Cervi, F., Dellapasqua, M., Franci, F., Girelli, V.A., Lambertini, A., Landuzzi, A., Mandanici, E., Pacini, A., Spreafico, M.C. & Tini, M.A.: "*La Geomatica per la modellazione 3D di placche rocciose di grandi dimensioni e applicazioni geologiche: il caso della rupe di San Leo (RN)*", Atti XIX Conferenza Nazionale ASITA, Lecco, ISBN 978-88-941232-2-7, pp. 123-130, 2015.
13. Bitelli, G., Dellapasqua, M., Girelli, V.A. & Tini M.A.: "*Problematiche nel rilevamento 3D in alta risoluzione per i Beni Culturali*", Atti XX Conferenza Nazionale ASITA, 711-713, ASITA, 2016.
14. Bitelli, G., Dellapasqua, M., Girelli, V.A. & Tini, M.A.: "*Il rilievo tridimensionale in alta risoluzione del complesso della fontana*

del Nettuno", in: "Nettuno. La fontana: studio, progetto, restauro", a cura di M. Gaiani, Bononia University Press, pp. 68-74, 2017.

15. Bitelli, G., Dellapasqua, M., Girelli, V.A. & Sbaraglia, S.: "*Historical Photogrammetry and Terrestrial Laser Scanning for the 3D Virtual Reconstruction of Destroyed Structures: A Case Study in Italy*". The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-5/W1, doi:10.5194/isprs-archives-XLII-5-W1-113-2017, 113-119, 2017.
16. Bitelli, G., Dellapasqua, M., Girelli, V.A., Sanchini, E. & Tini M.A.: "*3D Geomatics Techniques for an Integrated Approach to Cultural Heritage Knowledge: The Case of San Michele in Acerbli's Church in Santarcangelo di Romagna*". The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-5/W1, doi: 10.5194/isprs-archives-XLII-5-W1-291-2017, pp. 291-296, 2017.
17. Bitelli, G., Gatta, G., Guccini, A.M., Zaffagnini, A.: *"GIS and Geomatics for archive documentation of an architectural project: The case of the big Arc of entrance to the Vittorio Emanuele II Gallery of Milan, by Giuseppe Mengoni (1877)"*, Journal of Cultural Heritage, 38, pp. 204–212, 2019
18. Bruno N.: *"From survey to analysis for Cultural Heritage management: a new proposal for database design in BIM"*, PHD Thesis, Università di Parma, 2017.
19. BuildingSMART: "https://technical.buildingsmart.org", last reviewed, 27/09/2019
20. Chiabrando, F., Sammartano, G. & Spanò A.: "*Historical Buildings Models and their Handling via 3D Survey: from Point Clouds to User-Oriented HBIM*", The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLI-B5, pp. 633-640, 2016.
21. Dore, C. & Murphy, M.: "*Integration of Historic Building Information Modeling and 3D GIS for Recording and Managing Cultural Heritage Sites*", In VSMM2012. Proceedings of the 18th

International Conference on Virtual Systems and Multimedia. Virtual Systems in the Information Society, pp. 369-376, 2012.

22. Eastman, C.: "*An Outline of the Building Description System*", Issue 50 of Research report. Institute of Physical Planning, Carnegie-Mellon University, Pittsburgh, 1974.
23. Eastman, C.: "*The Use of Computers Instead of Drawings*", AIA Journal, March, Volume 63, Number 3, pp. 46–50, 1975.
24. Eastman, C., Teicholz, P., Sacks, R. & Liston, K.: "*BIM Handbook – A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors*", John Wiley & Sons, Inc., 2008.
25. Eve, S.: *"Augmenting Phenomenology: Using Augmented Reality to Aid Archaeological Phenomenology in the Landscape*", Journal of Archaeological Method and Theory, 4 (6), pp. 582-600, 2012.
26. Garagnani, S.: "*Building Information Modeling and real-world knowledge. A methodological approach to accurate semantic documentation for the built environment*", Digital Heritage International Congress (DigitalHeritage), 2013, Danvers, MA, IEEE The Institute of Electrical and Electronics Engineers, Inc., 2013, 1, pp. 489 – 496, 2013
27. Garagnani, S. & Manfredini, A. M.: "*Parametric accuracy: building information modeling process applied to the Cultural Heritage preservation*", International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Trento, Italy, Volume XL, Part 5/W1, pp. 88-92, 2013.
28. Garagnani, S.: "*Il processo costruttivo tra rappresentazione e conoscenza: la nascita del Building Information Modeling*", INGENIO n. 27, 23/09/2014, 2014.
29. Gauchel, J., Hovestadt, S., Van Wyk, and Bhat, R.: *"Building modeling based on concepts of autonomy"*, Proceedings of the AID 1992, Pittsburgh (PA), 1992.
30. gbXML. *"http://www.gbXML.org"*, last reviewed, 27/09/2019.
31. Girelli, V.A., Borgatti, L., Dellapasqua, M., Mandanici, E., Spreafico, M.C., Tini, M.A. & Bitelli G.: "*Integration of Geomatics*

Techniques for Digitizing Highly Relevant Geological and Cultural Heritage Sites: The Case of San Leo (Italy)", The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-2/W5, pp. 281-286, doi: 10.5194/isprs-archives-XLII-2-W5-281-2017, 2017.

32. Girelli V.A., Tini M.A., Dellapasqua M., Bitelli G.: "*High resolution 3D acquisition and modelling in Cultural Heritage knowledge and Restoration projects: the survey of the Fountain of Neptune in Bologna*", The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2/W11, pp. 573-578, doi: 10.5194/isprs-archives-XLII-2-W11-573-2019, 2019
33. Guarnieri A., Masiero A., Piragnolo M., Pirotti F., Vettore A. A geodatabase for multisource data applied to cultural heritage: the case study of Villa Revedin Bolasco, Legnaro (PD). The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLI-B5, 2016.
34. Guidi, G., Remondino, F., Russo, M., Menna, F., Rizzi, A. & Ercoli, S.: "*A multi-resolution methodology for the 3D modeling of large and complex archaeological areas*", International Journal of Architectural Computing, 7(1), pp. 39–55, 2009.
35. Guidi, G., Russo, M. & Beraldin, J.-A.: "*Acquisizione 3D e modellazione poligonale*", The McGraw-Hill Companies, 2010.
36. ISO 1992: "Product data representation and exchange – part 1; Overview and Fundamental Principles", STEP Document ISO TC184/SC4/PMAG.
37. Marques, L., Tenedorio, J.A., Buns, M., Romao, T., Birra, F., Marques, J., Pires, A.: "*Cultural Heritage 3d Modelling and visualisation within an Augmented Reality Environment, based on Geographic Information Technologies and mobile platforms*", ACE: Architecture, City and Environment, 11 (33), pp. 117-136, 2017
38. Murphy, M., McGovern, E. & Pavia S.: "*Historic Building Information Modelling – Adding intelligence to laser and image-*

based surveys of European classical architecture", ISPRS Journal of Photogrammetry and Remote Sensing, 76, pp. 89-10, 2013.

39. Oreni, D., Brumana, R., Della Torre, S., Banfi, F., Barazzetti, L. & Previtali M.: *"Survey turned into HBIM: the restoration and the work involved concerning the Basilica di Collemaggio after the earthquake (L'Aquila)"*, ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume II-5, pp. 267-273, 2014.
40. Pohi, J., and Rep, I.: *"An integrated intelligent CAD environment"*, Proceedings of the 4th International Conference on Systems Research, Informatics and Cybernetics, Baden-Baden, Germany, 1988.
41. Ponchio, F. & Dellepiane, M.: "*Multiresolution and fast decompression for optimal web-based rendering*", Graphical Models, Volume 88, pp. 1-11, 2016.
42. Potenziani, M., Callieri, M., Dellepiane, M., Corsini, M., Ponchio, F. & Scopigno R.: "*3DHOP: 3D Heritage Online Presenter*", Computer & Graphics, Volume 52, pp. 129-141, 2015.
43. Quattrini, R., Malinverni, E. S., Clini, P., Nespeca, R. & Orlietti E.: "*From TLS to HBIM. High quality semantically-aware 3D modeling of complex architectur*e", International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Avila, Spain, Volume XL, Part 5/W4, pp. 367-374, 2015.
44. Remondino, F.: "Heritage Recording and 3D Modeling with Photogrammetry and 3D Scanning", Remote Sensing, Vol. 3(6), pp. 1104-1138, 2011.
45. Rinaudo, F. et al.: "*Sistemi a scansione per l'architettura e il territorio*", Firenze: Alinea Editrice, 2007
46. Rinaudo, F., Chiabrando, F., Nex, F. & Piatti D.: "*New Instruments and Technologies for Cultural Heritage Survey: Full Integration between Point Clouds and Digital Photogrammetry*", In Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)

(Vol. 6436 LNCS, pp. 56–70). https://doi.org/10.1007/978-3-642-16873-4_5, 2010.

47. Roussou, M.: "*Virtual Heritage: From the Research Lab to the Broad Public*", F. Niccolucci, ed. Virtual Archaeology. BAR International Series, pp. 93-100, 2002.

48. Rutherford, J.: *"KNODES: knowledged-based design decision support*", CADD Future 1993, pp 257-374, 1993.

49. Sammartano G.: *"Suitability Of 3D Dense Models for Rapid Mapping Strategies on Cultural Heritage Documentation and Conservation"*, PHD Thesis, Politecnico di Torino, 2018.

50. Sanvido, V.: *"Linking levels of abstraction of a building design"*, Building and Environment, 27(2), pp195-208, 1992.

51. Selvaggi, I., Dellapasqua, M., Franci, F., Spangher, A. Visintini, D. & Bitelli G.: *"3D Comparison Towards a Comprehensive Analysis of a Building in Cultural Heritage"*, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-2, 1061-1066, doi:10.5194/isprs-archives-XLII-2-1061-2018, 2018.

52. Silani, M., Giorgi, E., Boschi, F., Bitelli, G. & Martellone A.: "*Seeing into the past: integrating 3D documentation and non-invasive prospecting methods for the analysis, understanding and reconstruction of the ancient Pompeii. The case of the House of Obellio Firmo (IX, 14)"*, Archeologia e Calcolatori, 28.2, pp. 361 – 367, 2017

53. Scianna A., La Guardia M.: *"Globe Based 3D GIS solutions for Virtual Heritage"*, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-4/W10, 2018.

54. Tan, B.K., Rahaman, H.: "*Virtual Heritage: Reality and Criticism. In: T. Tidafi and T. Dorta*", ed. Joining Language, Cultures and Visions: CAADFutures, pp. 143-156, 2009.