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BIM model for existing building stock: optimisation and validation of the processes

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Introduction

The early years of the twenty-first century saw the advent of the fourth industrial revolution based on the following concepts: connection between digital systems, definition of big data, and automated procedures. Many industrial sectors introduced these instruments and ensuing new work methods in production lines and factories. Unlike other sectors, the AEC sector (Architecture, Engineering and Construction) did not immediately adapt to this novel situation and only in recent years has it tried to reduce the technological gap. Many analyses, including the annual reports by the World Economic Forum (World Economic Forum, 2017) emphasise that the AEC sector has been in recession for several years and that the lack of updated systems is one of the main causes. The report also indicates the digital instruments required to relaunch the sector: they include BIM and its three definitions: Building Information Model, Building Information Modelling, Building Information Management. Specific norms and guidelines have been issued by numerous countries so that BIM can be introduced into the AEC sector, primarily for new buildings or important infrastructure work orders.

In the last few years there has been growing interest in the possibility to introduce a similar work method for existing buildings, especially public buildings, and for their maintenance and management. In particular, the 2011 census of buildings by the Italian Institute of Statistics (ISTAT, 2011)[1] reported that there were 14.5 million buildings in Italy, of which over 70% were built before 1980. It is important to remember that roughly 57% of this heritage was built using load bearing walls while almost 30% used reinforced concrete. One million of the 14.5 million buildings is publicly-owned while 23% (230,536) is used by public institutions. All existing buildings, especially public buildings, have to be maintained; achieving this goal requires reliable, updated data and graphics.

BIM makes it possible to create coherent, detailed digital models of buildings; these models can simplify planned interventions, improve the management of spaces and systems, reduce emissions, and optimise performance. Parametric modelling of existing heritage also enables digitalisation of the geometries of the building elements and storing of data which is then placed in a single, easy-to-consult updatable file. The information can be used to maintain and manage the building in question, create simulations, and develop guided tours. These instruments have yet another advantage: they facilitate collaborative participation. No more searching in archives for data, but instead simple access to a database using the internet, an option that was crucial during the lockdown triggered by the Covid-19 virus. However, BIM is not a magic bullet: it was developed to design and build new constructions, for which we now have consolidated procedures. Instead as regards existing buildings, the system is still rather problematic due to the fact that the platforms available on the market are not optimised for these functions. In fact, traditional three-dimensional design and modelling software programmes (CAD) make it relatively easy to reconstruct geometries. Parametric BIM software is less versatile and has more constraints compared to its predecessors; these difficulties have been widely illustrated in literature. The goal is to optimise the parametric model

[1] The figures refer to the last available census by ISTAT.

reconstruction process by creating applications that successfully discretise the geometry of the input data so that the building elements can be inputted more rapidly.

Having clarified the initial difficulties regarding the geometric characterisation of BIM models for existing buildings, it is important to point out that an object's form is only part of the data. A specific corresponding category exists for each building element that can be characterised using parameters and specific information. The BIM methodology envisages that complex information be stored in the general model; coherent information depends on the input data which often leaves no trace. It is therefore necessary to describe the control parameters that permit us to understand the nature of the data with which the digital clone of the building has been created, thereby allowing us to fully evaluate the end result. The studies reported in literature have been performed on different parameters focusing primarily on the geometry of the model and less on information.

After building a suitably developed model, with traces of all the inputs, the data in the model can be used to manage a building, even if BIM platforms do not include analytical instruments. These models therefore need to be imported into another platform either assigned or adapted to management; this platform must ensure traceability of all changes to the database and make the data easily accessible. These problems become even more evident when applied to a group of buildings since it is necessary to gather more information regarding the georeferencing of each element and the context in question. The work method that needs to be created must not only envisage an interconnected database system capable of exploiting certain potential features of BIM, but also work at a superordinate level. In particular, the goal was to develop a GIS-BIM system for building management after analysing published studies concentrating chiefly on problems of interoperability between the two systems; possible alternative options to this system were also analysed.

This process led to the drafting of guidelines, summarising the entire process from digitalisation to data management, analysing the fundamental figures in each phase and the skills required.

A review of the state of the art showed that scholars of scientific disciplinary sector ICAR/17 "Drawing" have for years focused part of their studies on the evolution of digital instruments and the safeguard of existing building heritage.

The study presented here continues along these lines in order to define a work method for the digitalisation and management of existing building heritage. It must be resilient, envisage sustainable procedures for both the public administration and private entities, and identify the potential of the current systems as well as any critical issues.

In particular, the objectives were as follows:

- creation of processes and new instruments to simplify data digitalisation;
- definition of parameters to describe the nature of the input data and reliability of the built model;
- definition of a BIM – GIS method to manage buildings;
- development of guidelines for both the public administration and private entities.

The innovative features of the doctoral thesis are:

- semi-automation of part of the CADToBIM and ScanToBIM processes;
- definition of the CoIN, Confidence of Information Needed, and SuRe, Survey required;
- multiscalar management of building heritage through the combined use of GIS and BIM platforms;
- complete discipline of the digital process, from data acquisition to building management and digital data.

The work method is based on six work phases, each one preliminary to the next; they are:

- Model Definition, indicating the geometric and information characteristics of the BIM models;
- Data Acquisition, in which details are provided regarding the data to be acquired and relative survey method;
- Model Reconstruction, during which different instruments of the BIM platforms are used to complete the digital twin of the building;
- Model Checking, including the operations needed to ensure that all the elements are coherent, both graphically and from the point of view of information;
- Model Fixing, envisaging integration, where necessary, of further studies so as to ensure correct completion of the study;
- Data Management, characterised by importation of the result obtained in a GIS platform, cataloguing, and reuse of the result.

The doctoral thesis is divided into five parts:

- definition of the state of the art, presenting the fundamental features of the issues in questions;
- description of the work method, including the strategies to optimise the processes;
- identification of the research field and case studies in order to validate the aforementioned methodology;
- results and conclusions;
- annexes.

This study was part of an Industrial Doctorate project involving two sponsors: the Negroni Key Engineering company with a consolidated background in the computer sector, more specifically in BIM, and Platinum partner of Autodesk; and the Universidad de Valladolid which for years has been performing critical studies in the field of photogrammetric and laser scanner surveying and digitalisation.

State of Art

The advent of BIM and the three meanings of the acronym

BIM modelling evolved from the development of previous systems to innovate processes and methods in the AEC sector (Architecture, Engineering and Construction) and is in fact based on the application of the parameterisation of objects. However it is incorrectly believed to be the direct consequence of computer-assisted drawing (CAD 2D) and three-dimensional modelling (CAD 3D): BIM drawings are not just two-dimensional drawings or rendered models. So in order to tell them apart from graphic documents created using digital tools, an acronym was invented condensing three different meanings:

- Building Information Modelling, the object resulting from the modelling operations;
- Building Information Modelling, a collaborative and participated work method based on open standards;
- Building Information Modelling, the possibility to manage the entire lifecycle of the building, from its design and construction to maintenance and demolition.

The Building Information Model is the product of the process illustrated below. It is important to emphasise that objects are modelled in a three-dimensional space and not simple geometries: as a result the model is not just a digital representation of a building, but contains all graphic and other data about the building. Initially the digital prototype of the building, it becomes the digital copy at the end of the worksite. Every element in the model is linked to a category with certain properties and common, consultable or modifiable characteristics. These categories of objects represent different features of the built, such as architectural elements, structural elements, and systems. Other categories of accessory elements also exist, for example non-building elements which are however crucial to the realisation and interpretability of the model: they include views and annotation symbols. The objects in BIM therefore represent databases that have to be compiled; the data they contain must be uniform and not contradictory. Furthermore, in parametric modelling, rebuilding an object is characterised by the conservation of all the geometries, Boolean operations, and constraints used to create it; this makes it possible to consult and modify its parameters and instantaneously modify the object, thereby decreasing the number of possible errors since these modifications can affect all the objects in the category in question.

Building Information Modelling is a work method based on interoperability, collaboration and participation. Interoperability is the possibility to actively participate in the participatory process without having to depend on proprietary files or specific computer-aided software programmes (CASE). International standards are being continually updated in order to define an open file format for BIM: the most famous format is IFC (Industry Foundation Classes). The latter is internationally regulated by ISO 16739 -1:2018 "Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries" and promoted by buildingSMART, a worldwide industry body driving the use of digital tools in the AEC sector; several different CASE software are associated with it: Autodesk, Bentley, Esri, Graphisoft, Trimble, etc. (buildingSMART, 2020). Interoperability thus permits information to be shared by the players active in the process, players who work on single models and databases either by using interchange formats or applications to transmit files between different software programmes. Sharing data and models is a simultaneous rather than sequential process, one that uses computerised management platforms, also called CDE (Common Data Environment), identified in Italy by the acronym ACDat (Data Sharing Environment). This software makes it possible to establish different level of access to the information; from those who can only visualise it to those who can modify the files, and keep track of the versions and variations to each document.

The Building Information Management acronym contains all the features relating to management of the built; BIM enables optimisation of the processes involving all the phases of the building's lifecycle because the data in the models can always be used. During the design phase it is possible to identify several problems that will arise on the worksite by using Clash Detection tools, i.e., verification of interferences; this involves checking whether that are compenetrations of mass (Hard Clash) or whether minimum spaces between elements have been respected (Soft Clash). This enables any incongruence to be solved even before it occurs on the worksite, thereby reducing the number of errors and saving precious time. In addition, all the scales of the model can be established and extracted so as to calculate all the quantities and work to be performed. It is also possible to use laser instruments, such as a Laser Scanner or Photogrammetry, to verify whether construction is proceeding as planned; on-site measurements can be compared to the model using interference verification instruments. The real potential of BIM is in fact evident when construction is completed; after the data in the model has been updated at the end of the worksite phase, it can be used throughout the building's lifecycle. This information is crucial either when planning maintenance or to manage the spaces and systems. At the end of the building's lifecycle the BIM model can provide information about which materials were used, making it possible to establish which materials can be recycled and how to dispose of those that are non-recyclable.

Eastman's handbook (Eastman, et al., 2011) is one of the most important publications on this issue; he explains the fundamental concepts of BIM and analyses the key advantages of introducing this methodology depending on the actors involved (Clients, Technicians and Contractors). He also provides: information about the main software programmes on the market, references to international regulations, and several examples and applications. Nevertheless, BIM is still not readily adopted by professional studios and public administrations that appear reluctant to use it: in fact many studios have simply focused on analysing the trend. One reason behind this approach is the fact that BIM software does not facilitate the creation of models. In fact, defining objects becomes extremely complicated (Garagnani & Cinti Luciani, 2011) without the ordinary, standardised solutions typical of the Anglo-Saxon world where most programmes are developed. Several problems of interoperability and transmission of data between different platforms have been reported, thereby reducing the possibility of establishing a participatory process (Migilinskas, et al., 2013). Updating the software and using specific plug-ins facilitates the interchange of models; however this procedure is still not completely efficient. Apart from the costs of updating the hardware and software tools, doubts about BIM are also fuelled by the investments required to introduce this method into the AEC sector (Liu, et al., 2015); these investments are substantial if one also considers the investment required to either train or hire staff. In their study Ku et al. (Ku & Taiebat, 2011) highlight the fact that training not only involves huge economic investments, but also a long timeframe to acquire BIM skills (roughly eighteen months). Apart from the problems already illustrated in literature, Sun et al. (Sun, et al., 2017) analyse how BIM continues to be held back by a lack of clear user guidelines and by the reticence of more conservative actors. To reduce the impact of a shift to the BIM methodology, and to remedy the lack of specialised personnel, some companies and studios have preferred to outsource these processes, either partially or completely (Fountain & Langar, 2018).

Regulatory aspects

The gradual introduction of BIM has required that countries regulate the processes and define specific norms, not only to protect interested parties, but also to clarify and delineate its applications.

The United Kingdom was one of the first to use BIM in projects; this is why their standards - BS 1192:2007 (British Standard Istitution, 2007)and BS PAS 1192-2:2013 (British Standard Institution, 2013)- remained one of the main international references for such a long time. A crucial input was made by Finland regarding the establishment of guidelines Common BIM Requirements 2012 (COBIM) (builingSmart Finland, 2012), divided into 13 handbooks written in Finnish and English. The buildingSMART Finland association also participated in drafting the guidelines which in 2013 were reviewed, translated and broadened by Building Smart Spanish prior to their publication in Spain. The Guías uBIM (buildingSmart Spain, 2014) includes 14 documents; the last one written in 2018 is entirely dedicated to cultural heritage. In 2014 the European Parliament legislated on the issue by passing Directive 24 (European Parliament, 2014) in which article 22 "Rules applicable to communication" paragraph 4, establishes that:

"… For public works contracts and design contests, Member States may require the use of specific electronic tools, such as of building information electronic modelling tools or similar…".

European Union countries began to upgrade their regulatory tools by introducing wording that allowed BIM to be used in procurement contracts and public competitions. In Italy the first step in this direction was the updating of the 2016 Public Contracts Code. Article 23 "Levels of planning for contracts, work concessions as well as services", paragraph 13, establishes that:

"Contracting authorities or entities may require for new works as well as recovery works, requalification or variants, primarily for complex works, the use of specific electronic methods and tools as referred in paragraph 1, letter h). Those tools shall make use of interoperable platforms by means of open, non-proprietary means, for the purpose of not limiting competitions between technology providers and the involvement of specific planning among designers. The use of electronic methods and instruments shall be required only by contracting authorities or entities with adequately trained staff. By means of a decree of the Minister of Infrastructures and Transports to be adopted by 31 July 2016, also relying on a Commission specifically appointed by that same Ministry, without additional charges for public finances, the modalities and timeframe for the progressive introduction of the mandatory nature of that abovementioned methods for contracting authorities and entities, conceding administrations and economic operators, assessed with reference to the typology of the works to be awarded and the strategy of digitalisation of public administrations and building sector shall be defined. The use of those methodologies shall constitute a parameter for the evaluation of the rewarding requirements set out in Article 38".

Ministerial Decree 560/2017 (Ministry of Infrastructure and Transport, 2017), also known as the Baratono Decree, was issued in 2017 to implement the aforementioned article. It outlines all the criteria for the introduction of BIM in public procurement contracts; in particular:

- Article 2 explains some of the terms used in the text of the decree;

- Article 3 illustrates what the clients have to do in advance, in particular they have to:
  - train staff regarding specific issues relating to the electronic instruments and methodologies related to modelling for buildings and infrastructures;
  - acquire or maintain hardware and software instruments;
  - explain the process regarding digital data control and management, as well as conflict management.
- Article 4 envisages the exclusive use of interoperable instruments and therefore of open and non-proprietary formats;
- Article 5 establishes that clients can request the use of BIM for all types of interventions so long as they have fulfilled the requirements of Article 3. In Article 6, this option becomes mandatory when the works exceed a certain threshold which decreases at predetermined intervals of time; it was 100 million in 2018 but in 2025 all public works requires the use of BIM;
- Article 7 contains a description of the structure and contents of the specifications, i.e., the document that has to be attached to the call for competition;
- Article 8 establishes a monitoring commission to understand the difficulties inherent in the application of the decree and to identify preventive and corrective measures so that it can be updated. Article 9 concludes the decree specifying the terms of its entry into force.

The decree laid the foundations for a constructive discussion about BIM; the technical specifications were instead laid down in UNI Standard 11337 "Digital Management of information construction processes" (UNI Ente Italiano di Normazione, 2017). The current standard actually replaces the previous standard "Criteria of codification of construction works and products, activities and resources" (UNI Ente Italiano di Normazione, 2009) of which only part three was maintained. It is important to mention that the draft of the text introduced BIM before PAS (Ingenio - Informazione tecnica e progettuale, 2020). The current standard is divided into ten parts, of which the following have been published:

- Part 1, "Models, drawings and information objects for products and processes" specifying and explaining the terms to be used;
- Part 3 "Models of collection, organisation and storage of technical information for construction products" and Part 4 "Evolution and information development of models, drawings and objects" outlining the concepts of "Level of Development of Objects – information attributes" (LOI), "Level of Development of Objects – Geometric attributes" (LOG) and Level of Development (LOD) of objects, with relative specifications;
- Part 5 "Information flows in digitalised processes" defines the procedures and management of the information requirements; it also illustrates which documents have to be compiled. They include Information Specifications (IS); and, as specified in the title, Part 6 "Guidelines for the drafting of the information specifications", contains guidelines for the drafting of these specifications;
- Part 7 "Requirements of knowledge, ability and proficiency of the figures involved in management and information modelling" outlines four professional figures, with

different roles, and lists the specifications regarding their certification, i.e., the skills they need to have in terms of working experience and specific proficiencies.

The international standard ISO 19650 "Organisation and digitisation of information about buildings and civil engineering works, including building information modelling (BIM) – information management using building information modelling", was published in 2018 and later adopted in Italy (UNI EN ISO 19650) (UNI Ente Italiano Normazione, 2020) and the United Kingdom (BS EN ISO 19650) (British Standard Institution, 2020). The standard published in Italian and English currently has two parts as well as national attachments that differ between the two countries:

- In Italy, UNI 11337 is an integral part of Standard UNI EN ISO 19650, which is nevertheless superordinate;
- In the United Kingdom, the international standard has absorbed the principles of BS 1192 and PAS 1192-2, which have been completely withdrawn (Ingenio - Informazione tecnica e progettuale, 2020).

In particular the international standard updates and modifies several concepts envisaged in previous standards:

- The LOD concept became obsolete after the establishment of a new parameter known as Level of Information Need (LoIN) (Pavan & Mirarchi, 2019);
- The presence of a dual CDE/ACDat, one by the client and one by the person entrusted with its implementation, that share several pieces of information (Ingenio - Informazione tecnica e progettuale, 2020).

LOD: characteristics, differences and evolution

Both the guidelines and the standards envisage a parameter describing the amount of graphic and non-graphic information associated with a specific object or category of objects: this parameter is usually indicated by the acronym LOD, Level of Development. Albeit with certain differences, these regulatory instruments identify a scale of increasing numerical or alphabetical values with a greater quantity of data. The LODs are characterised by another two parameters: one relating to the geometric features of the object, known as LOG (Level of Geometry) or LOD (Level of Detail), and another relating to the information, known as LOI (Level of Information); to avoid confusion, the acronym LOD will be used to indicate the Level of Development of the objects. The value scale of the LOD refers to the lifecycle of the building; most of the regulations establish six different levels, ranging from conceptualisation to completion of the building. Italian regulators have established seven levels, each with a letter in order to distinguish them from their foreign equivalent: the first six correspond to the ones used in other international standards while the seventh and last refers to the updating of the objects in use and also includes data regarding maintenance. In particular, they are:

- LOD A – Symbolic object;
- LOD B – Generic object;
- LOD C – Defined object;
- LOD D – Detailed object;

- LOD E – Specific object;
- LOD F – Executed object;
- LOD G – Updated object.

The Italian standards contain specific scales defining the objects, including for restoration, encumbered assets, tools, equipment, new constructions, restored buildings, the territory and infrastructures; this is the first time a standard envisages these two latter types of objects.

However, the new European regulatory upgrades establish a new parameter defining information regarding individual categories of objects: the Level of Information Need (LoIN). It differs from LOD insofar as it envisages that, apart from geometric features (LOG) and information aspects (LOI), documentary information, known as DOC, can be associated with each object. In addition, there is no predetermined reference scale, unlike the one for LOD; the client has to specify the characteristics of each object.

BIM for existing buildings: HBIM

While BIM was initially developed for the design and construction of new buildings, other instruments and methods were gradually being used to create digital models of existing buildings, especially historical buildings. Points clouds and mesh surfaces made it possible to rebuild realistic, detailed, three-dimensional models; the next step was to apply the BIM principles. Murphy et al. (Murphy, et al., 2009) established a work method for Cultural Heritage called Historical Building Information Modelling. It envisages integrating data from surveys performed using digital instruments (e.g., laser scanners and photogrammetry) with historical documents so as to parametrically model the elements of a historical building. This creates libraries of objects which are then used to rebuild a model of the building with less details than the one rebuilt using surfaces and meshes, but with all non-geometric data. The parametric model also facilitates the production of technical drawings and two-dimensional graphics. Later studies have opted to generalise the HBIM acronym, turning it into Heritage BIM (Brumana, et al., 2013), thereby extending the methodology to non-historical buildings (Centofanti, et al., 2016). Although it differs only slightly from the previous wording, there are substantial differences between BIM and HBIM, even if they do have some points in common; in fact, when working on existing buildings it is important to have reliable data before initiating modelling (Del Giudice & Osello, 2013). Should the data be insufficient, whether it be points clouds or two-dimensional drawings, then it has to be supplemented by survey activities in order to characterise the BIM model with all geometric and non-geometric data. The study by Volk et al. (Volk, et al., 2014) shows that the most serious problems regarding input data involve the positioning of the systems, reconstruction of the roofs, definition of the materials used, and the internal characterisation of the structures. Many studies have tried to solve some of these problems by merging different methodologies and survey instruments in order to make the input data more reliable and reduce the time of acquisition; in fact there is an increasingly frequent use of aerophotogrammetry from UAVs (Unmanned Aerial Vehicle) (Themistocleous, et al., 2016; Carvajal-Ramírez, et al., 2019), Mobile mapping (Campi, et al., 2018) or the combination of laser scanners and photogrammetric surveys (Bolognesi & Garagnani, 2018). Other studies examine the cost reduction achieved through survey activities using low cost instruments and verification of the validity of the ensuing results (D'Agostino, et al., 2015; Barbato & Morena, 2017; Atteni, et al., 2017). Input data represents one of the problems inherent in HBIM; others involve the modelling of the specific elements. The software is the same software used for BIM, i.e., linked to new constructions or in any case to modern buildings; as a result, reconstructing the non-standardised elements typical of historical buildings is rather complex. In fact, parametric modelling is very effective for geometrically regular elements, but becomes very complicated when it involves existing objects tendentially made up of heterogeneous and often unique forms (Logothetis, et al., 2015). The unique building elements highlight another difference between the two methodologies: the possibility to share objects between different projects. A platform to share objects exists for BIM elements; here they are catalogued, divided by category, and can be compared based on their technical specifications, for example the INNOVance Project (Pavan, et al., 2014; Daniotti, et al., 2017). Instead all the objects in HBIM projects have different characteristics which should preferably be placed in dedicated libraries, starting with accurate historical documentation and supported by digital surveys (Baik, 2017). While the elements are serialised by using parameterisation operations and simplifying the geometry, attempts are made to preserve their uniqueness and specific characteristics by linking the points clouds of each individual element (Attenni & Rossi, 2018). The reconstruction of complex geometries has fascinated several scholars who have used different instruments and methods. In his works Garagnani (Garagnani, 2013) presents a plug-in of Revit© 14 that recognises important vertices and corners in points clouds that can be used to reconstruct the elements. The illustrated methodology begins with normal survey operations using mass acquisition instruments, and continues with cleaning, decimation and reduction of noise; manual semantic segmentation of the points cloud is then implemented to identify individual elements. After that the result is exported into a ASCII format file containing the XYZ coordinates of every point; the result is then imported in Revit© using the GreenSpider plug-in that turns the text into reference points for the Revit© mass models. The plug-in also makes it possible to either decimate the points and transform them into elements that can be selected using snap, or create a curve interpolating the vertices; it is then possible to recreate a mass made up of surfaces. Instead the study by Tommasi et al. (Tommasi, et al., 2016) focuses on the reconstruction of complex elements, specifically the "Falconatura" of the Cathedral in Milan, using different methodologies and modelling software: direct modelling, using Rhinoceros© software, generative parametric software, using Grashopper© software, and finally object-based parametric modelling, using Archicad© 19 and Revit© 16. Comparing the methodologies and instruments highlighted the fact that parametric modelling based on objects, especially the Revit© software, is the best solution for the built, because apart from the geometric data it is possible to associate historical documentation and data from the points clouds. However the study again shows that none of the instruments currently on the market have all the tools required to achieve perfect modelling of existing buildings. Paris and Wahbeh (Paris & Wahbeh, 2016) demonstrate how it is possible to integrate algorithmic modelling for typical elements of cultural heritage; in particular, the study focuses on the reconstruction of the colonnade of the Royal Staircase in the Vatican. Starting with the construction of a parametric "column" object, the study defined several fundamental measurements manually extracted from the points cloud. Having collected this data and rebuilt the profiles of certain parts of the column, they were used as input data of the suitably drafted algorithm generating the solids in question in the right position, based on the coordinates of the imported points. Other studies concentrated on the reconstruction of complex elements, for example vaults, either by manually parameterising them, or by using external applications that allow the surface in question to be discretised. In fact, a geometric study of these elements makes it possible to approximate a reconstruction directly in a BIM environment, implementing in-place modelling and using snaps on the point cloud (Di Luggo & Scandurra, 2016). Further studies have tried to approximate the surface of a vault and parameterise its shape by geometrising it (Scandurra, et al., 2018). Instead the approach adopted by Oreni et al. (Oreni, et al., 2014) is very different; they show how NURBS surfaces (Not Uniform Rational Basis-Spines) can be used to improve interpolation of the surface of domes and vaults. Since this kind of surface cannot be created on a BIM software, a three-dimensional modeller is required (Rhino©); however it does not allow more information, e.g., materials, to be added. This work method envisages an initial interpolation on the points cloud of the surface in question, described using a NURBS surface, which is then parameterised and recreated in BIM, with appropriate simplifications. Other studies have led to the creation of an application that has automated the process needed to create the surface in BIM; achieving this required using the API (Application Programming Interface) of the Revit© software (Banfi, 2019).

Automatic reconstruction of three-dimensional models

The ambition to optimise the processes has led many researchers to try and automate the reconstruction process of geometric models, starting with points clouds. Some of these algorithms are based on the hypotheses by Manhattan World; the statistical studies by Coughlan and Yuille (Coughlan & Yuille, 1999) have shown that manmade structures can be approximated by flat surfaces, parallel to a triad of main planes, orthogonal to each other. This hypothesis was used to identify structures within images and is easy to verify in urban contexts and interiors; further in-depth studies have shown that it is also applicable in rural areas (Coughlan & Yuilla, 2000; Coughlan & Yuille, 2003). An attempt was made to apply this hypothesis to the automatic reconstruction of digital models from points clouds; due to the nature of the input data, the algorithms require the identification of continuous surfaces and not solid volumes. Studies have demonstrated gradual development of the algorithms of pattern recognition and reconstruction of the elements, identifying increasingly complex elements of the buildings: at first this chiefly involved walls and the holes inside (Adan & Huber, 2011). Later studies preferred to reconstruct the elements using iterative, statistically-based methods, such as the RANSAC method (RANdom SAmple Consensus); Sanchez and Zakhor (Sanchez & Zakhor, 2012) used this method to rebuild not only walls and floors, but also stairs. This solution was later studied in-depth in other studies, for example by Oesau et al. (Oesau, et al., 2014) and Li et al. (Li, et al., 2018), who integrated a horizontal segmentation of the points clouds into the RANSAC method to reconstruct the surfaces of a building. Yang et al. (Yang, et al., 2019) developed a method that goes beyond the Manhattan World Assumption and succeeded in reconstructing curved walls. This method also envisages the horizontal segmentation of the points cloud, but to define the curves it uses a different statistical method compared to RANSAC: the Mean Shift method. This method is also used in Machine Learning applications for Cultural Heritage and for the classification and segmentation of points clouds through primitives (Grilli, et al., 2017; Grilli & Remondino, 2019). Literature is full of examples of the automatic reconstruction of BIM models: Wang et al. (Wang, et al., 2015) analyse several instruments on the market and describe their advantages and limits; these instruments make it possible to select, identify and generate elements from a point cloud. They then present an algorithm for the automatic extraction of the geometries from points clouds, adding the results of three case studies. The algorithm enables recognition of specific elements such as walls, windows, doors and roofs based on the intrinsic definition of the elements themselves, e.g., verticality for the walls or horizontality for the roofs. In their study Macher et al. (Macher, et al., 2019) use the hypothesis by Manhattan World and the iterative RANSAC method to create an algorithm that recognises flat surfaces in points clouds which are then used to reconstruct walls in a BIM environment.

The authors also express interesting considerations about the almost complete lack of instruments that use points clouds to create BIM models, also known as the SCAN-to-BIM methodology.

The need for parameters regarding input data reliability

The reconstruction of a BIM model involves a data acquisition phase; the data must be quantitatively sufficient and also reliable. Therefore it is important to define a parameter summarising all the features of the input data. For example, in the Finnish COBIM guidelines (2002) two parameters are envisaged in series 2 "Modelling of the starting situation", paragraph 4 ("Requirements pertaining to source data"). The parameters refer to the requirements that may be needed to reconstruct a model: one for the survey instruments required, the other for the type of studies to be performed. Both parameters envisage three levels: those indicate a gradual increase in the precision of the surveys and the amount of the data to be reported. In the paragraph, it also specifies the resolution and accuracy of the individual instruments to be used for each level. A different approach is contained in the document drafted by the U.S. Institute of Building Documentation (USIBD), USIBD Level of Accuracy (LOA) Specification Guide (U.S. Institute of Building Documentation, 2016), describing the LOA, Level of Accuracy, parameter: it represents the required accuracy of the surveyed element (Measured Accuracy) and that of the reconstructed element (Represented Accuracy). It contains five different levels, from LOA10 to LOA50, corresponding to increasingly narrow intervals within which the measurement is considered acceptable. The first draft was published in 2015; later updates, version 2.0 (2016) and version 3.0 (2019), provided a more precise definition of the reference intervals and also introduced the UDLOA, User Defined LOA; this interval is specified directly by the user depending on operational requirements. However this parameter deals only with the geometric nature of the data and totally ignores the ontological or information nature of the elements. Studies by Bianchini and Nicastro (Bianchini & Nicastro, 2018) have led to the definition of the Level of Reliability parameter (LOR) containing information about the geometric correspondence of the element to the real one, but also the ontological correspondence and presence of information regarding the physical and technological characteristics of the material. The LoR value is between zero and ten, i.e., the maximum value of an element about which we know everything and which corresponds to the real one. Maiezza (Maiezza, 2019) works on the denomination of the LoR, but modifies its nature, adapting it to the dictates of UNI 11337 by defining an analogy between Level of Development and Level of Reliability. In fact, if the LoD are defined by a geometric quota (LoG) and an information quota (LoI), the corresponding LoR will be the sum of a quota relative to the accuracy of the geometric data, known as Level of Accuracy (LoA), and a quota regarding the quality of the information regarding a single element, known as Level of Quality (LoQ). The study by Graham et al. (Chow, et al., 2019) presents the parameter for LODIA, illustrating not only the features related to the geometries and data of the modelled elements, but also those related to the reliability and resolution of the input data. It is also important to emphasise that by accessing the API of the software it is possible to create plug-ins with which to verify the reliability of the BIM model reconstructed based on the points cloud taken as reference, as illustrated in the study by Macher et al. (Macher, et al., 2019).

The real potential of BIM: Facility Management

The introduction of BIM or HBIM methodologies requires enormous investments to build the models and ensure their upgrading; costs can be completely recovered only if the data is exploited during operations pertaining to the management, recovery and energy requalification of buildings (Brumana, et al., 2013; Osello, et al., 2016). In particular, using these methodologies for Facility Management (FM) facilitates the drafting of maintenance plans and reduces management costs (Carbonari, et al., 2015). In fact BIM models are more effective compared to CAD drawings because they provide more accurate geometric data and enable association of the information aspects of each individual element (Kassem, et al., 2013). This is the reason why parametric models will completely replace two-dimensional drawings in the near future, not least due to the fact that cloud-based instruments provide worldwide access to models (Azhar, et al., 2012). However some difficulties are slowing down the introduction of BIM in Facility Management, e.g., the lack of staff trained to use digital instruments and the problems of interoperability between platforms that lead to a partial or total loss of data of some elements (Pärn, et al., 2017). However barcodes can link elements pertaining to the real world with those of the digital world, as demonstrated by Chu et al. (Chuan, et al., 2012) who used the QR Code to catalogue medical equipment in a hospital. The study by Lin et al. (Cheng Lin, et al., 2014) showed that these barcodes can be associated with the elements of a BIM model, thereby making it possible to immediately modify the specifications of each element, so as to obtain continually updated data. However these barcodes do have several critical points, for example they are perishable and have to be replaced after the BIM model has been updated by expert staff. Other sensors can be used to solve the problems linked to the QR Code, e.g., the ones that use radio waves (RFID), WiFi footprints, Ultrasounds or Bluetooth systems (Beacons); Mirarchi et al. (Mirarchi, et al., 2018) focused on the latter and illustrated the advantages and disadvantages of all these systems.

Management of building complexes

The possibility to programme maintenance and easily update the data of the models has made the HBIM methodology a fundamental resource in building management, especially public building management (García-Valldecabres J., 2020). When the objective is to optimise the management of building complexes this method creates no problems in terms of the georeferencing of buildings. As regards the geometric features, BIM software programmes consider three-dimensional space on a Cartesian plane in which axis Z is orthogonal to the plane; this is a perfect reference when the objective is to define individual buildings. However, when a group of buildings is involved, this kind of simplification is unsuitable because it is important to know how the geoid of the earth is approximated. The problem increases when the elements have a planimetric development that is much bigger than the altimetric development, for example in infrastructures, or when the elements are distant from each other, e.g., a group of individual buildings. In addition, no specific instruments dedicated to the management of BIM platforms exist as regards information aspects. Studies have been performed to remedy the shortcomings of this method. Two main solutions have been identified: the use of specific Facility Management software or the GIS (Geographical Information System).

Management software and Italian universities

The Facility Management software programmes currently on the market have common characteristics and are used by several public and private agencies. They make it possible to:

- manage heterogeneous data, relating to spaces, archives and staff;
- catalogue and share documents;
- organise maintenance and periodic checks.

Some also provide for performing energy analyses; furthermore, most of the software currently available enables importation of geometric data, primarily CAD type data, but also BIM data. Several entities are using these instruments to manage building heritage; for example, this kind of instrument has been introduced by some Italian universities: the Politecnico di Milano, the Politecnico di Torino, and the University of Basilicata (UNIBAS). The two polytechnics have always been precursors, adopting these instruments to manage the University's building heritage; they both use the Archibus© platform which can acquire data directly from the Autodesk© software company, such as Autocad© and Revit©, and the Esri© software company, such as ArcGIS©. Technical offices currently use geometric data based on CAD files, but they have already established workflows for the future introduction of the BIM method. The University of Basilicata adopted a different approach; it based its work method on BIM data. In fact, in 2016 UNIBAS sent out a call for tender for the "Delivery of an information system to support heritage management and revision and updating of the University's inventory": it envisaged:

- delivery, installation and activation of an information system supporting heritage management operations;
- geometric reconstruction in BIM of the campus area with all the elements belonging to its movable heritage;
- allocation of tags based on RFID technology as well as the instruments needed to use it;
- reconnaissance and inventory updating;
- training regarding BIM methods and management system.

The reconstructed BIM model associates the RFID tag to the ID of the object in question in the management platform where it is possible to perform all cataloguing operations. In this case the management platform was NextFM© for which Revit© envisages a plug-in to directly export the geometries. However this work method is limited re the interoperability between platforms and formats: the management software enables the importation of all the geometric data of the BIM model, but not the information aspects. This requires manual insertion in the two platforms, increasing the time required and the size of the file to be consulted. To solve this problem the geometric components are separated (and entrusted to the BIM platforms) from the informative components, in part associated with the parametric model and in part loaded on the FM platform.

GIS and BIM – GIS: potential and problems

Of all the solutions that were studied, the ones illustrated here used the GIS, making it possible to simultaneously examine many elements in different areas and manage multiple heterogeneous data and not just data about buildings. Del Curto et al. (Del Curto, et al., 2019) performed an in-depth analysis of the characterises and problems of the BIM and GIS systems in order to develop a recovery plan for a twentieth-century building complex in Havana. Their study showed that the GIS was the preferred option as regards the management and analysis of information on different scales, even though the geometric data was limited to two-dimensional elements. Other studies have tried to define the processes that could integrate the BIM and GIS methods, trying to optimise their potential and mitigate the problems. Bianco et al. (Bianco, et al., 2013) defined a work method to manage building heritage data; it involves creating BIM models, with all the necessary data, and then inserting them in a WebGIS as three-dimensional models. The aim is to use virtual and augmented reality to create a digital cadastre containing accessible data and information regarding individual buildings (D'Auria & Strollo, 2017) (Osello, et al., 2018). The interoperability of the open BIM and GIS formats, i.e., the IFC and CityGML, is still fraught with quite a few problems concerning the import of data, both in terms of information (Ma & Ren, 2017), geometry and semantics (Zhu, et al., 2018). These problems are often due to the different nature of the solid modelling types envisaged in the two file formats: in fact, if the IFC format envisages CSG and BRep type modelling, CityGML only uses BRep. Biljecki and Tauscher (Biljecki & Tauscher, 2019) carefully examined these errors and divided them into three macro categories: the ones that depend on the output file. In particular, this first category of errors depends on the creation of open format files which can present imperfections that spread inside the output files. Open formats have these drawbacks when they are used in environments that differ from those in which they are created: IFC or CityGML files, exported from a platform, are incorrectly imported in the software of another company, with ensuing data loss (Noardo, et al., 2019). The second category groups all the problems occurring during conversion of the files; this procedure can lead to the definition of invalid geometries or to an erroneous semantic classification of the elements. The third and last category refers to the interpretation of the databases after conversion of the files; the GIS software cannot manage the huge amount of data in the imported BIM models, and this then blocks the system. All the data transfer operations between the two platforms are bound by a third software known as ETL (Extract, Transform, Load), illustrated by Vacca et al. (Vacca, et al., 2018); in fact the authors use the FME© software, with different plug-ins, to shift data from Revit© to ArcGIS©. Arroyo Ohori et al. (Arroyo Ohori, et al., 2018) outline a "BIM to GIS" method for the conversion of a BIM model, in a IFC format, to a GIS model, in a CityGML format, passing through an ensemble of objects, in .obj format, that preserve the semantic information. However the authors consider that the algorithm does not provide an acceptable solution since it makes numerous errors in the reconstruction of the GIS. Barbato et al. (Barbato, et al., 2018) describe a "GIS to BIM" workflow envisaging the reconstruction of objects in a BIM environment, starting with two-dimensional shapefiles, produced using GIS, and QGIS software Barbato et al. (Barbato, et al., 2018). They are imported in Revit© using the Dynamo© visual scripting open source platform after defining an algorithm that recreates a three-dimensional mass object from a reference surface, simultaneously associating the data defined in the layer. Solving the problem of the BIM GIS interoperability is an issue that also interests the industrial and academic world. In 2017 a collaboration project was signed between Autodesk© and ESRI©, two of the most important producers of BIM and GIS software. This strategic partnership led to the definition of a new workflow: since 2019 it is possible to directly import the native files of Revit© (.rvt) in ArcGIS©. The adequately georeferenced model in BIM is directly uploaded in GIS, creating a specific layer that includes both the geometries and information aspects. Up till then FME© software had to be used to transform the data, with all the aforementioned problems (Autodesk. Inc, 2020; Esri, 2020) (Fig. 1).

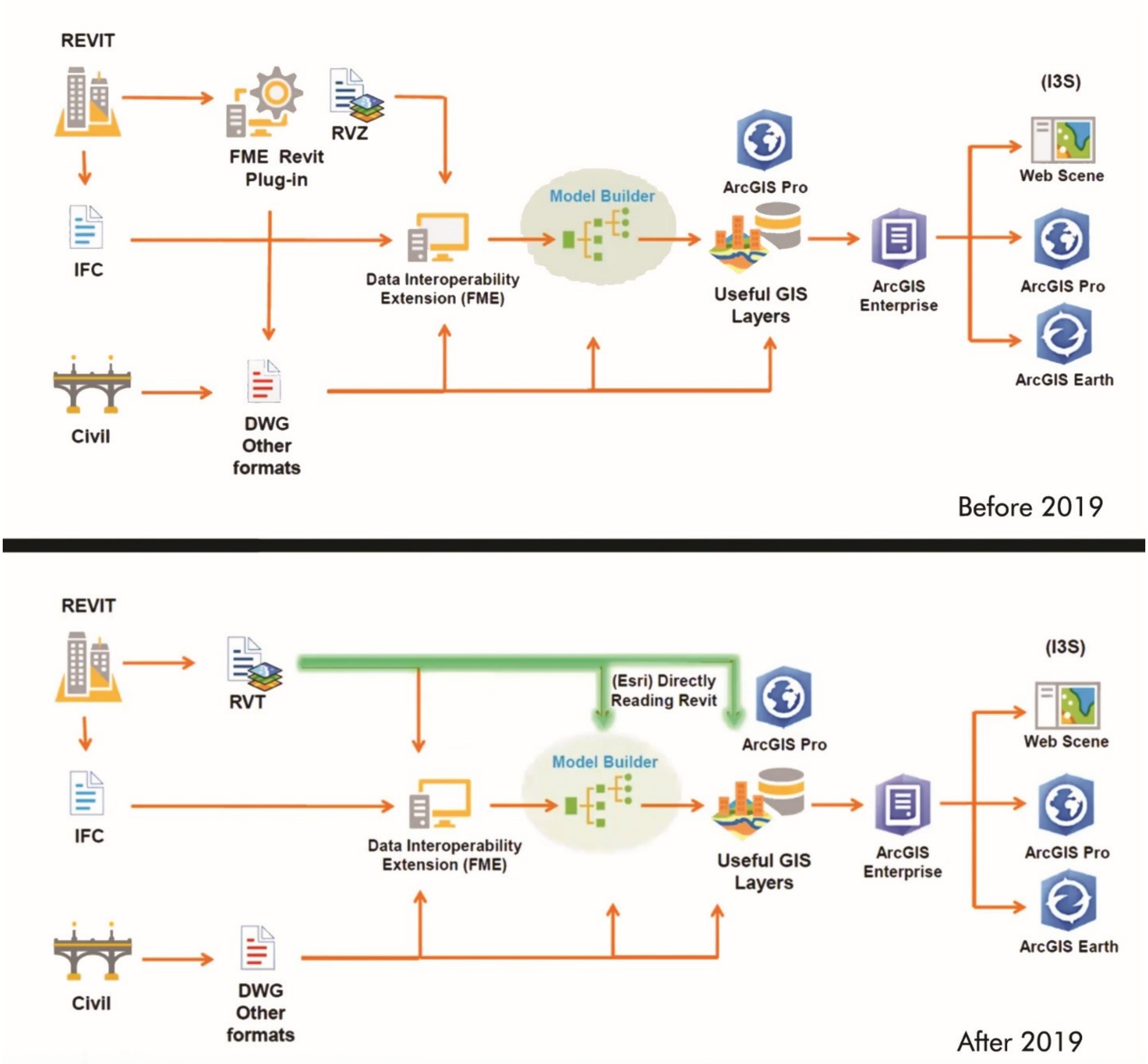

Fig. 1 - Workflow for BIM GIS interoperability, based on the Revit© and ArcGIS© platforms. Top: pre 2019; below: post 2019 (Esri South Asia, 2020).

Objectives and innovative features

Compared to the state of the art illustrated earlier, the outlined research was intended to:

- Create processes and new instruments to simplify data digitalisation;
- Describe the parameters that make it possible to illustrate the nature of the input data and reliability of the built model;

- Define a BIM – GIS method for building management;
- Draft guidelines for the digitalisation and management of existing building heritage.

In particular, the innovative features of the research are:

- Elaboration of semi-automatic processes for recognition of input data elements based on two-dimensional CAD (CADToBIM processes) and points clouds (ScanToBIM processes);
- Definition of two vectorial parameters: CoIN, Confidence of Information Needed, reassuming the geometric and information features, and SuRe, relating to the integration of surveys to be performed in order to complete the process;
- Optimisation of building management by adjusting the information in the various systems, thereby allowing multiscalar interpretation of building heritage.
- The complete discipline of the digital process extends from acquisition to data management.

Methodology

The purpose of this work is the optimisation and validation of the importation process of geometric and non-geometric data relating to the building stock, in particular the existing one, within a BIM platform in order to create a digital management system. The research conducted on the state of the art was preparatory to the definition and development of a work methodology valid for both historical and non-historical buildings. The below points will be presented:

- the objectives and the working hypotheses;
- the description of the work phases and the theoretical trend;
- the real trend;
- the optimised trend and optimisation strategies.

Objectives and working hypotheses

In the life cycle of a building, management is the phase that has the greatest impact in economic terms and having reliable and updated data allows reducing the resulting costs. In fact, public and private institutions are adapting their systems and training their staff to be able to integrate digital systems that optimise these processes; in particular, there are specific regulatory obligations for public administrations, as previously mentioned.

Four objectives were set at the basis of the methodology presented below, which are:

- Digitalise the building stock;
- Manage the building stock;
- Manage heterogeneous data;
- Reduce costs and expenses.

Consequently, two working hypotheses were identified for the correct development of processes, represented by the presence of:

- Resources;
- Heterogeneous data.

Actually, the resources represent the only necessary and sufficient condition for the development of the methodology this point includes both the appropriate tools, hardware and software, as well as the staff trained on the topics covered and the platforms used. It should be reiterated that the update is mandatory for public administrations.

On the other hand, being in possession of heterogeneous data allows optimising the whole process, reducing the time deriving from the acquisition activities and consequently the costs. This point includes different types of data, which can be divided into:

- Non-graphic data;
- Two-dimensional graphics;
- Three-dimensional models and parametric models;
- Point cloud;

- Pictures.

However, the hypothesis of the presence of heterogeneous data is not mandatory for the purposes of carrying out the reconstruction and data management activities, since a preliminary acquisition phase is still envisaged; however, it has to be pointed out that their presence reduces the economic condition.

The methodology presented below uses BIM for the reconstruction of digital models of buildings and GIS for the management of the building stock and related data. Management software was excluded, as it requires specific training, it is very complex to use and not user friendly. At the same time, the GIS platforms are multifunctional, allowing the analysis of a multitude of heterogeneous data not only relating to construction; moreover, this type of tools is already introduced in the workflows of many public and private entities.

Work phases and the theoretical trend

Six work phases have therefore been identified, each preparatory to the following, which are examples of the methodology presented:

- **Model Definition,** phase in which it is necessary to detail the specifications and characteristics that the model has to possess at the end of the process;
- **Data Acquisition,** phase during which all the data necessary for the reconstruction of the model are collected, through investigations, surveys and acquisitions;
- **Model Reconstruction,** phase in which the work is done directly in the BIM platform with the imported data;
- **Model Checking,** a phase in which the focus is not only on the correct geometry of the product but also on the coherence of the associated information;
- **Model Fixing,** phase in which the model is corrected, organising new targeted data acquisition campaigns, if necessary;
- **Data Management**, the final stage of the process in which the model is ready to be consulted and used within the GIS platform.

The theoretical trend of an application of the presented method is then outlined: for example, take a generic building on which some work has to be carried out on specific elements. After having determined the entity and type of interventions, it is necessary to describe the characteristics that the digital model must provide, both in geometric and informative terms. Thereafter, all of the documents in the archives are acquired, in both paper and digital format; they have to be first catalogued and subsequently verified to confirm their reliability. If the data collected were sufficient, the model would be reconstructed directly; if this is not the case, it is necessary to identify the missing data and consequently organise survey campaigns, which make it possible to exceed the information gap necessary for the correct completion of the processes. The tools used vary according to the type of data to be collected and the precision they must have. The data is then exported in the format most suitable for importing into the BIM platform used, after carrying out the cleaning and normalisation operations. The reconstruction of the digital model of the building began the structural elements and the external facades; then continues with the internal walls, vertical connections and systems.

Once the model is completed, the standard procedures for verifying geometric interference and information inconsistencies are implemented; the elements that must be corrected are then noted. Once the changes are complete, the process is completed by importing the data and the BIM model into the GIS platform, where they are stored; these can also be consulted or analysed directly from the platform. It is possible to describe the qualitative trend of the processes on a two-dimensional graph: the time is placed on the abscissa axis while the work phases are reported in progressive order on the ordinate axis (Fig. 2).

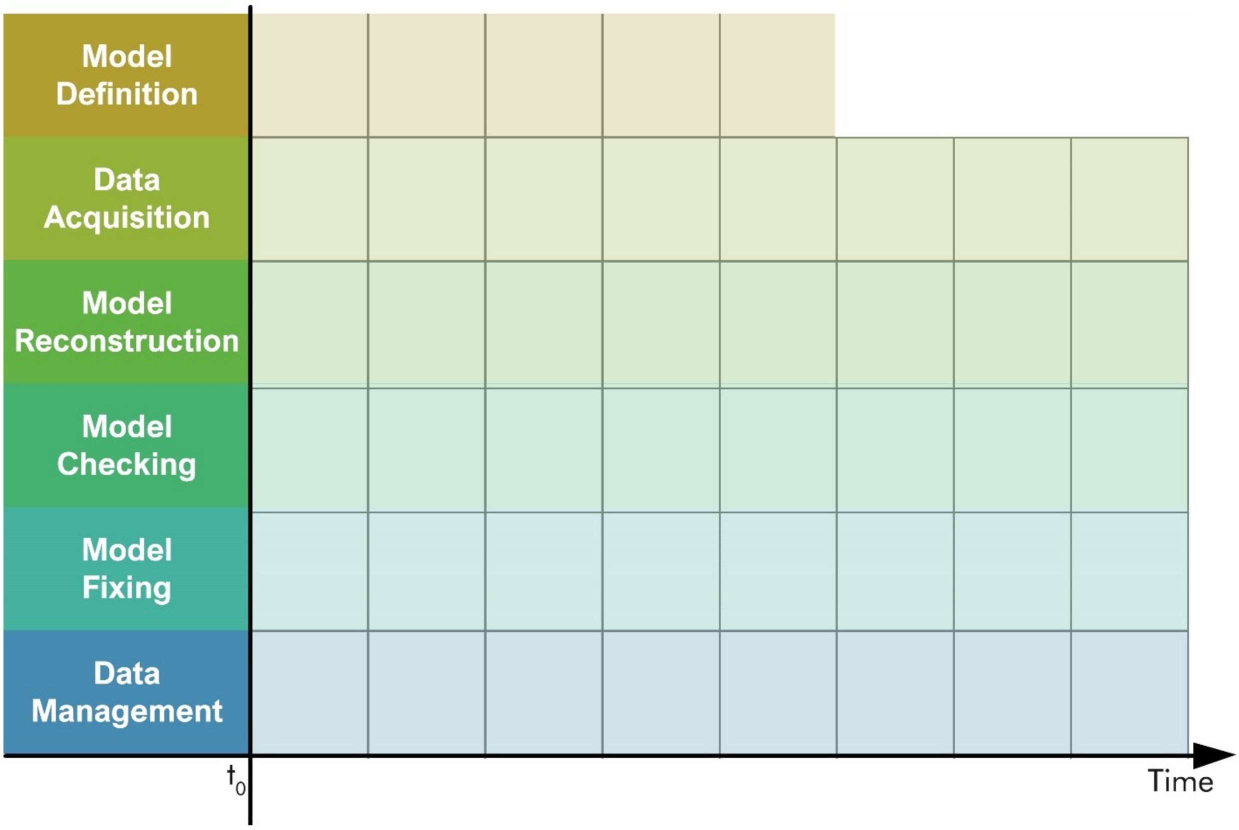

Fig. 2 - Construction of the axes

The previously hypothesized process can be graphed with a linear trend, which varies according to the size and complexity of the building analysed; it can be therefore written the equation of a straight line on a Cartesian plane:

$$y = mx + c \tag{1}$$

Where:

- x = time
- y = processes

It is necessary to find the null points of the graph, to fully understand the nature of the constant c and the angular coefficient m. In particular, the value x set to zero is indicative of a process that has not yet started and the constant c can be obtained:

$$c = y(0) \tag{2}$$

which represents the set of all the operations to be carried out to complete the process. The value y equal to zero denotes the time when all the activities have been completed and the value of the angular coefficient m can be obtained:

$$m = -\frac{c}{x} \tag{3}$$

That indicates the complexity of the operations to be carried out, being the relationship between the activities to be done and the time needed to carry them out. In fact, as complexity increases, the time needed to complete the processes will increase (Fig. 2). For simplicity of reading, the equation (1) can be rewritten as:

$$p(t) = ct + j \tag{4}$$

Where:

- t (time) = the time taken (time);
- $p(t)$ (phase) = the stages of the process (phase);
- j (job) = the activities that have to be carried out to complete the process;
- c (complexity) = the complexity of the activities to be carried out.

The previously stated equations (2)(3) can be rewritten as:

$$j = p(0) \tag{5}$$

$$c = -\frac{j}{t} \tag{6}$$

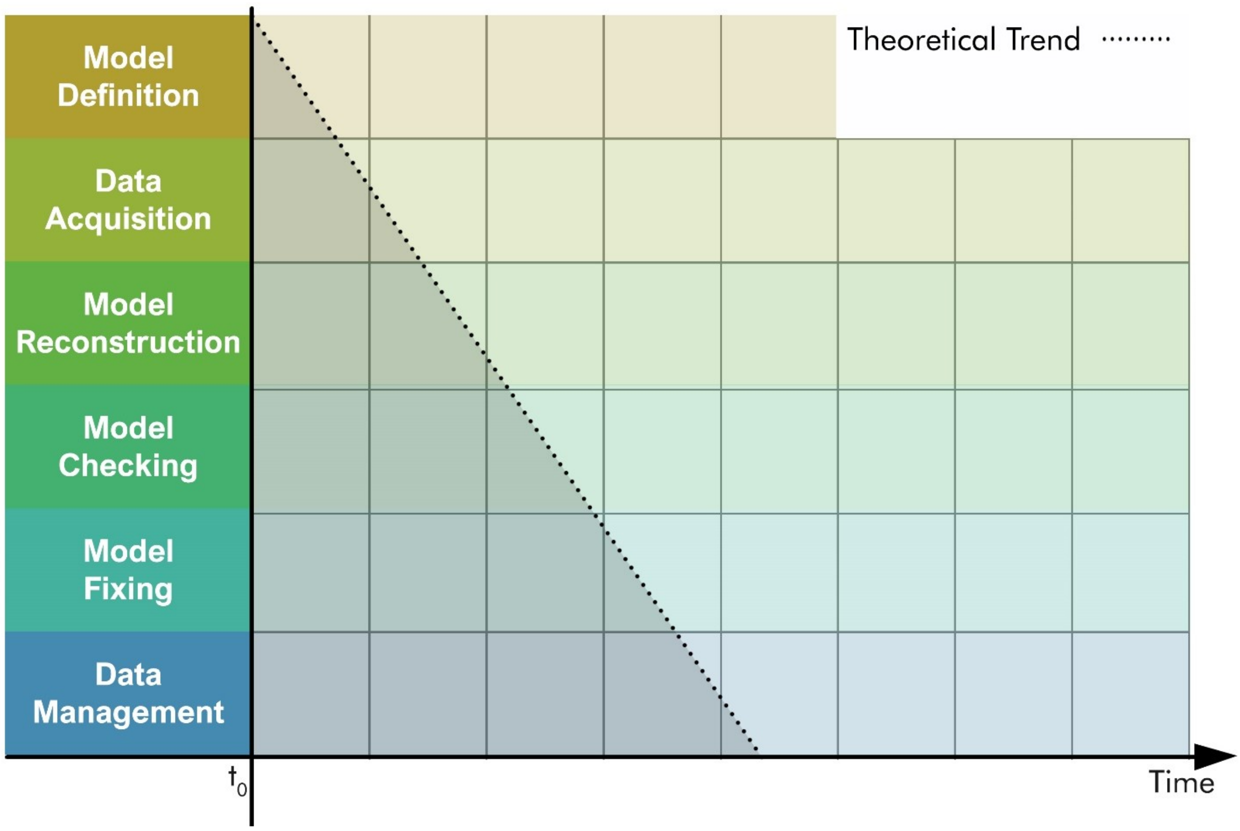

Fig. 3 – Theoretical Trend

Real Trend

Observation of the real trend highlights the difference from the theoretical trend due to the influence of multiple factors, not considered in the initial graph. A first aspect concerns the complexity of the activities, which is not constant throughout the process and can vary according to the different phases. The graph of a segment is then outlined, with different angular coefficients c depending on the phase. Furthermore, they do not depend only on the building in question; one or more figures who carry out all the activities are associated with each phase and their experience locally modifies the slope of the graph. At the same time, the randomness of c also depends on the slowdowns mainly caused by the technical times required to complete the activities. A further criticality that can be highlighted in the real trend is the presence of discontinuities in the process, caused by activities that have to be repeated. This type of problem arises mainly when there is an incorrect evaluation of the acquired data, previously judged sufficient and/or correct for the reconstruction of the model. There are two stages in which this problem is most likely to arise:

- **Model Reconstruction,** when the data are not sufficient to complete the building modelling work

- **Model Fixing,** when the integration of data has led to such changes that a further phase of Model Reconstruction is required, followed by all the others.

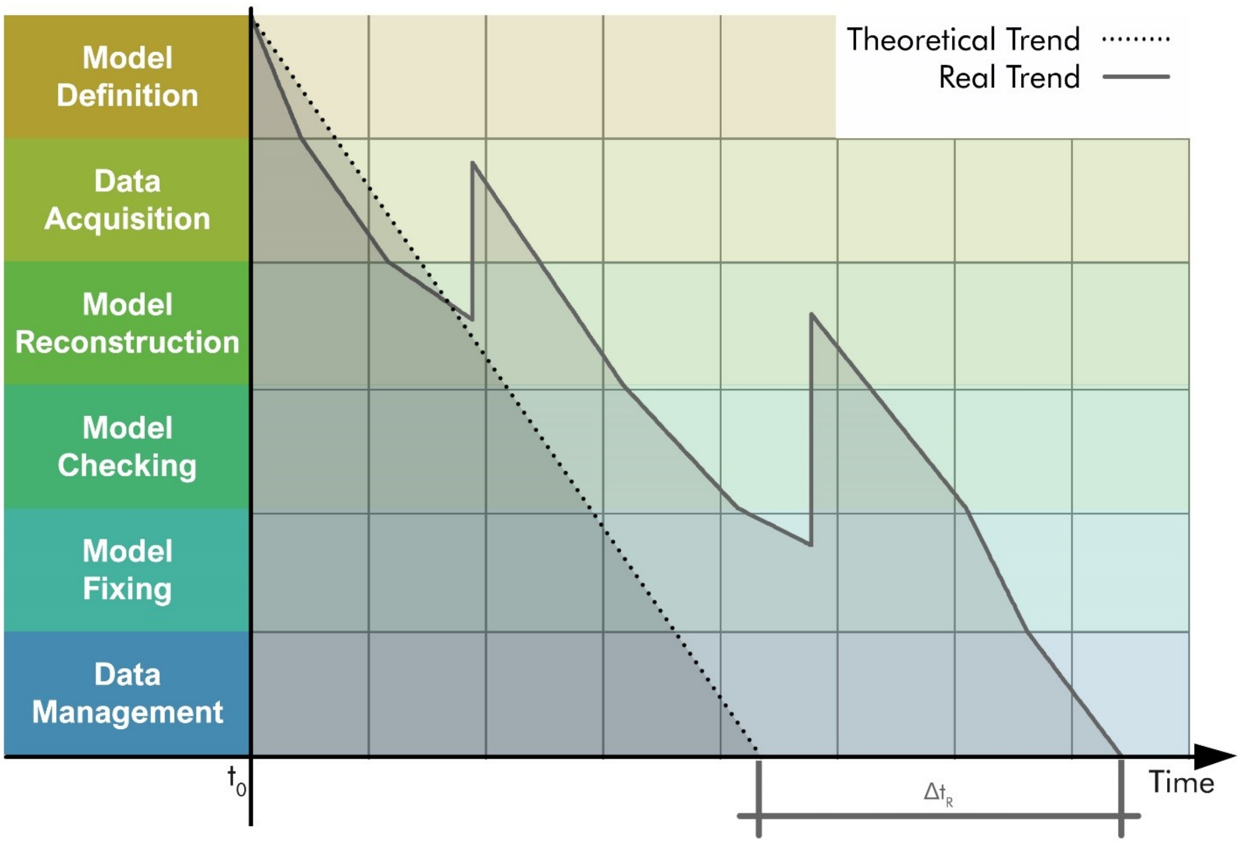

Fig. 4 – Real Trend and Δt_R

These discontinuities may occur several times throughout the process and cannot be predicted, due to human and/or unforeseen errors; in the following two of them are considered, one during the reconstruction phase and one in the correction phase.

The result thus obtained differs from the theoretical one previously analysed: as can be seen in the graph (Fig. 4), a time interval Δt_R, is formed, which represents how much all the difficulties affect the overall process.

It is highlighted that the Δt_R, interval also corresponds to an increase of expected expenses, which depend not only on the necessary investments for new data acquisitions but also on the costs associated with failure to obtain the resource.

Optimised trend and optimisation strategies

Therefore, after having understood some of the causes that lead to a time expansion, it is necessary to outline strategies aimed at reducing this interval, making it tend to the theoretical process as much as possible. A new interval Δt_O, is defined, which represents the difference between the time required to carry out the optimised process and the theoretical one. The process can be defined as optimised if it occurs that:

$$\Delta t_O < \Delta t_R \quad (7)$$

Therefore, a point that respects this inequality (7) is taken and the optimised trend can be traced with the same characteristics as the real one: in particular, it is expected in this case that there are two discontinuities (Fig. 5).

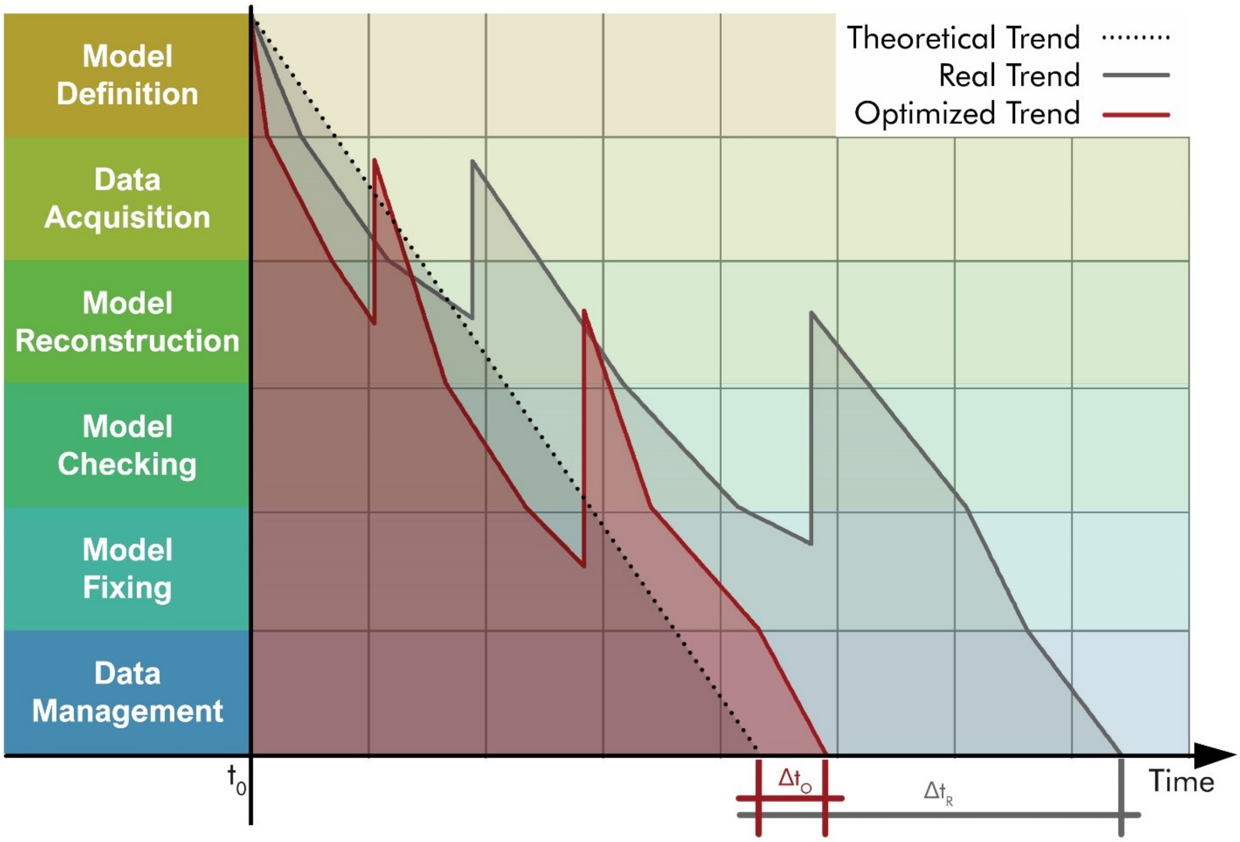

Fig. 5 - Optimised Trend and Δt_O

The resulting graph can be analysed to highlight how to intervene: the first aspect to be noted is that the number of processes j remains unchanged. Attention must therefore be paid to the value of the angular coefficients c, i.e. on the complexity of the processes the variation can occur either globally, involving all phases, or locally, within a specific phase.

There are three optimisation strategies, which are:

- The definition of a BIM GIS methodology and the consequent drafting of guidelines, describing the step-by-step progress of the processes contained in each phase of work (global);
- The writing algorithms for the recognition of geometric elements in BIM software (local);
- The creation of parameters that define the reliability of the input data, necessary for the reconstruction of the building model (local).

Those strategies can be used alone or combined with the others, to maximize the optimisation efficiency and reduce the interval Δt_0. In fact, all of them were implemented in the development of the case studies and guidelines, shown in the annexes, to validate the methodology.

Definition of the BIM GIS methodology

The work phases described above can be optimised by describing in detail all the procedures they consist of. This strategy, in fact, allows systematising the processes, so that all the technicians involved are aware of the activities they have to perform. By doing so, the variability of the angular coefficients that depend on the experience of the operator who intervenes in the specific phases is reduced: the possibility of human errors is also limited.

Beyond the procedural aspects, it is necessary to distinguish which data is included in the BIM model and which in the GIS model, avoiding unnecessary repeated fields in the databases. The functions for which the two platforms are intended must therefore be divided in particular:

- BIM is associated with all the aspects related to the single building;
- GIS is associated with all the aspects related to the management of the building stock.

Specifically, all the propriety and facility management functions were therefore delegated to BIM; two different models can be provided, one for each thematic, or a single container for all data. However, the latter solution can generate problems in the management of digital documents, which can risk taking up a lot of disk space; it is therefore preferable to use it only for small-sized buildings. On the other hand, GIS is associated with the management of the information aspects of the buildings, as well as with the archiving of documentation and BIM models, appropriately georeferenced. The types of data that must be contained for each building complex are listed below:

- Metadata;
- Data relating to the building:
    - Encoding;
    - Denomination;
    - Title of use;
    - Address;

    - City;
    - Year of construction;
    - ...;
- Data relating to the model:
    - Type of data available;
    - Data format;
    - Creation date;
    - Name of the creator;
    - Last update;
    - Presence of outdated data in the models;
    - …;
- Data relating to the systems:
    - Status;
    - Average annual consumption;
    - Date of last maintenance;
    - Maintenance company;
    - …;
- Data relating to the security:
    - Security manager;
    - Last fire test;
    - Last check of fire extinguishers;
    - Last fire test of the doors;
    - …;
- Data relating to the function:
    - Type of building;
    - Intended use;
    - Faculty present;
    - Offices present;
    - Main references;
    - Average number of people;
    - Number of rooms;
    - Number of classrooms;
    - Number of employees;
    - …;
- Data relating to the heritage:
    - Presence of archives;
    - Presence of libraries;
    - Presence of valuable objects;
    - …;
- Documents:
    - Contracts;
    - Historical;
    - Publications;
    - Photographs;
    - …;

After defining the informative aspects, the geometric representation of the elements in GIS was the main focus. In BIM, in fact, geometries and information are closely related to each other by the LOD/LoIN, which are evaluated as needed. On the other hand, a protocol were defined for the GIS, as the system uses both two-dimensional and three-dimensional geometries. The creation of a new three-dimensional model in GIS would lead to an increase in the economic condition: in fact, it would be necessary to either rebuild the 3D geometries of the building, or have specific software that allows the conversion. In the first case, the increase in costs derives from a double reconstruction of the models (BIM and GIS), a work which, however, can be expensive for the type of result obtained. In the second case, however, it was already highlighted in the chapter of the State of the Art that Revit© and ArcGIS© represent the only reliable tools for importing BIM models into GIS. However, it was therefore decided to describe the geometries in GIS only with two-dimensional shapefiles in order to not to limit the methodology to just two tools.

The last aspect to be analysed is the sharing of information between different environments. As the databases cannot be joined (due to the problems already mentioned), two separate levels of intervention are created: one on a territorial scale, linked to GIS, and one on a building scale, associated with BIM. It was necessary to develop an innovative system of connection between the platforms in order to try to solve the interoperability problems. With this innovative system, it is possible to interact with the parametric model directly in the BIM platform by selecting the shapefile of the corresponding building in GIS.

Two case studies are presented below in which the working methodology was tested. In the chapter of the annexes, there are the guidelines that provide both an explanation of the methodology and the step-by-step processes.

Definition of recognition algorithms

Recognising the elements and simplifying their input into BIM allows reducing the complexity of the model reconstruction processes and, consequently, also the times. In fact, the automation of part of these operations facilitates the work of the technicians, even if it is not possible yet to create the complete model without any supervision, as shown in the literature. An assisted procedure is required for the semantic association of elements to geometry, which can be defined as semi-automatic.

Currently, it is possible to find applications dedicated to ScanToBIM on the market, which represent one of the few solutions for HBIM optimisation. Since these applications have high costs, the use of this software violates one of the assumptions of the methodology, namely the reduction of costs. It was therefore decided to analyse their operation in order to be able to define procedures for the creation of finalised applications. The studies carried out have highlighted macro-sets of activities to be performed:

1) Data discretisation through filters to limit the number of inputs to be examined;
2) Identification of the elements that have certain characteristics
3) Tracing the geometry, with the positioning of symbols suitable for the immediate recognition of the element.

To develop these applications the following can be used:

- Traditional programming;
- Visual scripting tools integrated into BIM platforms;
- Combination of the two possibilities.

As is known, traditional programming is the foundation of any type of software, but it requires a set of skills that are not common in the AEC sector. However, if there were employees with this knowledge and/or a research and development department, you could actively collaborate in writing an algorithm aimed at creating an application.

Visual scripting represents another possibility, the use of which is part of the background of qualified technicians. Some problems can be solved with algorithmic modelling, including those related to data interchange between different platforms and the modelling of complex geometries.

The last option is to combine the two resources, trying to maximise the potential of both. In this way, all the operations that concern the aspects directly related to the reconstruction of the object are made with visual scripting, while the management of lists and data is made with traditional programming. In addition, many software houses release APIs (Application Programming Interfaces), which are the procedures and tools present in a software. They can be queried and included in the development of the application, with a consequent increase in its potential.

In the rest of the thesis, two different algorithms are presented, one for CADToBIM processes, which uses algorithmic modelling only, and one for ScanToBIM, which required a combined use of the two types of programming.

Creation of the Parameters

One of the most delicate phases to face is that of model definition. An incorrect assessment can generate considerable delays in the following phases, with a consequent increase in costs. As previously mentioned, the standard provides for an Employer Information Requirements is made, containing all the specifications that the individual elements must have, specifically in terms of LOD/LoIN. However, there is a lack of information regarding the input data that is used to construct the elements, in fact, a parameter that describes the reliability of the inputs has not yet been provided.

It was therefore decided to create a parameter that takes note of the nature of the data used for the reconstruction of the *digital twin* of the building. The parameter expresses the reliability of the starting data used for the creation of a single element, both in geometric and informational terms, and can be associated with them to simplify subsequent file updating operations. The CoIN, Confidence of Information Needed, was therefore defined as a parameter with a vector structure, whose values were representative of the reliability of:

- External geometry (C_E = *External characterisation*);
- Internal characterisation (C_I = *Internal characterisation*);
- Mechanical characteristics (C_M = *Mechanical characterisation*);

- Thermodynamic characteristics (C_T = *Thermodynamic characterisation*).

Therefore, it was obtained that the COIN is a function of the four functions and the LOD/LoIN:

$$CoIN = f\left(C_{E,} C_I, C_M, C_T, LoIN\right)$$

The vector is formed by substituting the value of the single rate at the corresponding position:

$$CoIN = [n_{C_E}, n_{C_I}, n_{C_M}, n_{C_T}]$$

A distinction was also made based on the function that the CoIN can assume:

- $CoIN_R$, where R indicates Required, represents the reliability necessary to achieve a certain LOD/LoIN;
- $CoIN_A$, where A indicates Available, indicates the reliability of the data already in possession.

SuRe, Survey Required, can be described as a further parameter that is the difference between the two previously described.

$$SuRe = COIN_R - COIN_A$$

The resulting value expresses whether there are information gaps and what they are. Positive values will correspond to more investigations from which to perform, although they will not be necessary for the presence of negative or null values. This awareness makes it possible to simplify the preliminary operations of estimating the conditions necessary for the completion of the total process.

Further specifications are presented within the guidelines, shown in the annexes.

Research field and case studies

This chapter presents the applications of the working methodology on case studies identified within a specific research field, which is the existing public building. First, the reasons for which the choice fell on the public heritage, in particular the university one, are outlined; the case studies are then defined and analysed. It is important to reiterate that the platforms used below are not binding on the development of the methodology.

The existing building stock and university buildings

Throughout Europe, it is very often preferred to safeguard and recover the elements of the existing building stock rather than demolish and rebuild them. In fact, data from the EU Building Stock Observatory (BSO) show how a considerable portion of the building was built before the 1980s (Fig. 6). When considering only residential construction, this portion varies from around 50% in countries such as Ireland, Greece and Cyprus to over 70%, as we can see in Germany and Sweden.

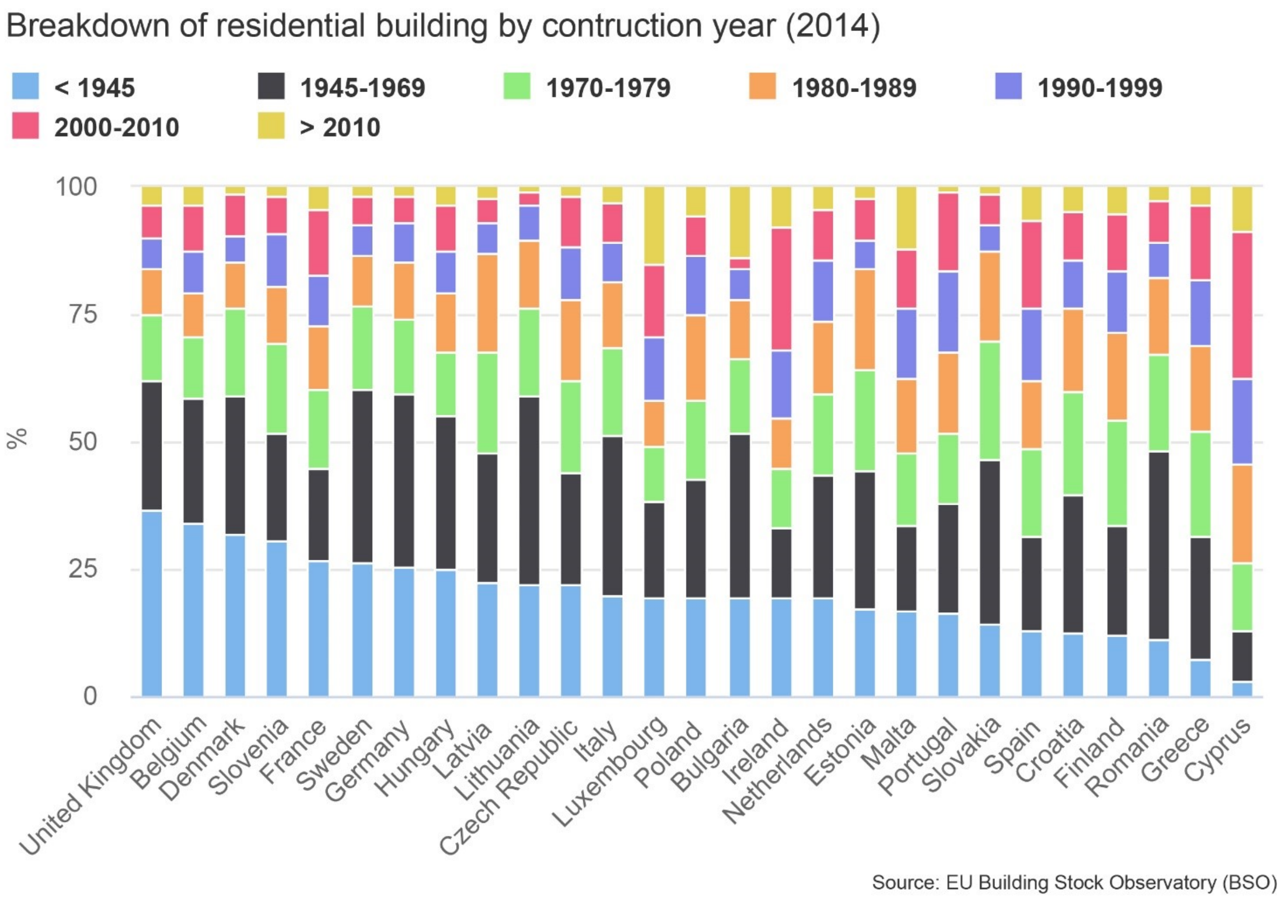

Fig. 6 - Classification of the European residential building stock. Source EU Building Stock Observatory (BSO) (EU Building Stock Observatory (BSO), 2013).

The Italian situation is well described by the latest ISTAT census of 2011, which confirms the European trend. In particular, the entire building stock is made up of about 14.5 million buildings, around 57% of which have load-bearing masonry structures while almost 30% of them are in reinforced concrete. Of the 14.5 million, just over one million (1.056.404) is publicly owned and used for different functions: 76% (755.907) is intended for residential and commercial purposes while 24% (251.206) is used for institutional purposes (Ministero dell'Economia e Finanza - Dipartimento del Tesoro, 2020)(Fig. 7).

NUMEROSITA'

FINI ISTITUZIONALI - Numerosità

Tipologia unità immobiliare	Unità immobiliari		di cui con superficie:
	(numero)	(%)	(%)
Fini istituzionali	**251.206**	**100%**	**94,51%**
di cui:			
Utilizzato	**229.887**	**91,51%**	**94,61%**
Dato in gestione ad altra Amm. Pubblica	7.450	2,97%	96,86%
Dato in uso a titolo gratuito a privato	15.389	6,13%	98,01%
Dato in uso a titolo gratuito ad altra Amm. Pubblica	14.266	5,68%	95,46%
Dato in uso a titolo oneroso a privato	28.552	11,37%	97,49%
Dato in uso a titolo oneroso ad altra Amm. Pubblica	4.672	1,86%	97,69%
Dato in uso governativo	10	0,00%	100,00%
In ristrutturazione/manutenzione	2.574	1,02%	94,83%
Inutilizzabile	7.099	2,83%	92,27%
Non utilizzato	**21.319**	**8,49%**	**93,43%**

RESIDENZIALE E COMMERCIALE - Numerosità

Tipologia unità immobiliare	Unità immobiliari		di cui con superficie:
	(numero)	(%)	(%)
Residenziale e commerciale	**805.198**	**100%**	**94,41%**
di cui:			
Utilizzato	**755.907**	**93,88%**	**94,74%**
Dato in gestione ad altra Amm. Pubblica	117.876	14,64%	98,23%
Dato in uso a titolo gratuito a privato	16.069	2,00%	99,35%
Dato in uso a titolo gratuito ad altra Amm. Pubblica	4.741	0,59%	95,15%
Dato in uso a titolo oneroso a privato	447.165	55,53%	98,49%
Dato in uso a titolo oneroso ad altra Amm. Pubblica	5.816	0,72%	98,68%
Dato in uso governativo	1	0,00%	100,00%
In ristrutturazione/manutenzione	2.628	0,33%	97,87%
Inutilizzabile	9.708	1,21%	94,99%
Non utilizzato	**49.291**	**6,12%**	**89,29%**

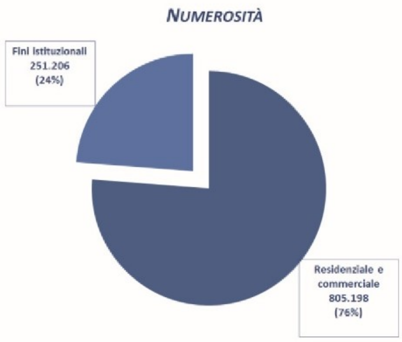

Tabella 8 - Fabbricati - numerosità e superficie per tipologia di Amministrazione proprietaria - Anno 2016

TIPOLOGIA AMMINISTRAZIONI	Unità Immobiliari		*di cui con superficie*	Superficie	
	(numero)	(%)	(%)	(mq)	(%)
Amministrazioni Centrali	**37.844**	**3,58%**	**94,59%**	**39.743.590**	**10,98%**
Stato e Agenzie Fiscali	31.752	3,01%	94,19%	36.644.093	10,12%
Altre Amministrazioni Centrali	6.092	0,58%	96,70%	3.099.497	0,86%
Amministrazioni Locali	**775.086**	**73,37%**	**94,12%**	**299.972.279**	**82,86%**
Regioni	17.779	1,68%	84,19%	8.526.289	2,36%
Città Metropolitane e Province	12.679	1,20%	95,10%	23.364.192	6,45%
Comuni	714.872	67,67%	94,31%	213.497.908	58,97%
Unioni di Comuni e Comunita' Montane	1.464	0,14%	98,16%	1.309.271	0,36%
Camere di Commercio e Unioni delle Camere di Commercio	1.546	0,15%	97,41%	1.238.859	0,34%
Enti locali del Servizio Sanitario	17.428	1,65%	96,99%	37.595.872	10,39%
Università	4.808	0,46%	98,17%	11.944.858	3,30%
Altre Amministrazioni Locali	4.510	0,43%	82,86%	2.495.031	0,69%
Enti Nazionali Di Previdenza E Assistenza Sociale Pubblici	**34.458**	**3,26%**	**77,51%**	**4.847.516**	**1,34%**
AMMINISTRAZIONI LOCALI NON S13	**202.760**	**19,79%**	**98,34%**	**17.455.915**	**4,82%**
di cui:					
Automobile Club d'Italia	505	0,05%	98,81%	201.174	0,06%
Aziende di Servizi alla Persona	8.574	0,81%	97,18%	3.324.095	0,92%
Aziende,Enti e Istituti Territoriali per l'Edilizia residenziale	199.546	18,89%	98,38%	13.768.781	3,80%
Altro	391	0,04%	98,98%	161.865	0,04%
TOTALE AMMINISTRAZIONI	**1.056.404**	**100%**	**94,43%**	**362.019.300**	**100%**

Source: Ministero Economia e Finanze

Fig. 7 - Extract from the "Rapporto sui beni immobili delle Amministrazioni Pubbliche - Anno 2016" (Report on the real estate assets of the Public Administrations - Year 2016). (Ministero dell'Economia e Finanza - Dipartimento del Tesoro, 2020).

Institutional purposes include all the typical functions of Public Administrations, such as administrative and social; this group includes hospitals, schools, universities, etc. For regulatory compliance, public bodies must adapt their systems and digitalise the assets under their responsibility. Therefore, they represent a perfect case study for the validation of the working methodology, as the basic assumptions of the same are also respected. The public administrations have the data of all the buildings within their competence, and must have suitable tools and trained personnel.

To define the field of study, a share of the assets significant for analysis was identified: university buildings. This group is made up of 4808 elements, that is 2% of the buildings for institutional purposes and 0.5% of the total. The heterogeneity of the buildings and the characteristics of the institutions fall within the defined study parameters. Furthermore, the Agenzia del Demanio in 2017 signed an agreement with some universities to complete the digitalisation of buildings. Among the various universities, the choice fell on the University of Naples Federico II.

The assets of the University of Naples Federico II

The University of Naples Federico II is made up of 152 buildings (that is 3% of the university buildings), most of which are located in the metropolitan area of Naples (Fig. 8). The building stock presents heterogeneous elements in terms of year of construction, type, volume and function. The decision was not only moved by the diversity of the investigated set; in fact, the technical office showed an interest in the development of a fully digital management system. It was also possible to quickly access both documents and premises with the support of the administration.

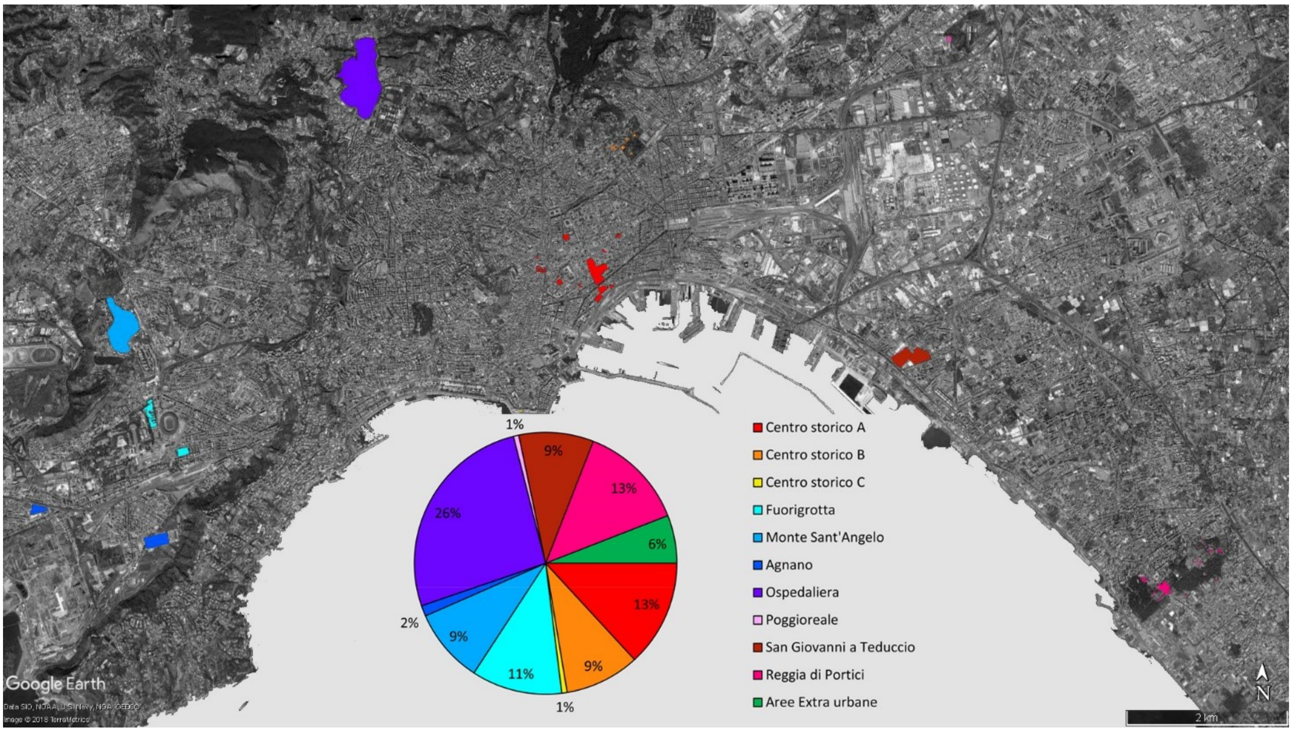

Fig. 8 - Building stock of the University of Naples Federico II - Identification of buildings in the metropolitan area of Naples.

The first operation to be carried out was the classification of the buildings: the parameters expressed by the technical office are in fact related only to the localisation (Tab. 1). Two criteria have therefore been defined for the distinction of buildings, each of them linked to a phase of the methodology, which are the presence of sufficient data in the archive and the year of construction. The first criterion concerns the data acquisition phase: their presence reduces the number of surveys to be carried out and consequently the economic resources to be committed. The second criterion concerns the model reconstruction phase: times may vary according to the complexity of the objects to be modelled. Objects with simple and standardised geometries are already included in the basic tools of the software used, while irregular geometries require longer reconstruction times. Two macro-categories of buildings have therefore been circumscribed, based on the construction technologies used:

AREA	n° Buildings
Centro storico A	20
Centro storico B	14
Centro storico C	1
Fuorigrotta	17
Monte Sant'Angelo	14
Agnano	2
Ospedaliera	40
Poggioreale	1
San Giovanni a Teduccio	14
Reggia di Portici	20
Aree Extra urbane	9
TOTAL	152

Tab. 1 - Summary table of the number of buildings, divided by area of competence.

- Historical, that is, with non-serialised elements and a structure mainly based on load-bearing walls or thrusting structures;
- Modern, that is with serialised elements and a structure mainly based on beams and pillars.

Thus, four subsets are formed, and this allows distinguishing the buildings based on the difficulties that could be encountered.

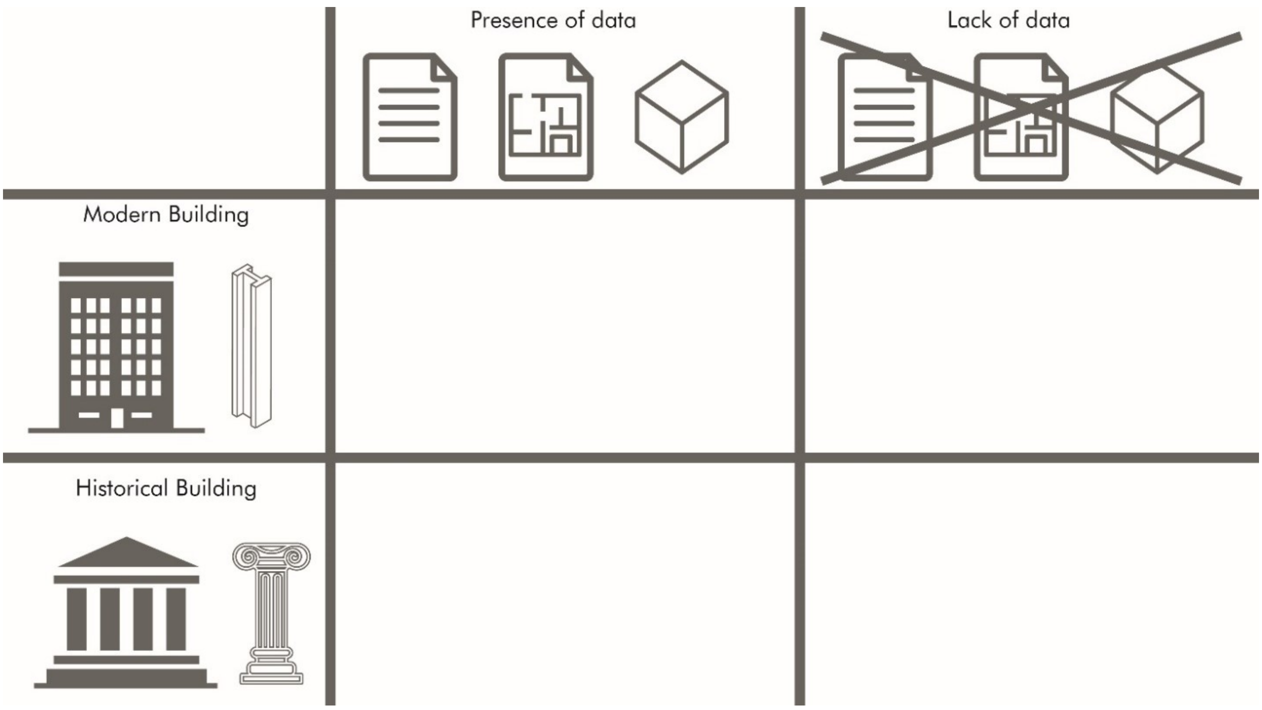

Fig. 9 - Classification of buildings.

In collaboration with the technical office, two building complexes have been identified that represent two opposed cases:

- *Palazzo degli Uffici*, which is a modern building with a multitude of drawings already in vector format;
- The former complex of *Santa Maria degli Angeli alle Croci,* currently the Veterinary Faculty, which is a historic building with no sufficient data for a complete reconstruction.

At the same time, the Model Definition phase was carried out for both buildings. The administration expressed the need to have a first model to be used for management, which could be updated subsequently. It was decided to reconstruct the architectural elements with LOD C as a priority and, where possible, also the structural ones, with the same LOD.

Palazzo degli Uffici

Overview

Fig. 10 - View of the Palazzo degli Uffici - Author's photo.

Palazzo degli Uffici (Fig. 10) is located in the city of Naples, in via Giulio Cesare Cortese n ° 29, and catalogued inside the *Centro Storico A* (Fig. 11). Isveimer (*Istituto per lo Sviluppo Economico dell'Italia Meridionale* [Institute for Economic Development of Southern Italy]), commissions the project to the Roman architect Luigi Moretti. The building was built between

1970 and 1973 and subsequently acquired by the university in 1997. The building is divided into three volumes in reinforced concrete: the main one with ten levels, two of which underground, and two symmetrical with three levels, of which one underground.

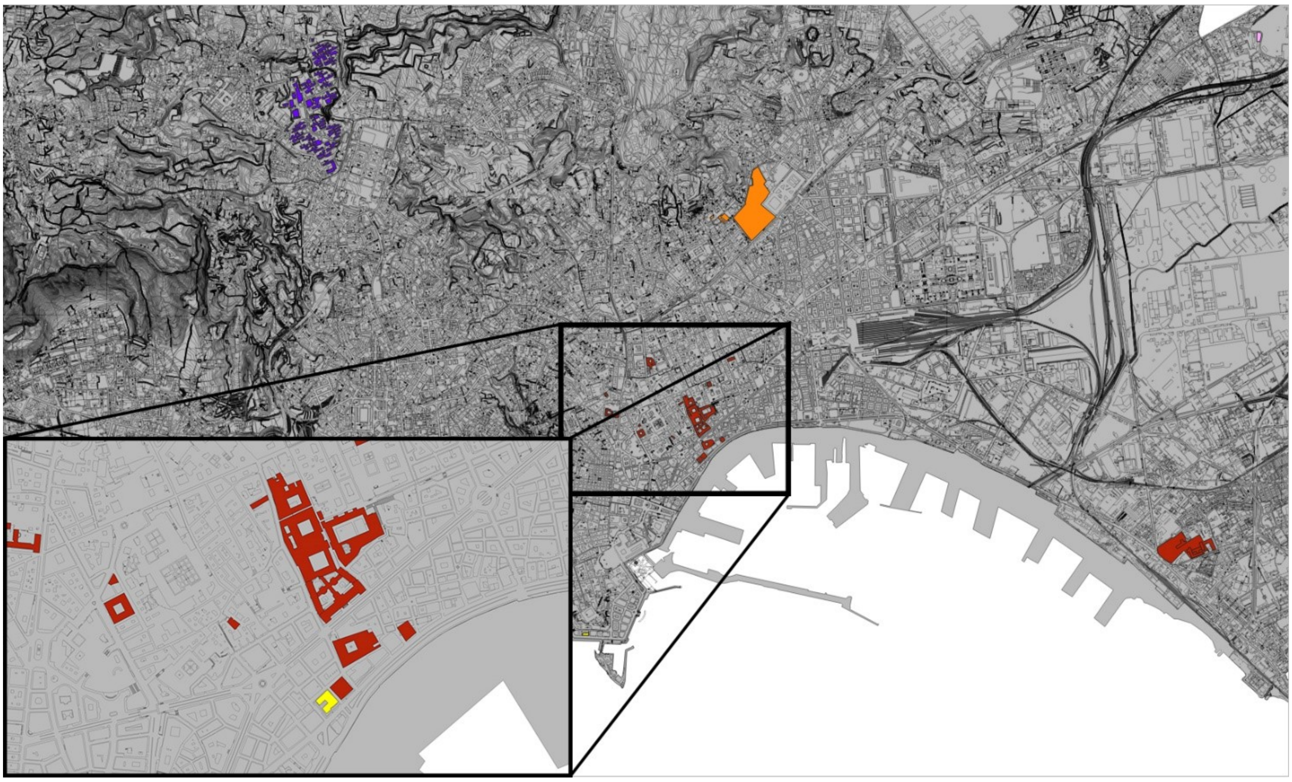

Fig. 11 - Territorial overview of Palazzo degli Uffici.

Data Acquisition

The activities of Data Acquisition have begun after the conclusion of the ones of Model Definition. The archives of the university's technical office have been then consulted; a large number of drawings, both in paper and digital format, were kept there. Only the data that could be directly imported into BIM were taken, i.e. those in CAD format. The documents are 129 in total and include Architectural, Structural and MEP information (Fig. 12). Most of them are the result of surveys conducted between 2016 and 2018; no new surveys have been planned. Tab. 2 shows the cataloguing of all the digital documents contained in the archives.

Model Reconstruction

Revit© was the software chosen for the reconstruction, both for direct collaboration with NKE, Autodesk Platinum Partner, and because it is currently one of the most widely used BIM platforms worldwide. Analysing the data collected, it was decided to reconstruct two models, one architectural and one structural. Before starting the modelling operations, a federated model[2] was created in which the elevations and inter-floors were defined.

[2] "A federated model is a combined Building Information Model that has been compiled by amalgamating several different models into one (or importing one model into another)." (NBS Enterprises , 2017)

Palazzo degli Uffici - Via Giulio Cesare Cortese, 29			
Survey 2016			
Plans		Scale	Partials
	Hydric System – Sanitary Chart	1:50	4
	Hydric System – Load Chart	1:50	11
	Hydric System – Unload Chart	1:50	11
	Fire prevention System	1:50	12
	Architectural - Intended use	1:50	12
	Architectural - Workstations	1:50	10
	MEP System – Heating	1:50	9
	MEP System – Air conditioning	1:50	11
	MEP System - Electrical and Specials	1:50	12
	MEP System - LAN Network	1:50	9
	MEP System - Piping and Ducting	1:50	1
	MEP System – Hydronic layout		1
	Security and access control system	1:50	11
Survey 2018			
Plans			
	Structural	1:100	6
Sections			
	A-A'	1:100	1
	B-B'	1:100	1
	C-C'	1:100	1
Drawings 2003			
Elevations			
	Via de Gasperi - Via Nuova Marina	1:100	1
	Via dei Chiavettieri	1:100	1
	Via Angelo di Costanzo	1:100	1
Sections			
	Standard section - Tower	1:100	2
	Standard section - Small volumes	1:100	1
	Total		129

Tab. 2 - Cataloguing of the CAD drawings of Palazzo degli Uffici, located in via Giulio Cesare Cortese n ° 29, Naples.

The individual models were thus connected to the coordination model and the levels were standardized (Fig. 13): plans were associated to these levels. The data was then imported into the BIM environment. One of the first problems met was the lack of known georeferenced points that could be used for importing files. The pillars were considered as fixed and reliable elements of the drawings to complete the height alignment operations.

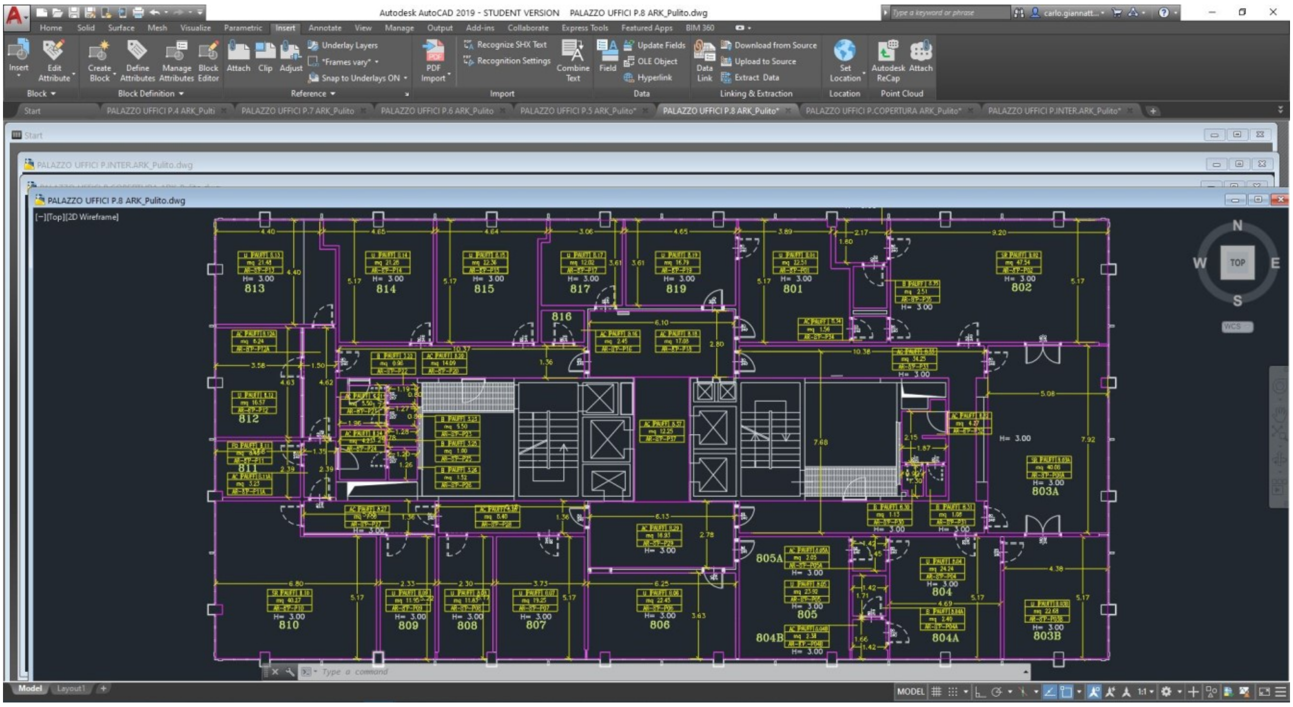

Fig. 12 - Visualization of CAD data.

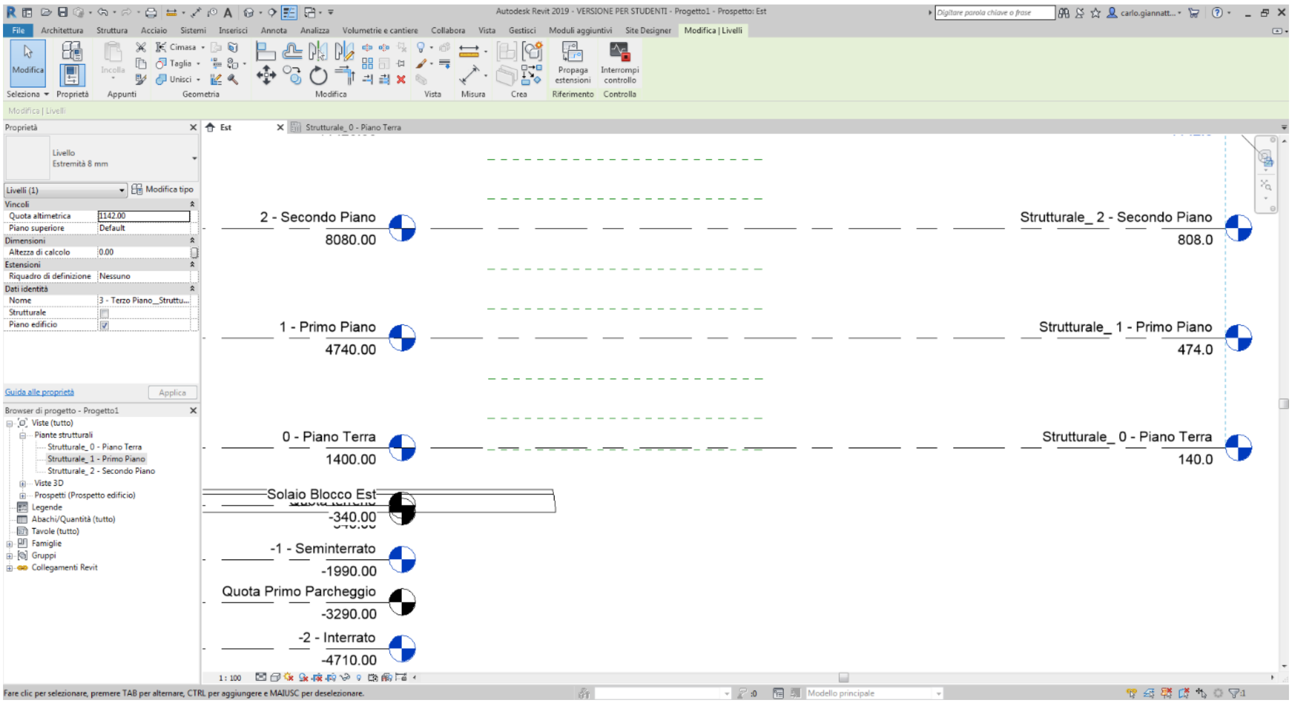

Fig. 13 - Models connection and levels creation.

The vertical structural elements for both models were reconstructed following the specifications of the guidelines (shown in the annexes). A pattern recognition application for rectangular and circular geometries has been created with the Dynamo© software to simplify the object placement. For each floor, the application algorithm returns the position of the pillars through a coloured fill and a cross placed in the centre of the figure, defining a snap (Fig. 14). The fill proved to be very useful also in the verification phase, showing the presence of misalignments in the vertical trend.

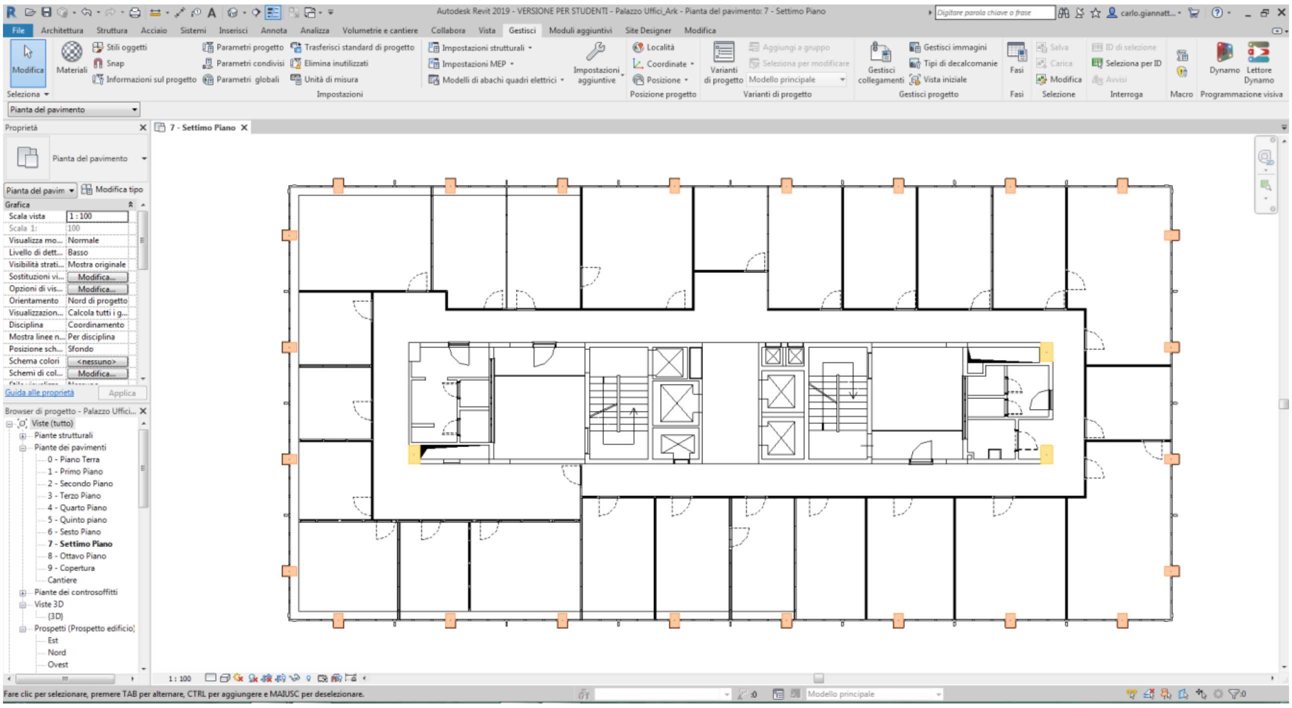

Fig. 14 - Result of the CADToBIM pattern recognition algorithm.

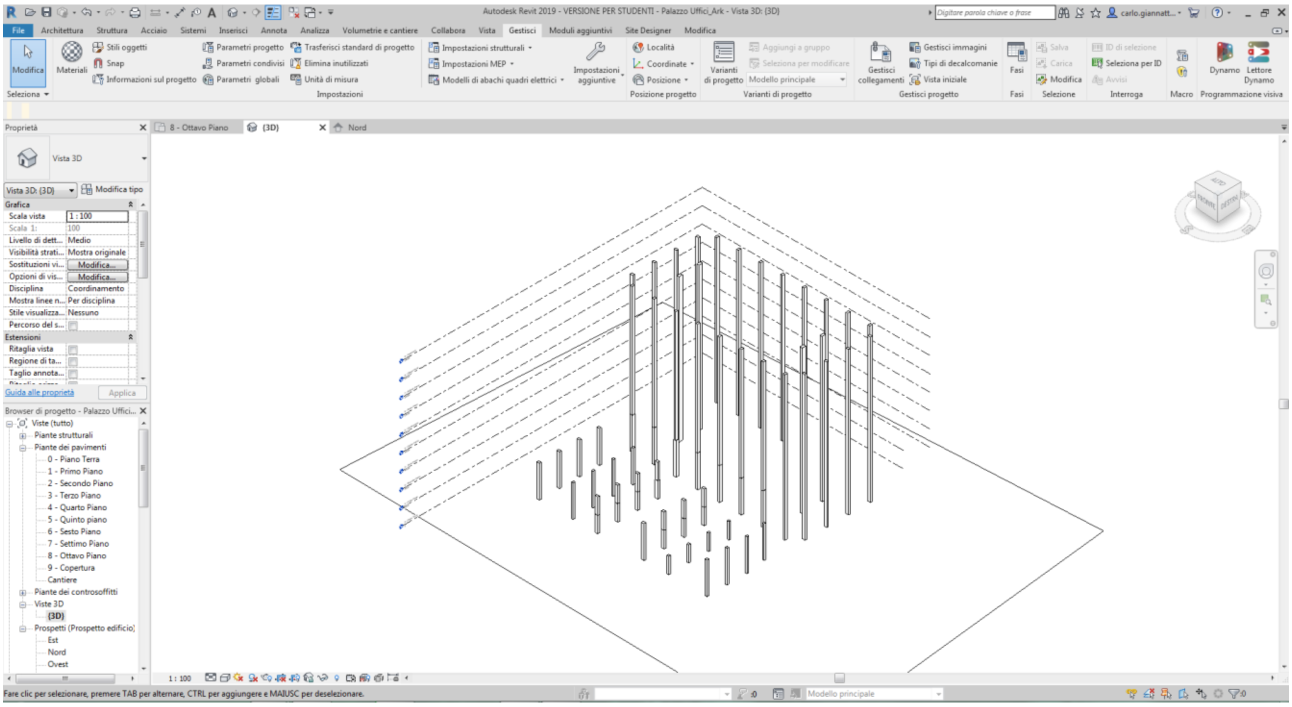

Fig. 15 - Completion of the reconstruction of the vertical structure.

Once the vertical structure was completed (Fig. 15), the structural walls, the connecting beams and the slabs were reconstructed in the structural model; finally, all the elements were detailed with the rebars. Some inconsistencies were found in the drawings of the technical office; the elements in question have been marked with a comment to simplify subsequent verification operations. Once the structural model was completed (Fig. 16), the architectural one was constructed, starting from the external walls, modelled as curtain walls. After a parametric grid has been defined, these elements allow having different panels, both in terms of material and geometry, and provide horizontal and vertical mullions (Fig. 17). The slabs, the dividing walls and windows fixtures were then created for each floor. The model was completed with the georeferencing and positioning of the building.

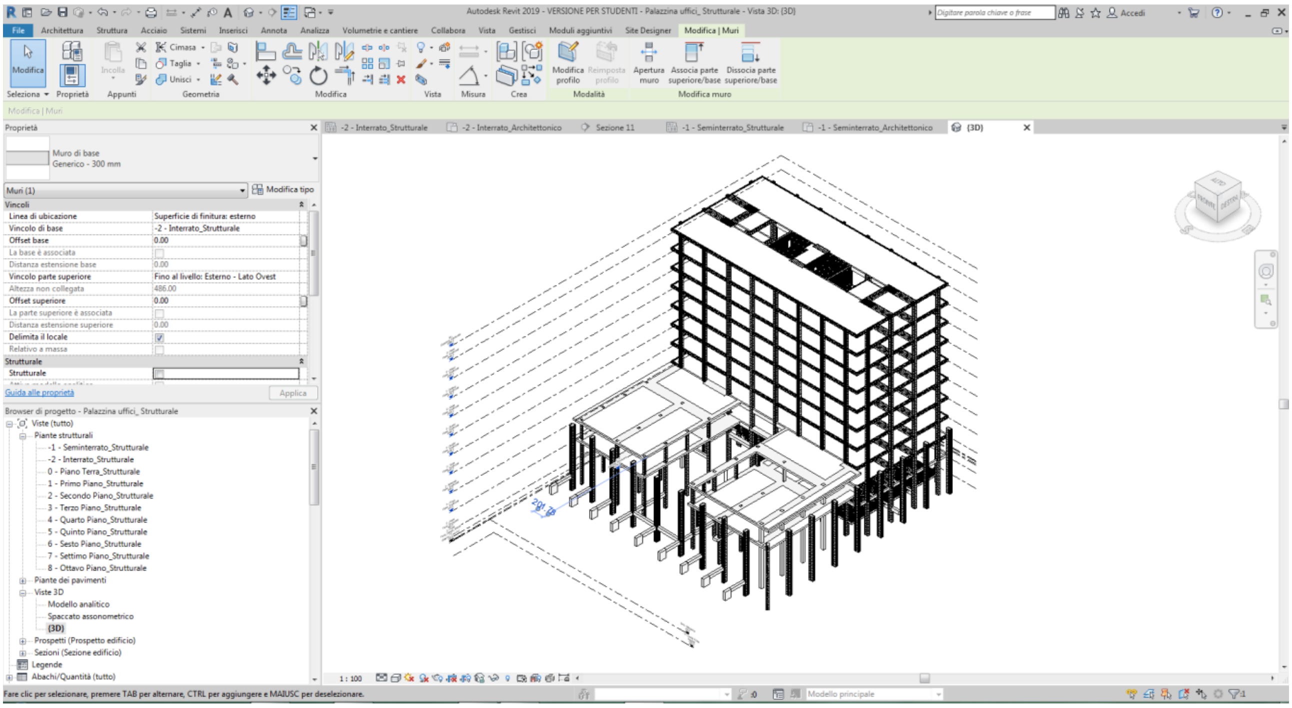

Fig. 16 - Completed structural model.

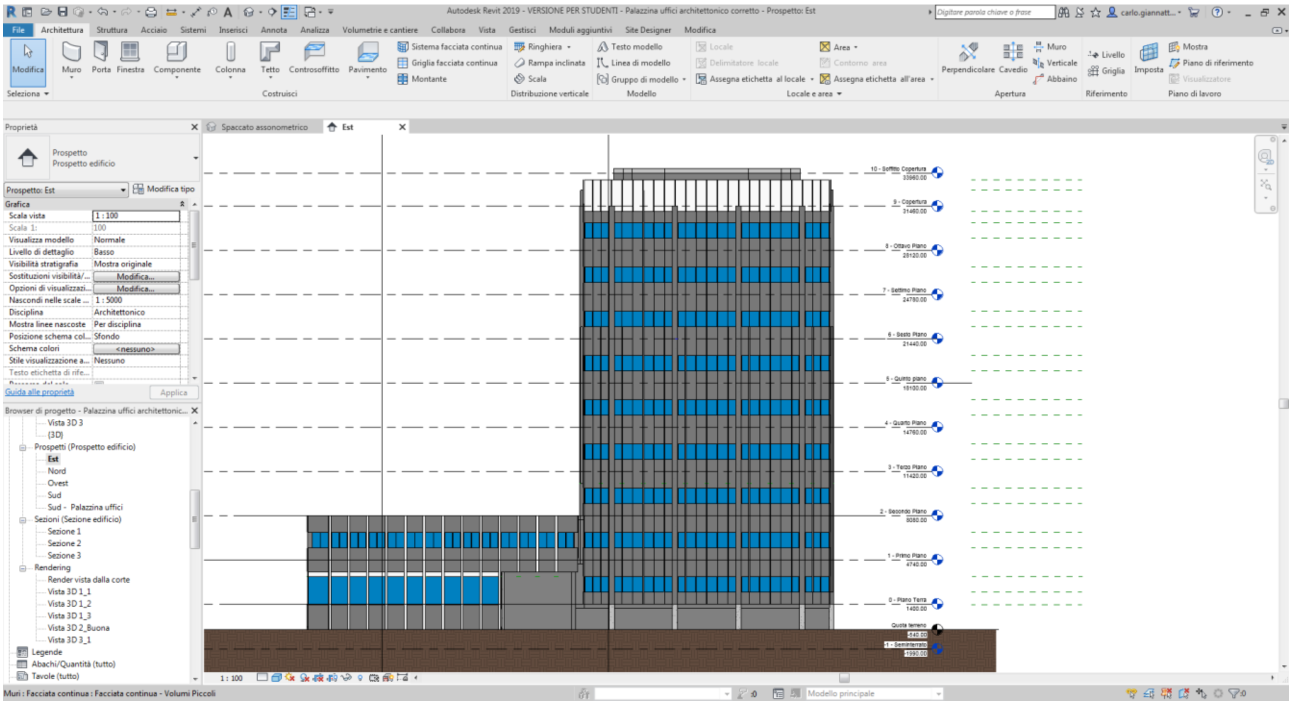

Fig. 17 - Parameterization of curtain wall elements.

CADToBIM pattern recognition algorithm

A pattern recognition application for the identification of rectangles and circles was developed for CADToBIM processes; it can be reused by the technical office. The chosen geometries discretise different types of elements, such as columns, shafts, mullions and pipes. The application was developed within the Dynamo© visual scripting platform, integrated into Revit©. The necessary inputs for the algorithm operations are:

- the CAD drawing to import;
- a numerical interval expressed in terms of minimum and maximum;
- a view on which to display the result of the process.

Vector data are easily imported into the Dynamo© environment and they can be filtered based on their nature, geometric and non-geometric. The straight lines are then separated from the curves; the circumferences can be easily found in this way. Lines are then analysed to find rectangular geometries and only segments that have a certain length are selected; the range is established based on the average size of the elements to be searched. Lines that fall within the size range are added to a list. For each element in the list, the condition of intersection with another line present in the set is checked. If this condition was not respected, a closed figure would not be obtained and therefore a quadrilateral would not be found. This operation also allows eliminating all the double lines present in the drawing. Lists of intersection points are then created, which should represent the vertices of the searched polygons. If a list contained more than four elements, the discretisation process also found elements adjacent to the columns. An iterative process was then generated that excludes the external points and keeps only the internal ones. However, if the result contains more than four elements, it is excluded to avoid errors. Thus a series of lists containing four points are defined, which are sorted in order not to create a self-intersecting figure. The forms are then identified, once the

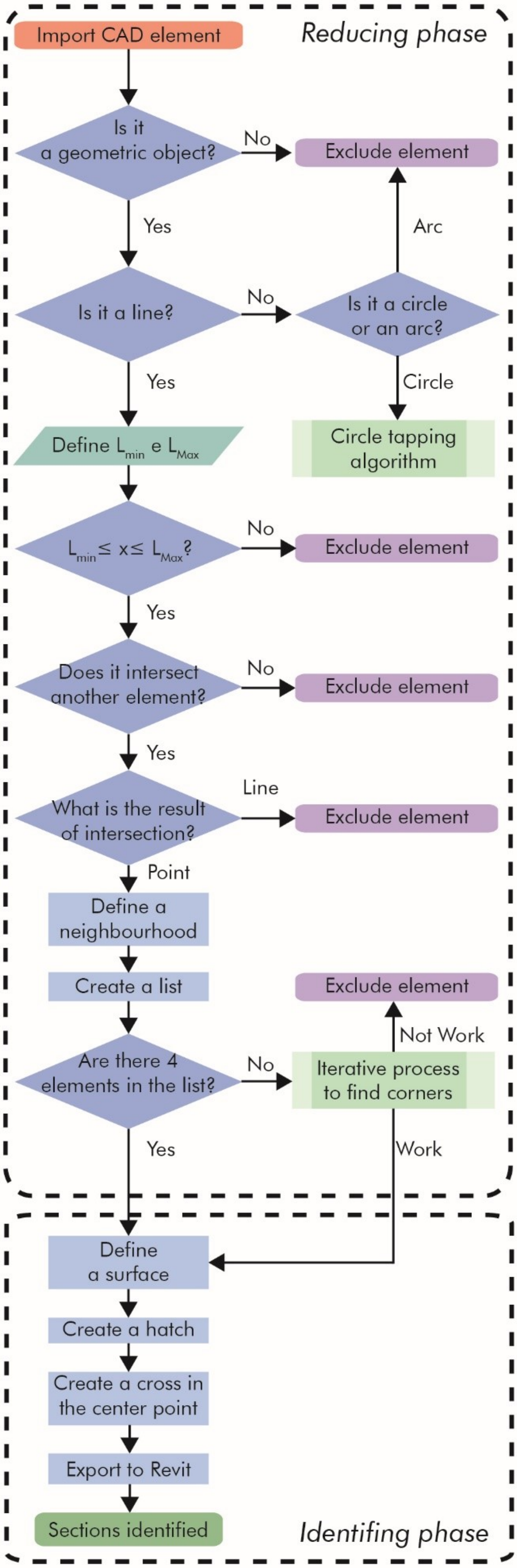

Fig. 18 - CADToBIM algorithm for the recognition of rectangles and circles.

vertex recognition has been completed. In fact, a flat surface and a uniform colour fill are created, which changes according to the size of the sides of the geometry under examination. A cross is placed at the centre of each surface to create a snap to support the reconstruction of the BIM elements. The result thus obtained was then exported to the Revit© environment (Fig. 19).

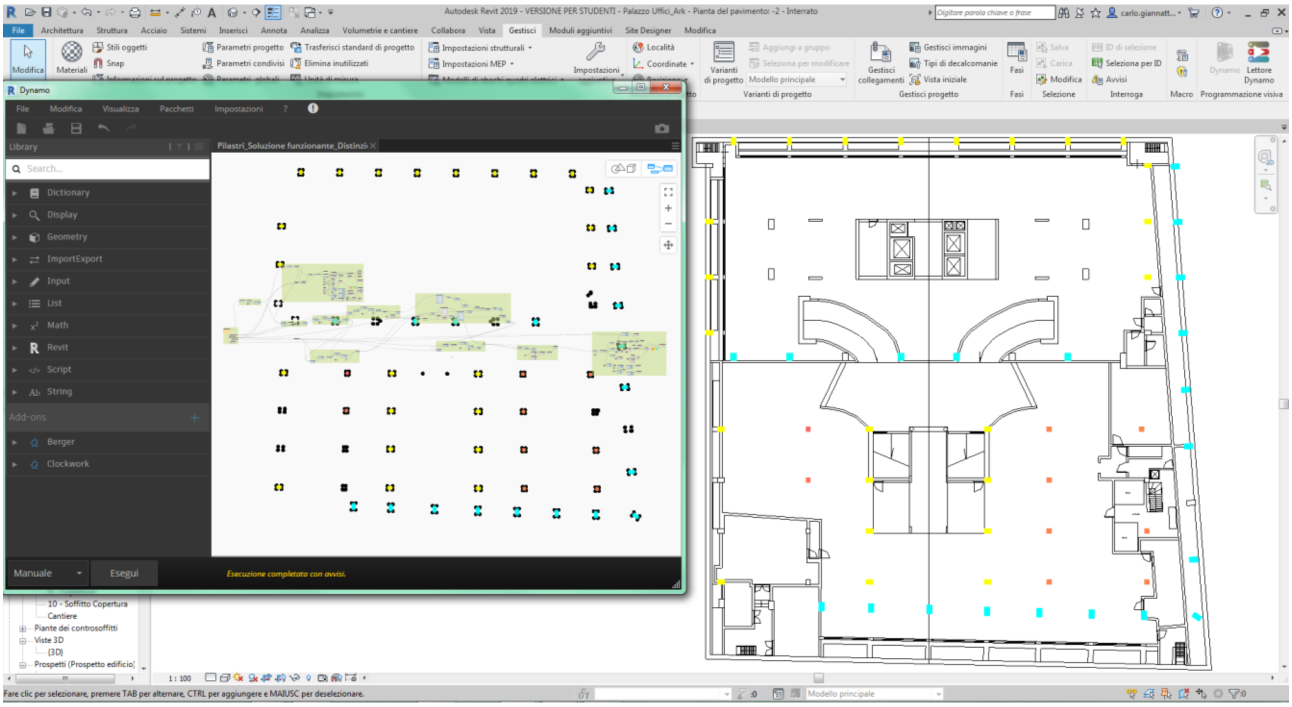

Fig. 19 - Results export from Dynamo© to Revit©- CADToBIM Algorithm.

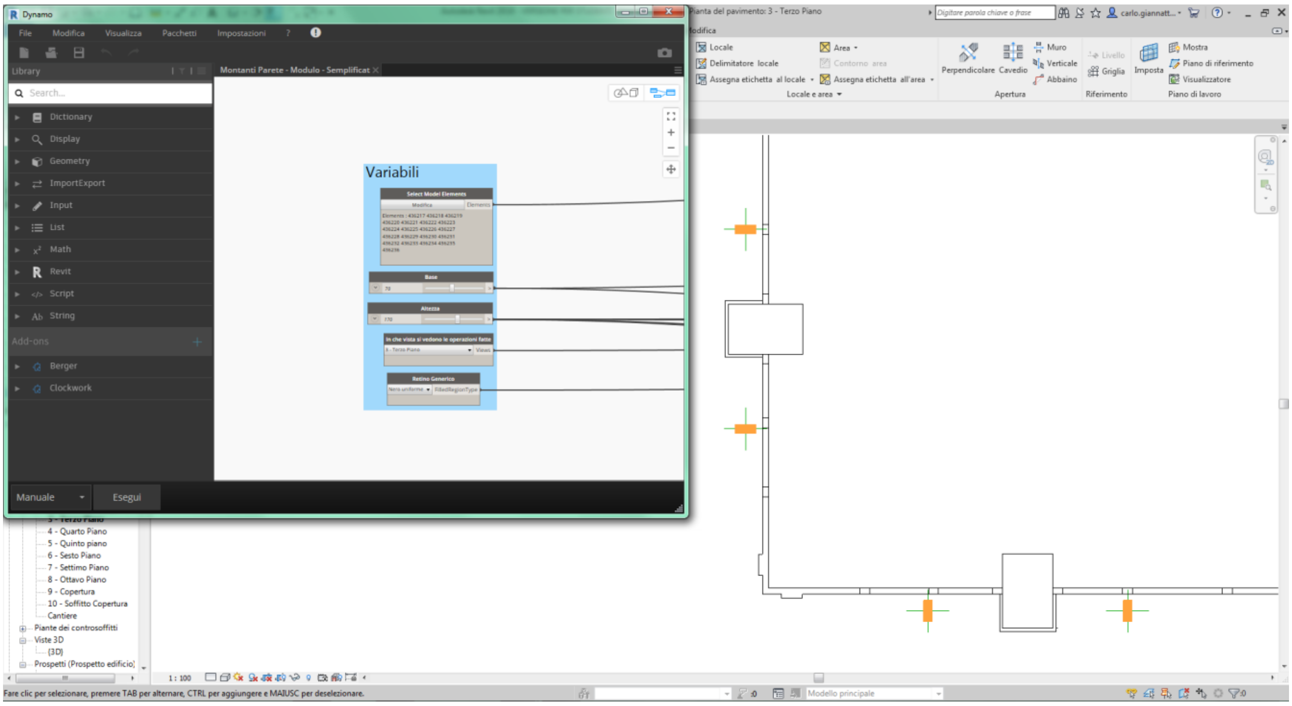

Fig. 20 - Screenshots of the second CADToBIM algorithm.

With some changes to the first algorithm, it was possible to create an additional application that allows recognising rectangles of specific sizes. The second application was very useful in the reconstruction of the curtain wall mullions (Fig. 20).

Model Checking

The verification phase was divided into two stages: the identification of inconsistencies and the selection of possible solutions. Many of the issues identified were highlighted during the model reconstruction phase. The fill created by the pattern recognition application showed that for some elements there was a difference of a few centimetres between the CAD plan and the vertical development of BIM structures (Fig. 21). These objects were then identified to be checked with localised surveys (i.e. using a laser distance measurer) that will be carried out during the subsequent correction phase.

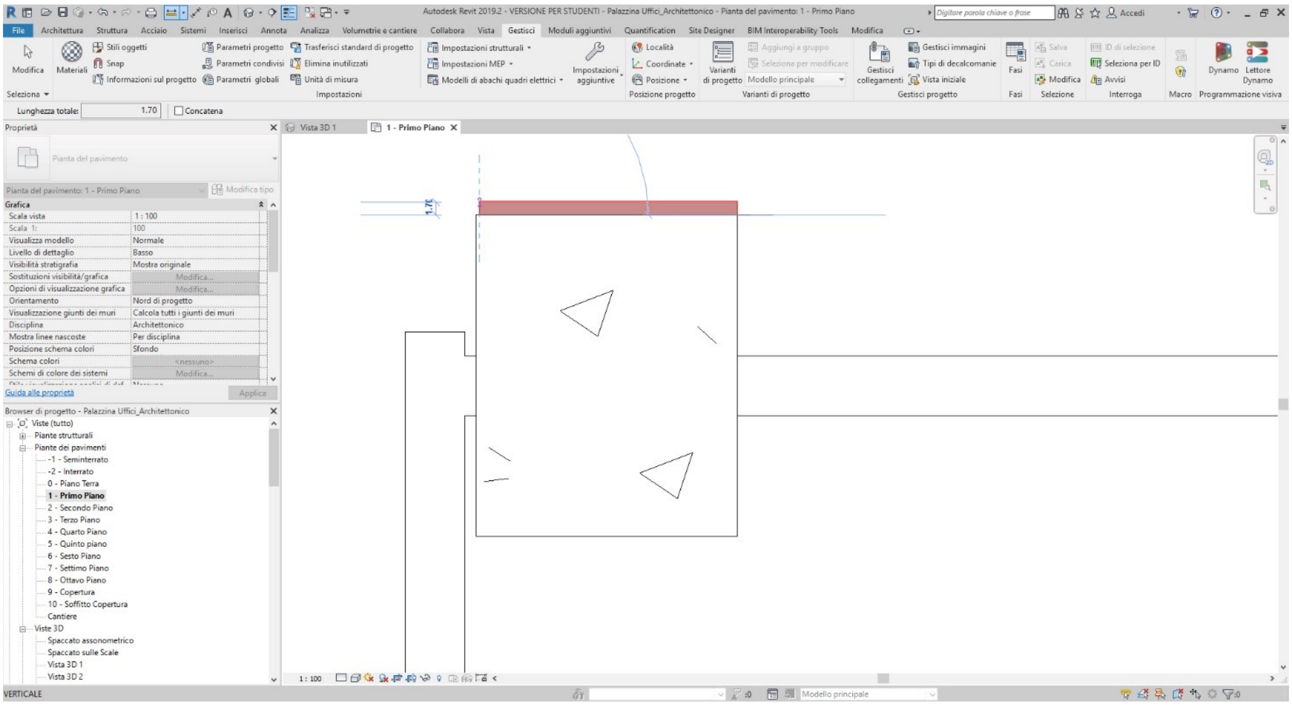

Fig. 21 - Identification of inconsistencies between CAD drawings and BIM elements. In red, the fill recreated with Dynamo© and in white the Revit© sectioned elements.

Some inconsistencies were found in certain structural elements, related to the diameters of the rebars. A non-destructive investigation campaign must be organised, using a covermeter, in order to verify this information. These checks would require a considerable amount of time and money to validate the data contained in the documents. It was therefore decided to mark the elements but not to schedule further investigations for the moment. The BIM model can be consulted later and the elements to examine can be identified and selected through filters and schedules (Fig. 22).

During the final stages of the modelling phase, it was realised that the data of the external colonnade was not enough: the drawings do not fully describe the complexity of the columns. A photogrammetric survey campaign was organised for the creation of a point cloud in order to obtain reliable information.

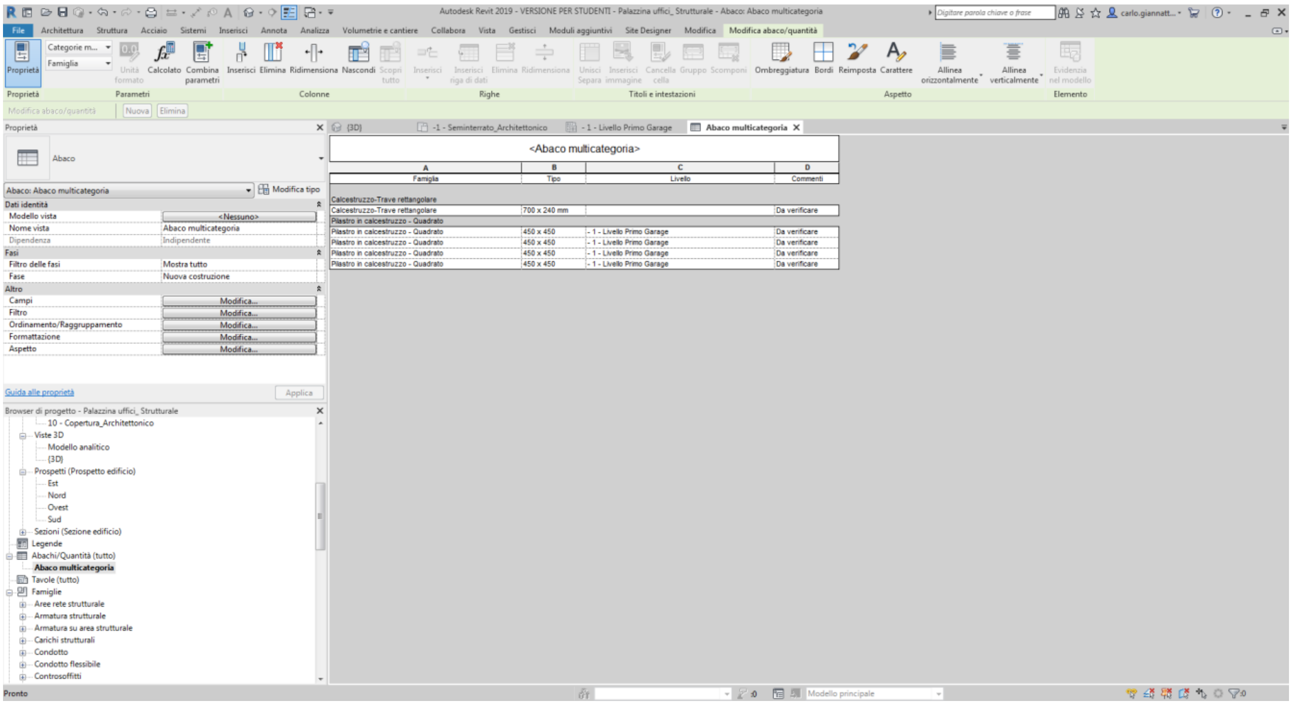

Fig. 22 - Elements selection to verify through a comment based filter.

Model Fixing

The data acquisition activities planned for the correction of the model were carried out. A laser distance measurer was used to check the placement of the pillars; the operations were completed without difficulty. The construction of the point cloud of the colonnade has instead presented many problems; the columns are light coloured and have no edges. It was necessary to place planar markers on the interested surface to be able to complete the reconstruction; the Agisoft Photoscan© software has in fact an automatic marker recognition function for the alignment of the cameras (Fig. 23).

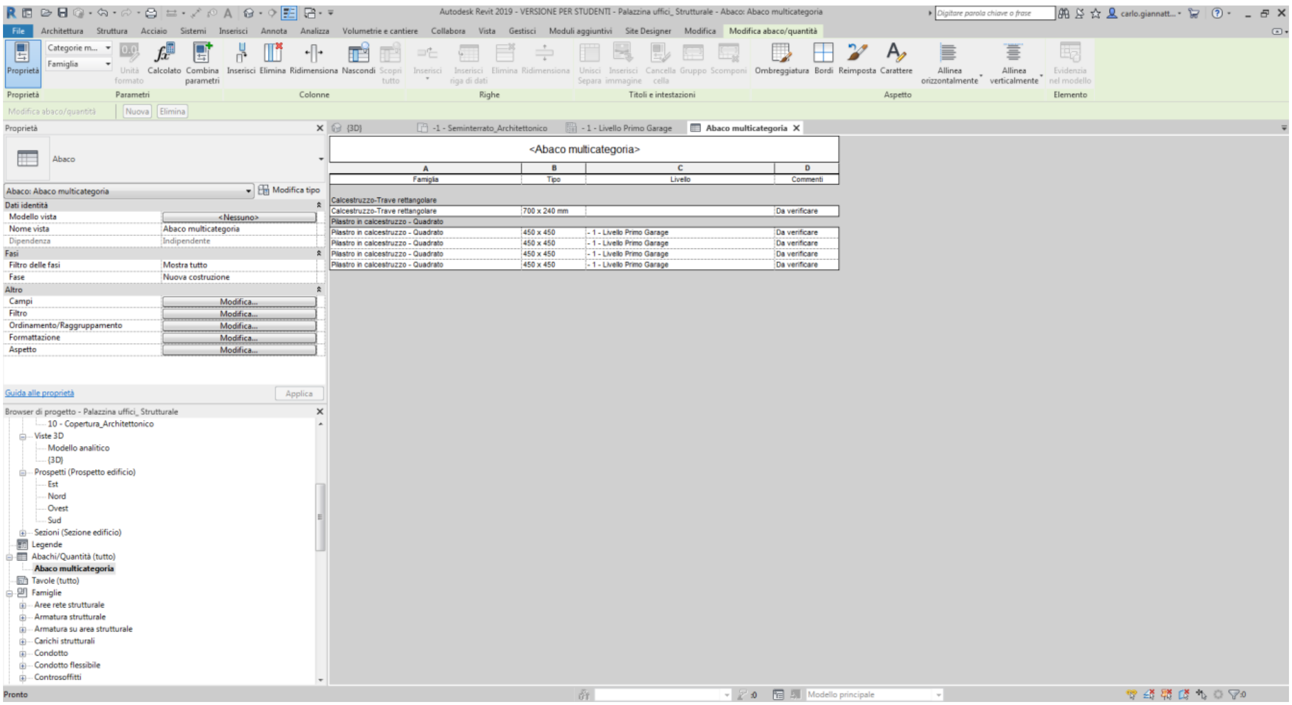

Fig. 23 - Screenshot of Agistoft Photoscan©. Recognition of planar markers.

61 photographs were taken and 21 markers positioned for the point cloud of a single column: the result obtained was valid for the requirements even if it had noise due to the reflectance of the investigated surface. There have been multiple steps from one platform to another in order to import the point cloud into Revit©: from Agisoft Photoscan© to CloudCompare© in e57 format for cleaning operations, from CloudCompare© to Recap© for orientation and the creation of the rcp file, from Recap© to Revit© for the construction of the BIM model (Fig. 24).

Fig. 24 - Workflow of the point cloud creation and import process.

The resulting point cloud has been imported into the Revit© environment. However, the first attempts at reconstruction were unsuccessful, both in the case of "Pillar" families and "In-Place Mass Objects". The column has variations of the sections in both main directions, which could not be described by these methods. Also, in this case, the complexity of the object required the use of the Dynamo© algorithmic modelling tool, in order to obtain a result both geometrically and semantically valid. It was possible to discretise the column geometry after having defined a sufficient number of horizontal sections; likewise the two skylights present at different heights were built (Fig. 25). The object thus created perfectly describes the real one, even if it cannot be modified: the volume generated by Dynamo© is monolithic and not parametric (Fig. 26).

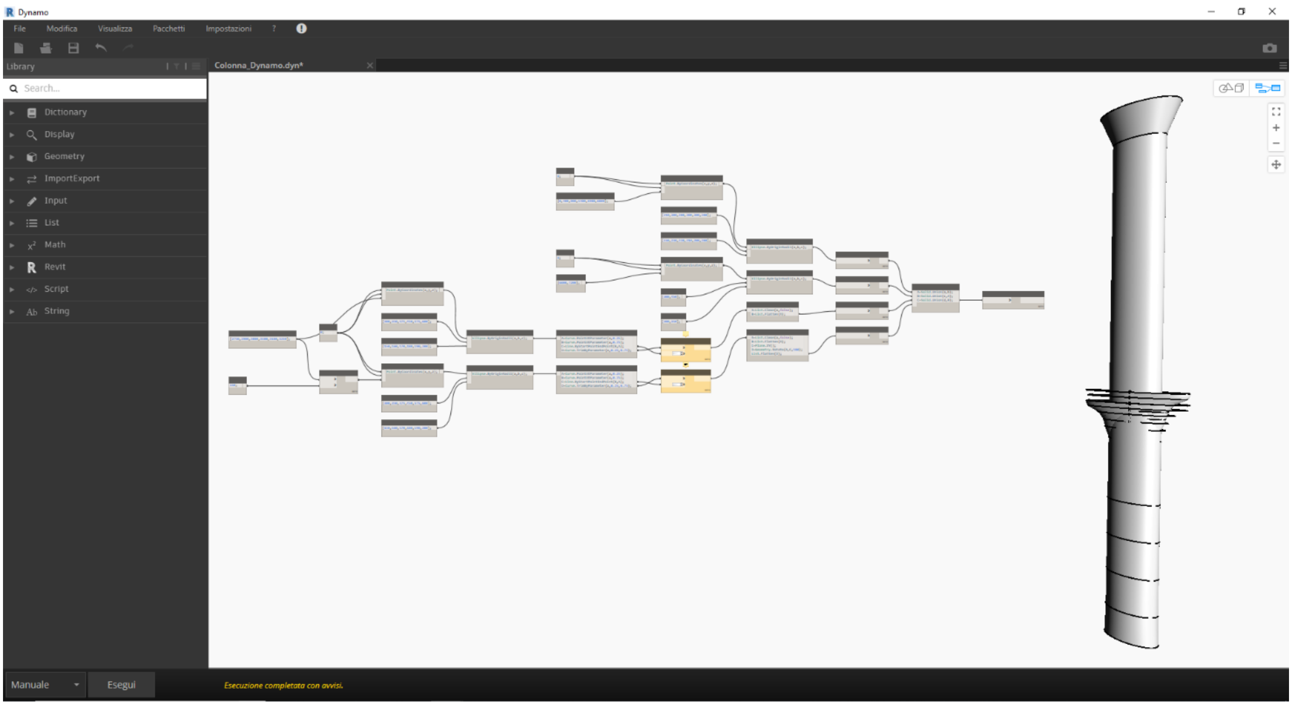

Fig. 25 - Dynamo© screenshot for the creation of the column.

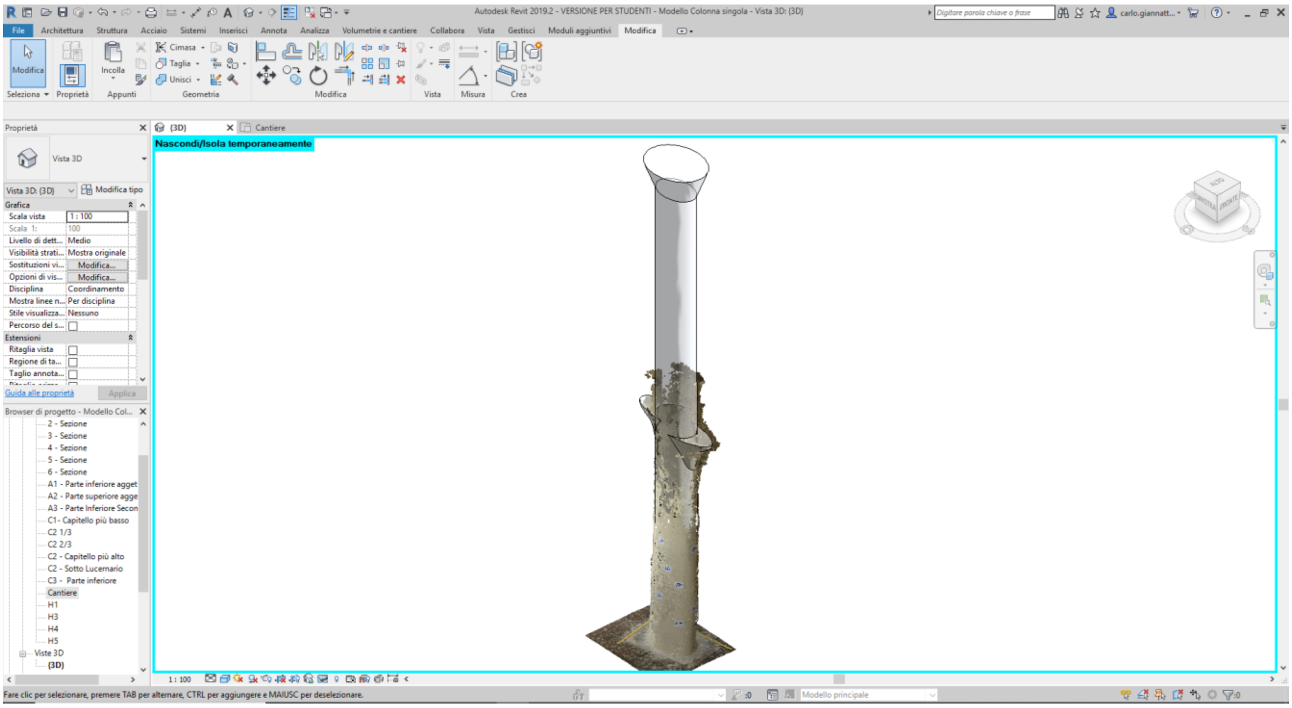

Fig. 26 - Comparison between the point cloud and the BIM model of the column.

In order to finish the model of the colonnade, it was necessary to create the roof that connects all the columns. Divided on two levels, the geometry could only be discretised through a local modelling of the "Roof" element; this tool in fact allows reconstructing an extrusion from a surface. The extrusion path was then described parallel to the building and an orthogonal view to the path was created, in this case the point cloud was used as a reference as well. The operations were similar for the two levels of the roof (Fig. 27), thus completing the building model (Fig. 28).

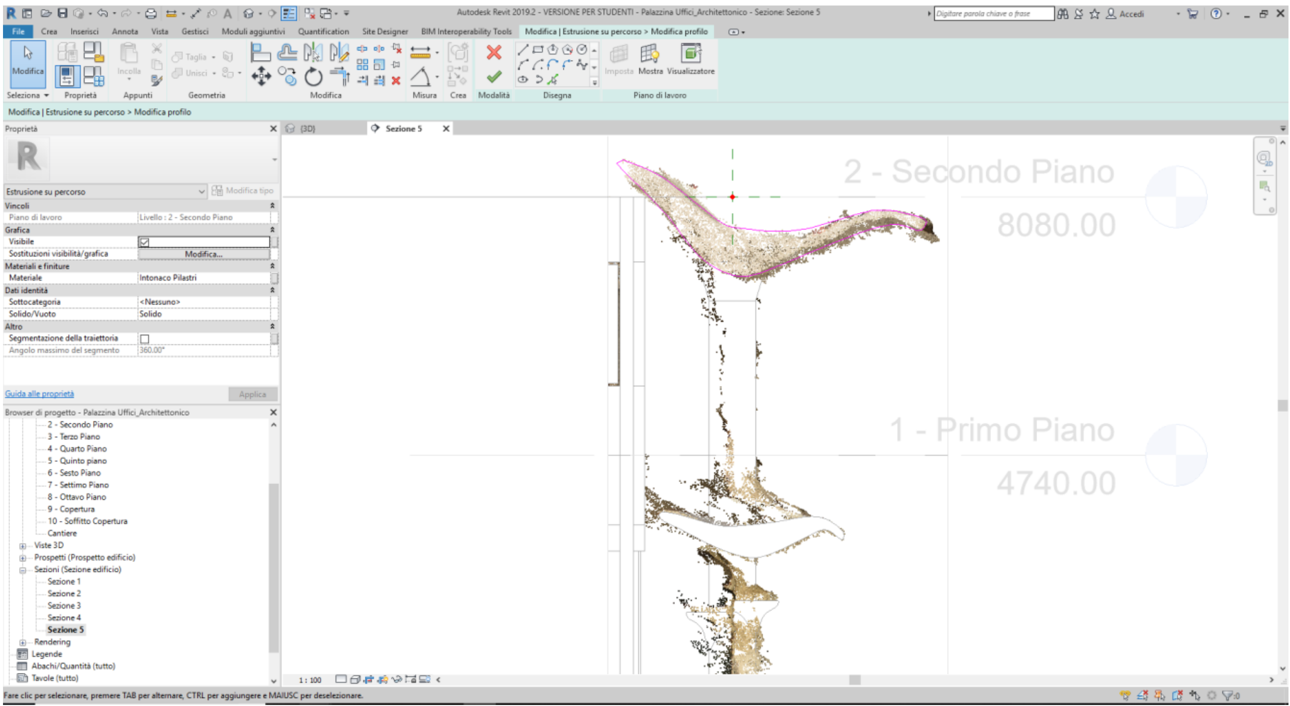

Fig. 27 - Construction of the roof by extrusion using the point cloud as a reference.

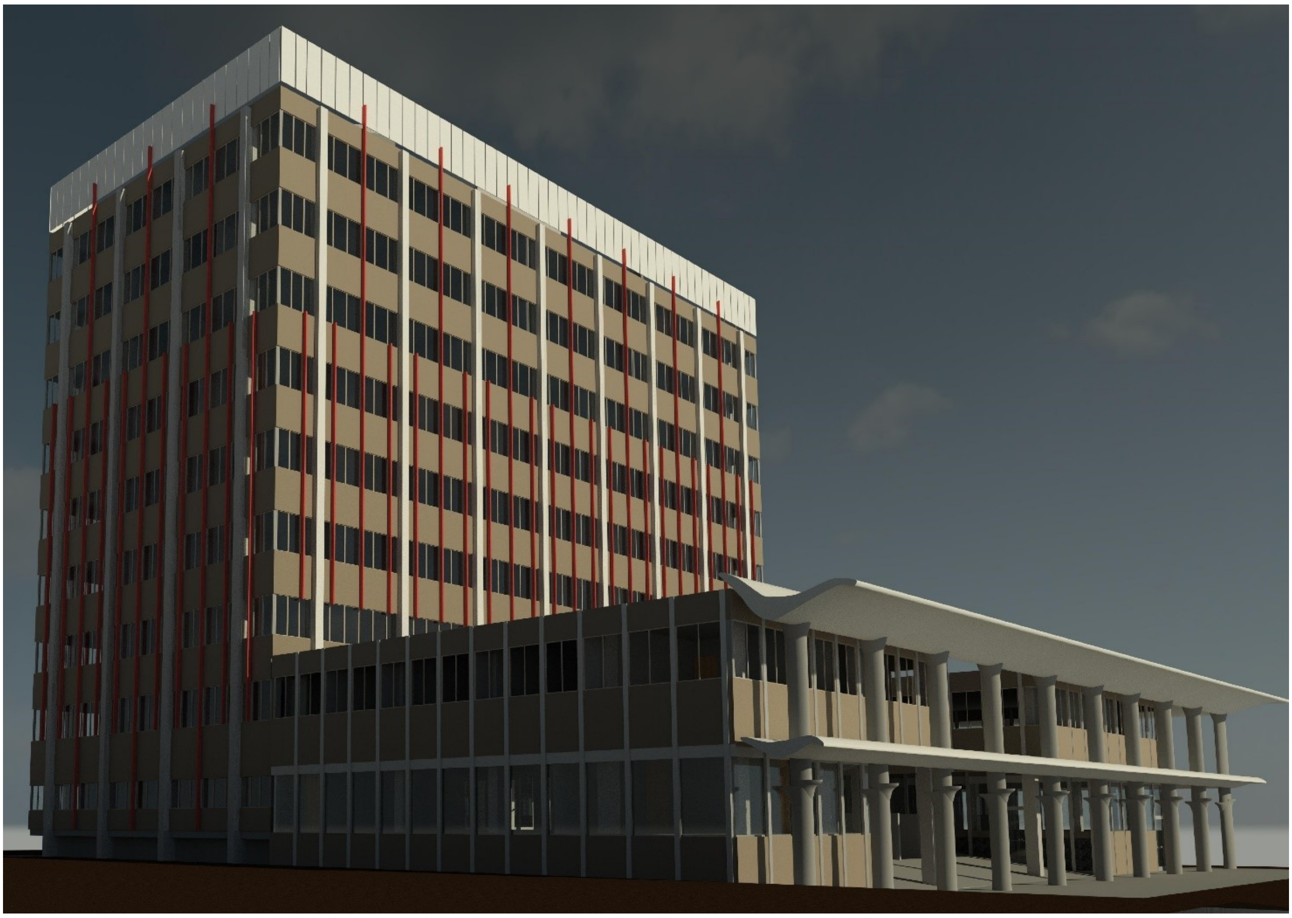

Fig. 28 - Rendering of the completed model.

Faculty of Veterinary

Overview

Fig. 29 - Satellite photo of the Faculty of Veterinary, former Complex of Santa Maria degli Angeli alle Croci.

The Faculty of Veterinary is located in Naples, in via Federico Delpino n ° 1, and catalogued within the *Centro Storico B* area (Fig. 30). The building is part of the former complex of *Santa Maria degli Angeli alle Croci*; it was built at the end of the 16th century by the Observant Friars. The complex was outside the limits of the ancient city and was composed only of the church and the annexed convent but it has undergone many changes and additions throughout the centuries. Cosimo Fanzago carried out the first interventions in the mid 1600s, between 1639 and 1647; Belisario Corenzio and his workshop frescoed the walls of the cloister during these works. In the 19th century, the Napoleonic suppression of religious orders also affected this complex: the church remained under the management of the friars while the convent became the Veterinary Institute. The change of function required extension works, with the construction of stables, classrooms and laboratories. Further changes took place in the first half of 1900, when it joined the University of Naples Federico II and became the Faculty of Veterinary, and in the 1950s, with the construction of the student house. In 2015, the modern wing of the complex collapsed due to subsurface subsidence.

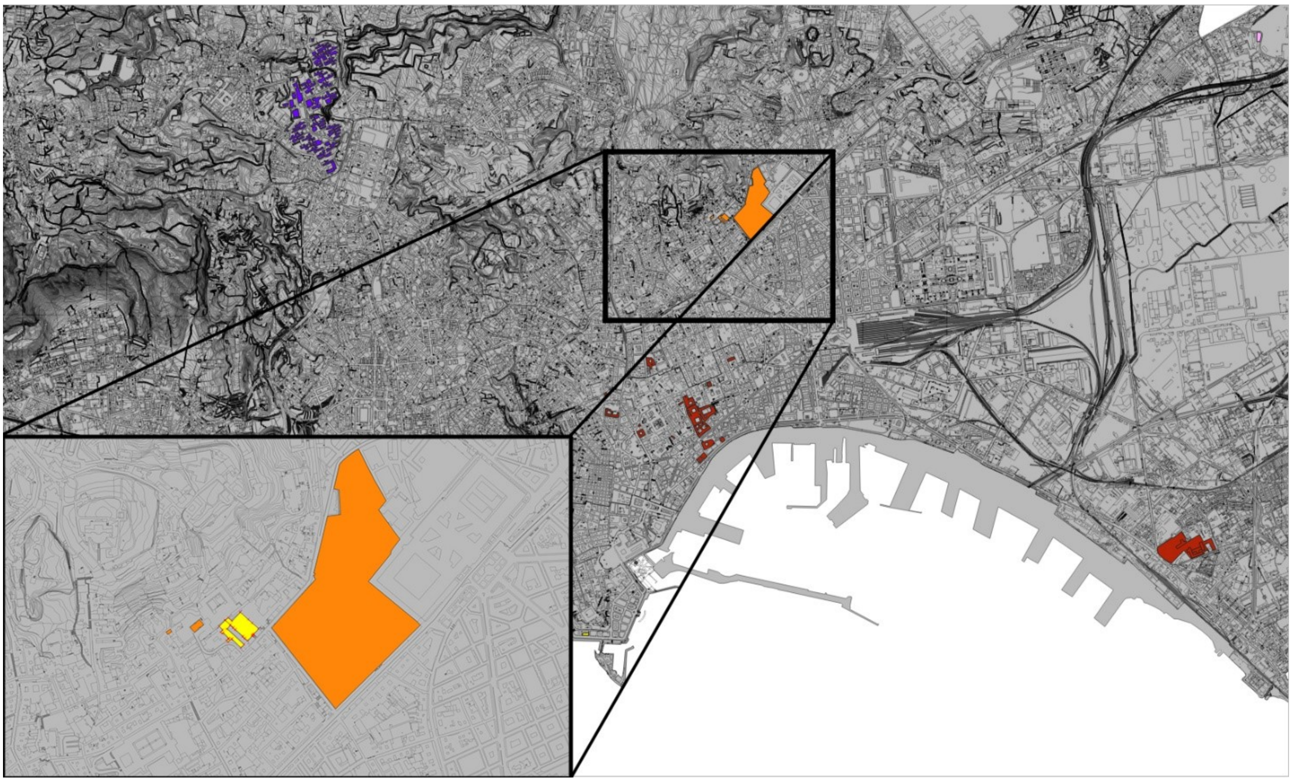

Fig. 30 - Territorial overview of the Faculty of Veterinary.

The Faculty of Veterinary expands over four levels above ground and it is composed by two buildings with very different characteristics. The former convent has a load-bearing masonry structure and has a courtyard development: the colonnade frescoed by Belisario Corenzio, which borders the church of *Santa Maria degli Angeli alle Croci*, is placed at its centre. The modern building connects to the previous building and creates another courtyard, used for access to all spaces; the volume is supported by a frame system in reinforced concrete (Fig. 31).

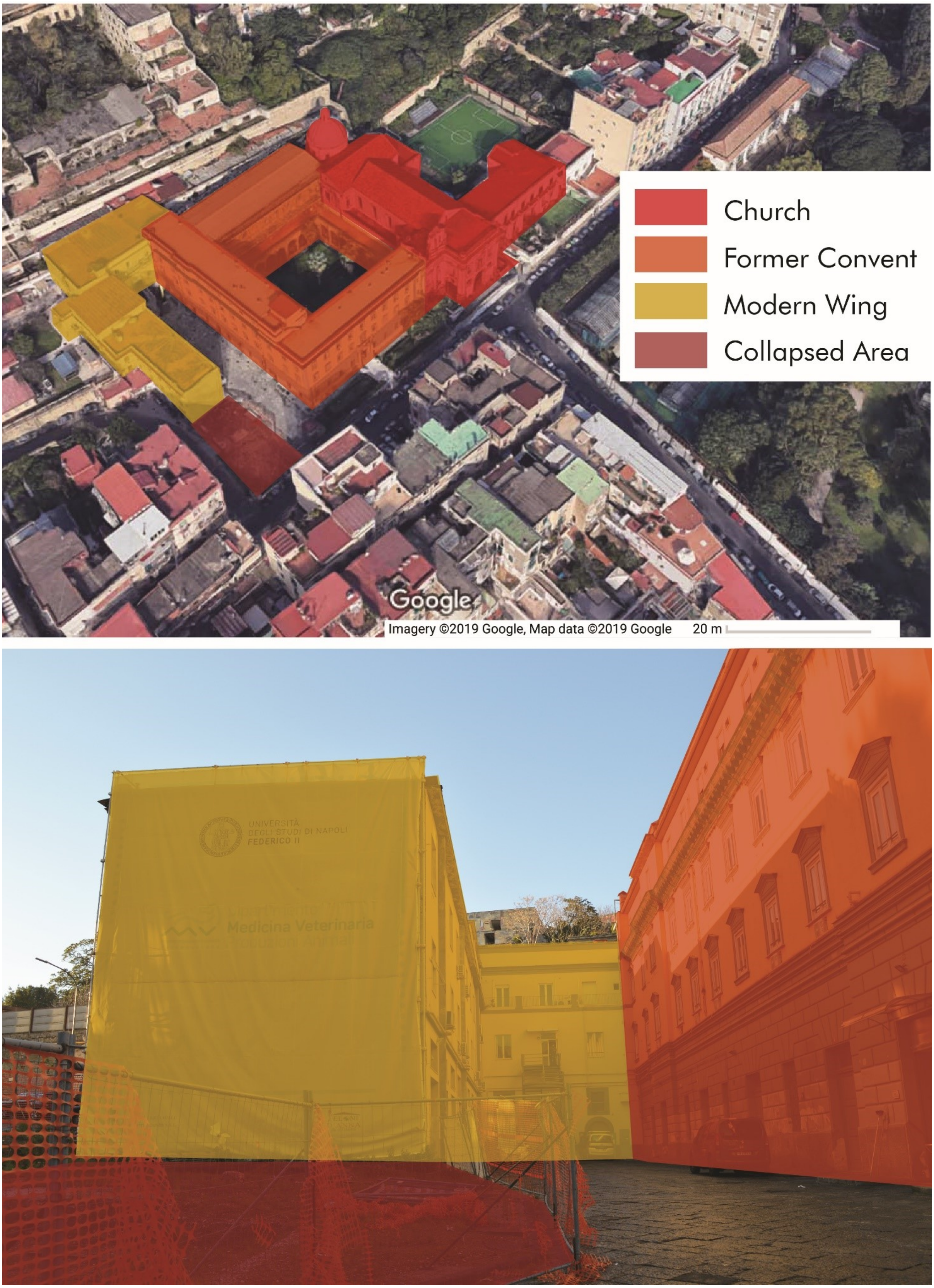

Fig. 31 - Faculty of Veterinary - Identification of areas. Above, satellite photo. Below, photo by the author.

Data Acquisition

As previously announced, the research carried out in the archives confirmed a lack of graphic information. In particular, there are twelve drawings in CAD format, divided between plans and elevations; they are the result in part of a digitisation of drawings and in part of a survey. The documents were catalogued but they were not sufficient for the BIM model reconstruction (Tab. 3). It was therefore necessary to provide for an exhaustive campaign of investigations.

Faculty of Veterinary - Via della Veterinaria, 2				
Survey				
	Plans		Scale	Partials
		Architectural - Intended use	1:100	5
Digitisation drawings	1992			
	Sections			
		C-C'	1:50	1
	Elevetions			
		Cloister - East	1:50	1
		Cloister - North	1:50	1
		Entrance - Courtyard	1:50	1
		Entrance - Via Veterinaria	1:50	1
		Entrance - Medicine	1:100	1
		Entrance - Emergency Stairs	1:50	1
		Total		12

Tab. 3 - Cataloguing of the CAD drawings of the Veterinary Faculty, located in via Federico Delpino n ° 1, Naples.

Preliminary inspections were then carried out to understand the volumes of the buildings and how to survey them; 300 photographs were taken with a Nikon D3200 camera to document these activities. Two clouds of points have been created by digital photogrammetry, one of the cloister and the other of the external courtyard; they were useful for the spatial volumetric comprehension rather than for the modelling of areas. It was easier to identify the instrumentation to be used and the data to be collected with the support of these reconstructions.

Two different survey campaigns were organised: one with the purpose to create a point cloud of the building common spaces and another in order to document the frescoes in the cloister with orthophotos. The first campaign involved the combined use of laser scanner and drone to fully describe the complexity of the building and to have sufficient and reliable data to create the BIM model. In the second campaign, photographs were taken using a tripod, in order to better manage the acquisition parameters and ensure a better result. In both cases, all the operations had to be carried out in a single working day, with no interruption to the normal activities of the faculty.

The first survey campaign

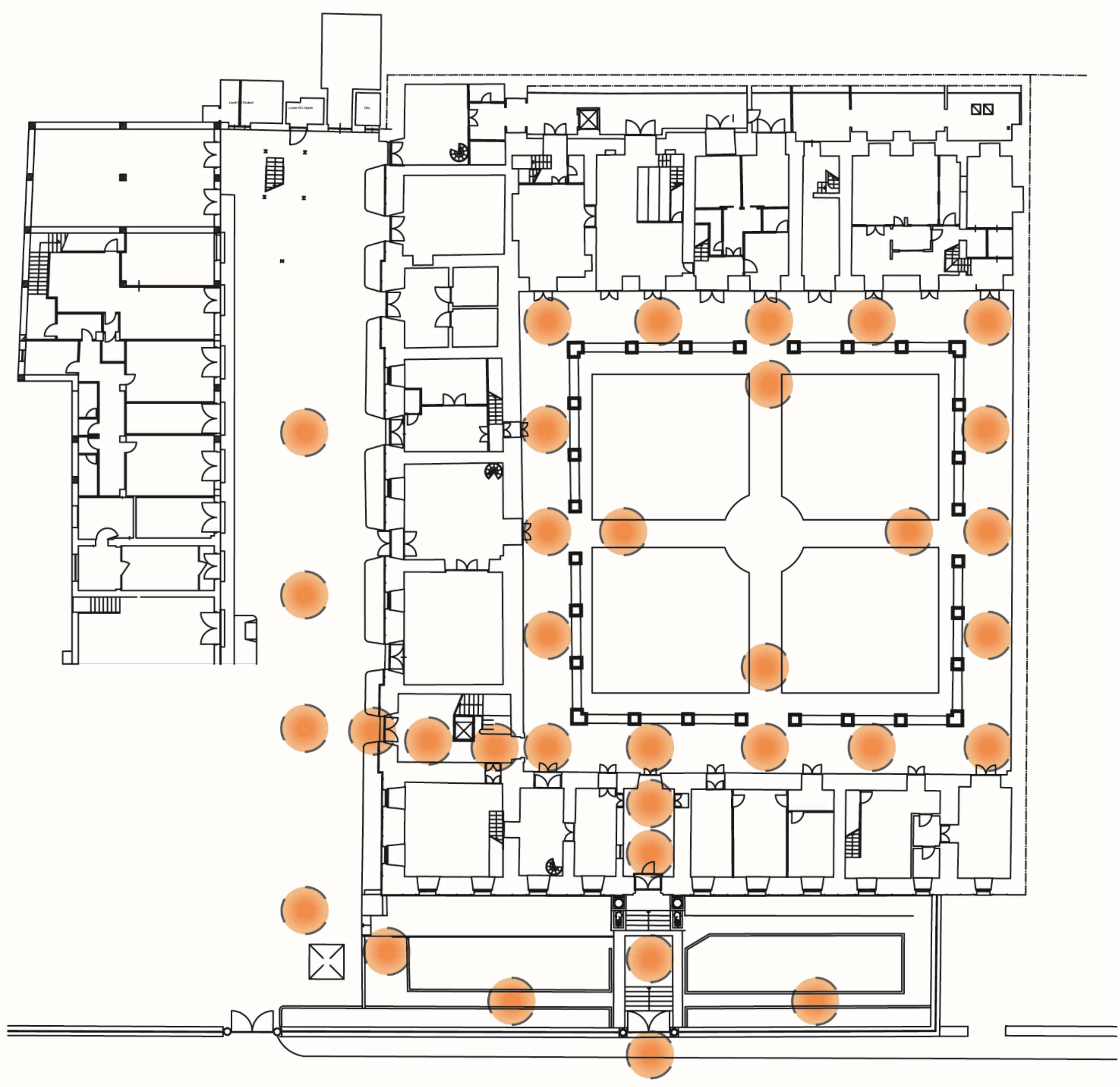

Fig. 32 - Scan positions on the ground floor of the Veterinary building.

Scan positions were defined to comply with time restrictions (Fig. 32); they were identified on previously acquired plans. A laser scanner model Faro Focus S70, suitable for both indoor and outdoor acquisitions, and the DJI Spark UAV system, a 300-gram drone with an integrated 12 Mega Pixel camera were used (Fig. 33) during the first survey campaign. In all areas to be studied, planar markers were placed to ensure a better result and to speed up the process of alignment and elaboration of the scans. They were positioned in a manner that allowed to clearly see at least four markers in each pair of scans. In a day's work, 40 scans were acquired, divided into two levels, and about 450 photographs were taken with the drone, focusing on the cloister. The collected data were catalogued and archived; a computer with a 2.20 GHz i7-8750H processor, 16 GB of RAM and 4 GB of dedicated video card was used for subsequent processing.

Fig. 33 - Documentation of survey activities. On the left, the DJI Spark UAV system. Right, the Faro Focus S70 laser scanner.

The scans were preliminarily imported into the proprietary software SCENE©; the platform has automatic tools for aligning scans through the recognition of markers and plans. It took 50 iterations and about 7 hours of work to obtain a point cloud of over 700 million points; the resulting file in e57 format occupies a total of 10 Gigabytes. The document thus obtained is not easy to manage; a cloud decimation process was performed to overcome this problem. The output of the process led to the creation of a 1.4 GB file in e57 format, with a one point every 10 mm; this value was considered adequate for the reconstruction of the BIM model. The 3DF Zephyr Aerial© software was used to process the drone photographs; all the operations of alignment of the cameras, creation of the sparse point cloud and the dense point clouds were performed in about 9 hours. The result is a point cloud of about 17 million, whose file in e57 is about 620 Megabytes.

Once the point cloud creation operations were completed, they were imported into Cloud Compare© for noise reduction and cleaning operations. To join the two point clouds, the laser scanner one was used as a reference for orienting and scaling the aerial photogrammetry point cloud. Homologous points of both clouds were identified and the transformation process was launched (Fig. 34). The resulting cloud was imported into Recap© (Fig. 35), where it was further cleaned and the origin was modified to simplify the modelling in Revit© (Fig. 36).

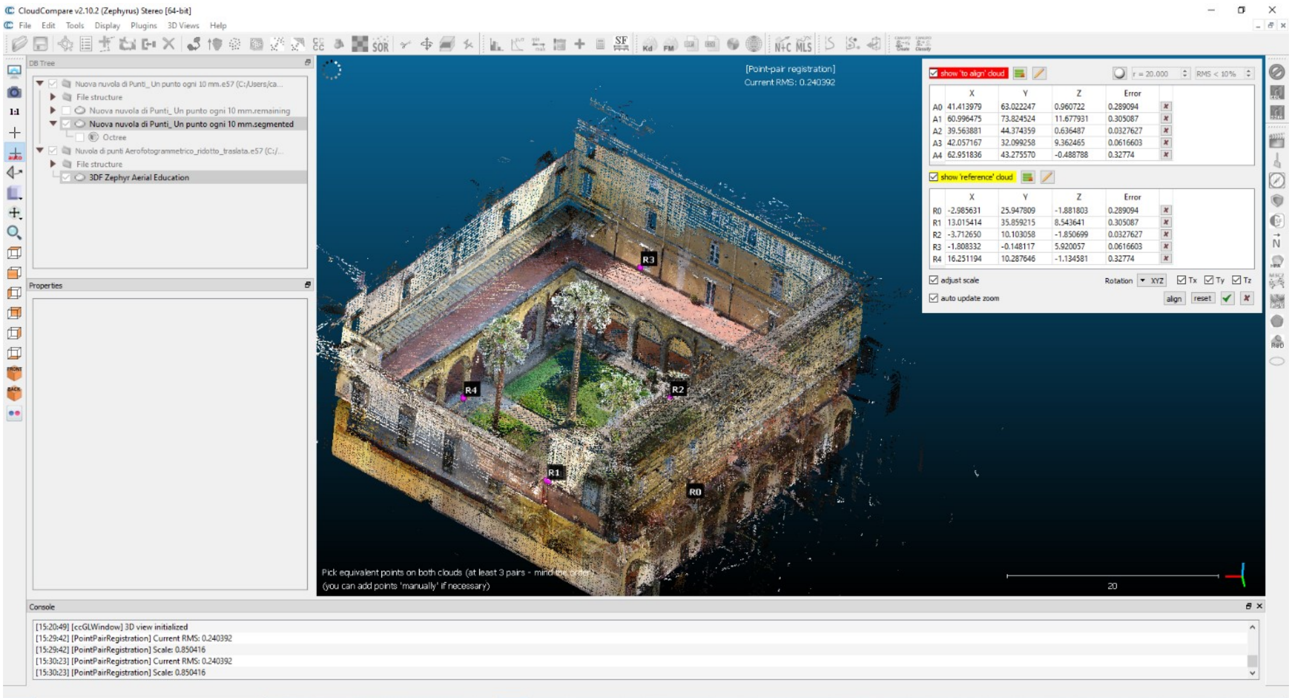

Fig. 34 - Alignment of the two point clouds in Cloud Compare©.

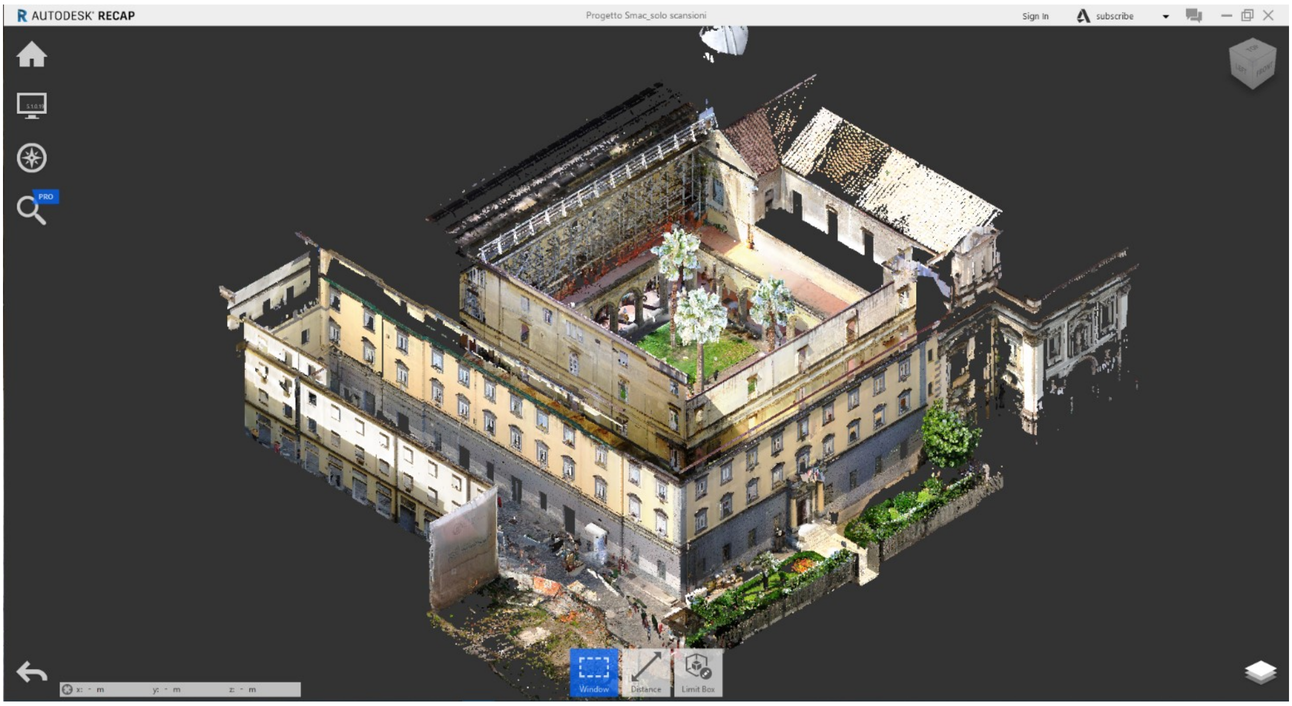

Fig. 35 - Point cloud complete in Recap©.

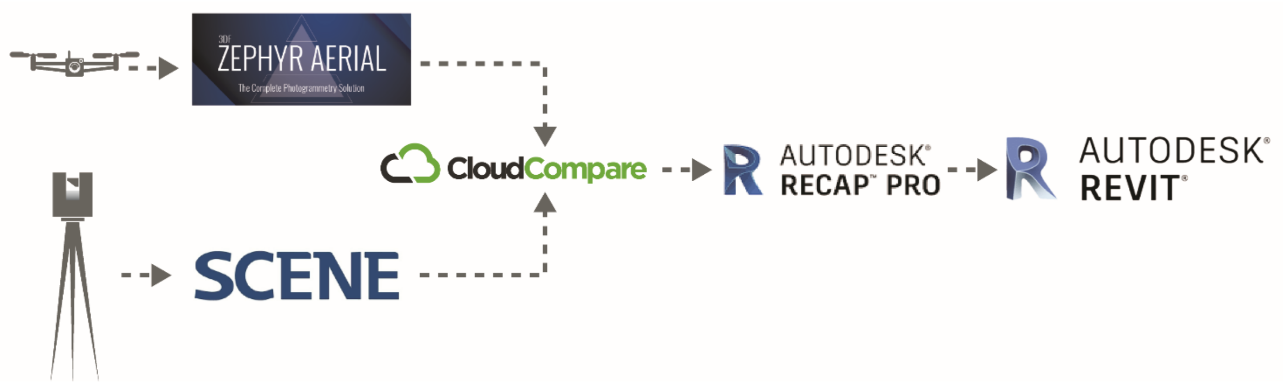

Fig. 36 - Acquisition and elaboration workflow.

The second survey campaign

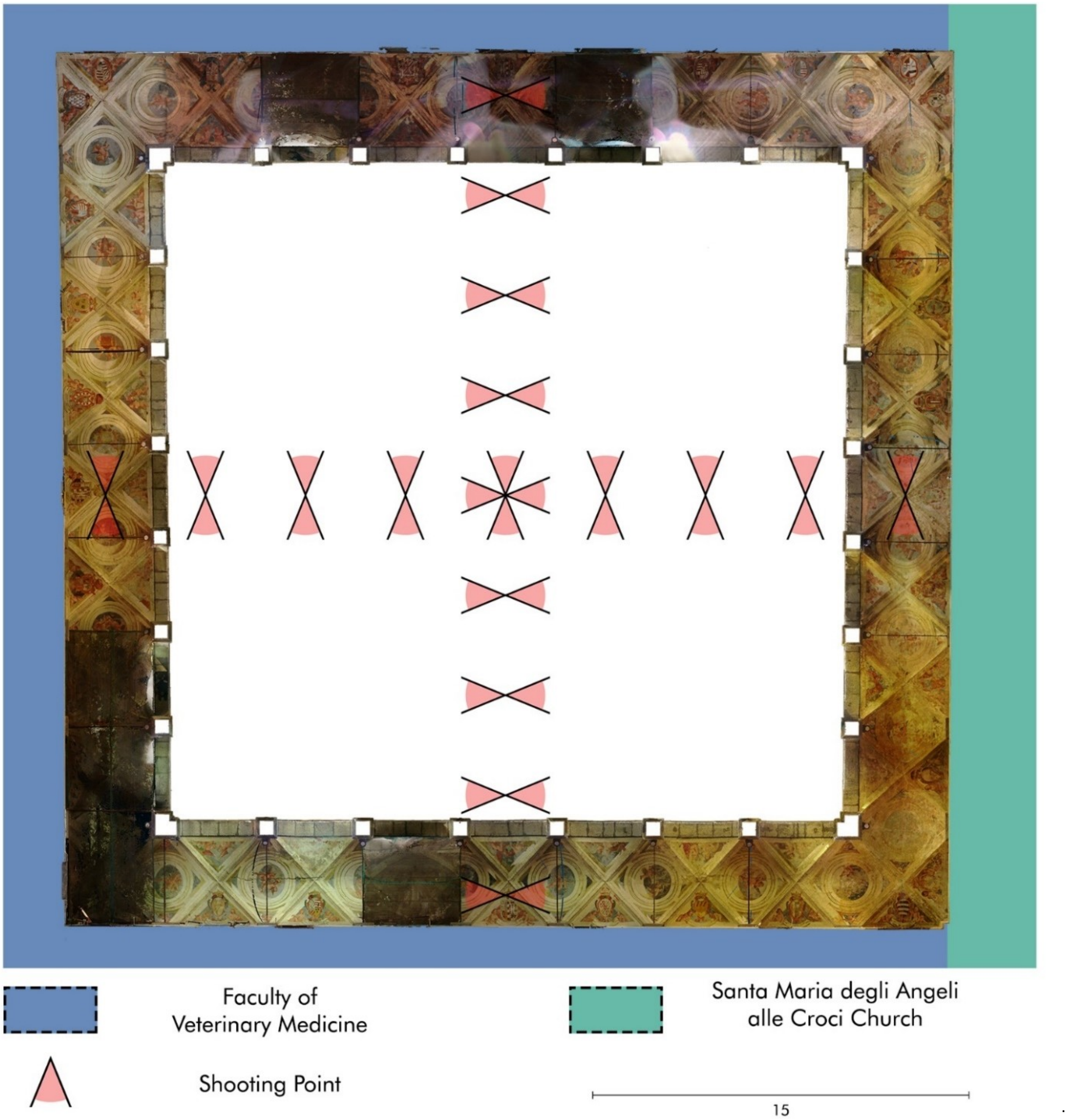

Fig. 37 - Positioning of the shooting points.

The second campaign of acquisitions concerned the survey of the frescoed walls of the cloister, where episodes inspired by the sacred scriptures are portrayed. This survey is functional to the documentation of the conservation status of the frescoes rather than modelling. Also, in this case, the shooting points were identified (Fig. 37), in the same way as the scan positions were designed. The survey activities were performed in the early morning to have a homogeneous light and avoid direct sun on the frescoes. The camera used was a Nikon D3200 with a Nikon DX AF-SR Nikkor 18-55mmm 1: 3.5-5.6G lens. All the photographs were taken with focal length locked at 55mm to avoid barrel aberrations, typical of wide-angle prime lenses, or pincushion aberrations, typical of zoom lenses. The parameters set were:

- **Focal Length[3]:** 55mm
- **F-number:** f / 36
- **Sensitivity:** ISO-100
- **Exposure time:** variable (up to 6 seconds)

A stabilised tripod was used due to the variable and long exposure times; the camera was levelled at each change of shooting point. 132 photos were taken overall, which were later divided and catalogued. The software used for the processing was Agisoft Metashape© and four different files were created. For each wall, the process lasted about an hour and included photos import, masks creation, cameras alignment, dense point cloud creation, scale definition and texturing. Finally, the orthophotos in TIFF format were exported (Fig. 38).

Fig. 38 - Orthophoto of the cloister walls.

[3]The focal length is referred to DX lenses

Fig. 39 - Documentation of the survey activities.

Model Reconstruction

At the end of the acquisition phase, it was decided to reconstruct only the architectural model, for the lack of sufficient structural and MEP data.

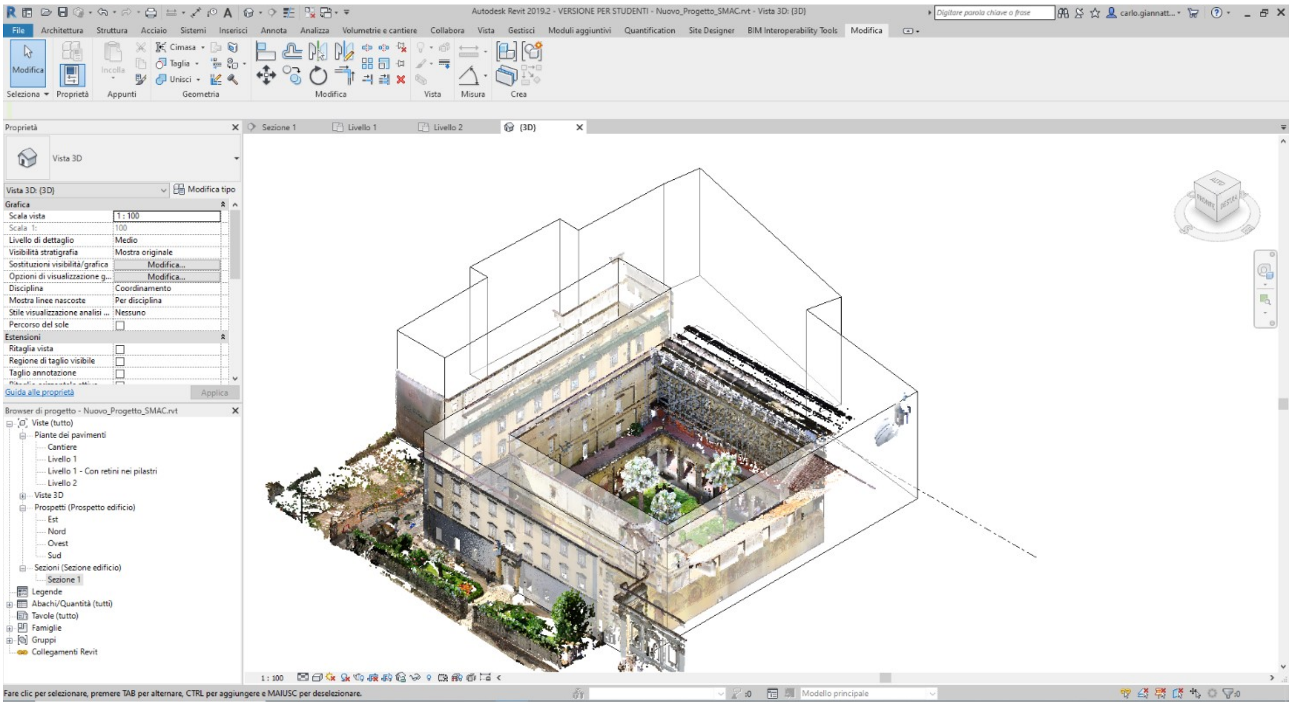

Fig. 40 - Mass object creation of the general volume of the building.

Both the point cloud and the CAD drawings were imported into the BIM environment; the latter were used for the construction of the internal partitions and for the definition of the walls thickness. Afterwards, the levels and views were set before starting the modelling of the architectural objects. The general volume of the building was then reconstructed through the creation of an In-Place Mass Objects (Fig. 40): it makes it possible to identify support surfaces for architectural elements such as walls, floors and roofs. The mass overcame the modelling limits related to the point cloud; the Revit© software recognizes some snaps on the point cloud but they are not very easy to manage and can lead to errors. The mass was therefore a reference in the creation of external walls, floors and roofs. In the following, the cloister was modelled, which presented two different difficulties: the positioning of the columns and the reconstruction of the vaults. In particular, the problem of the columns is comparable to that of the pillars of the CADToBIM process, i.e. the definition of the centre of the section, input point of the BIM object. Algorithmic modelling was used to create an application for the automatic recognition of isolated geometries in ScanToBIM processes to overcome this limit of the BIM platform. The operator can distinguish the pillars through a coloured fill and place the appropriate elements using the snap given by the cross (Fig. 41).

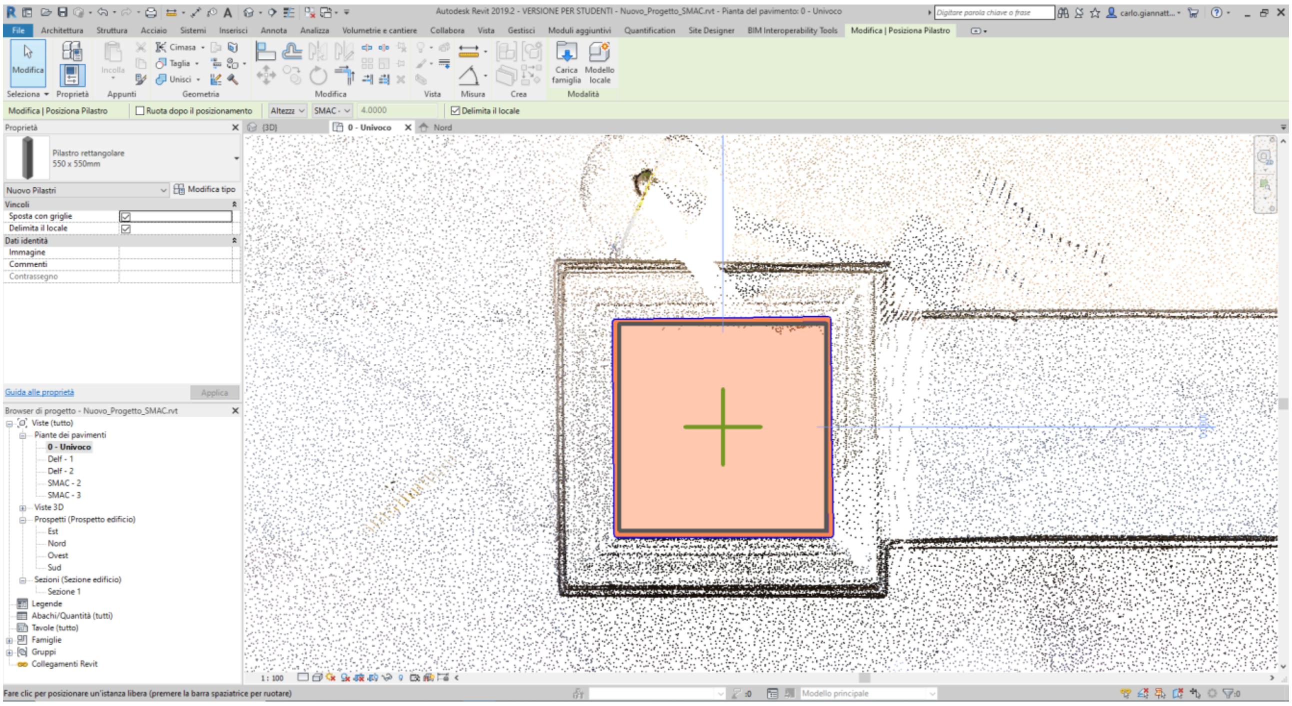

Fig. 41 - Result of ScanToBIM algorithm and positioning of the pillars.

The software does not provide immediate solutions for vault construction. Since no detail modelling was required, another mass object was created in order to create the curved surfaces easily. Solid full and empty geometries were used and the average trend of the cross vaults was discretised (Fig. 42). During the creation of these elements, the software reported an error message when the voids intersected and there was no solid geometry to cut. To solve this problem, the solid geometries to be cut were modified locally, increasing the available surface area, and then the voids were reapplied. Then a semantic doubt arose about the nature that the element should have, since there is no category "Arches" and/or "Vaults"; various alternatives were then analysed. The “slab” elements were immediately excluded because the software does not allow the creation of objects based on curved surfaces. These geometries can only be described with "roof" or "wall" elements: the latter was preferred because it interpolates the mass object better and has a behaviour similar to vaults and arches. They were then associated with the previously constructed surfaces (Fig. 43).

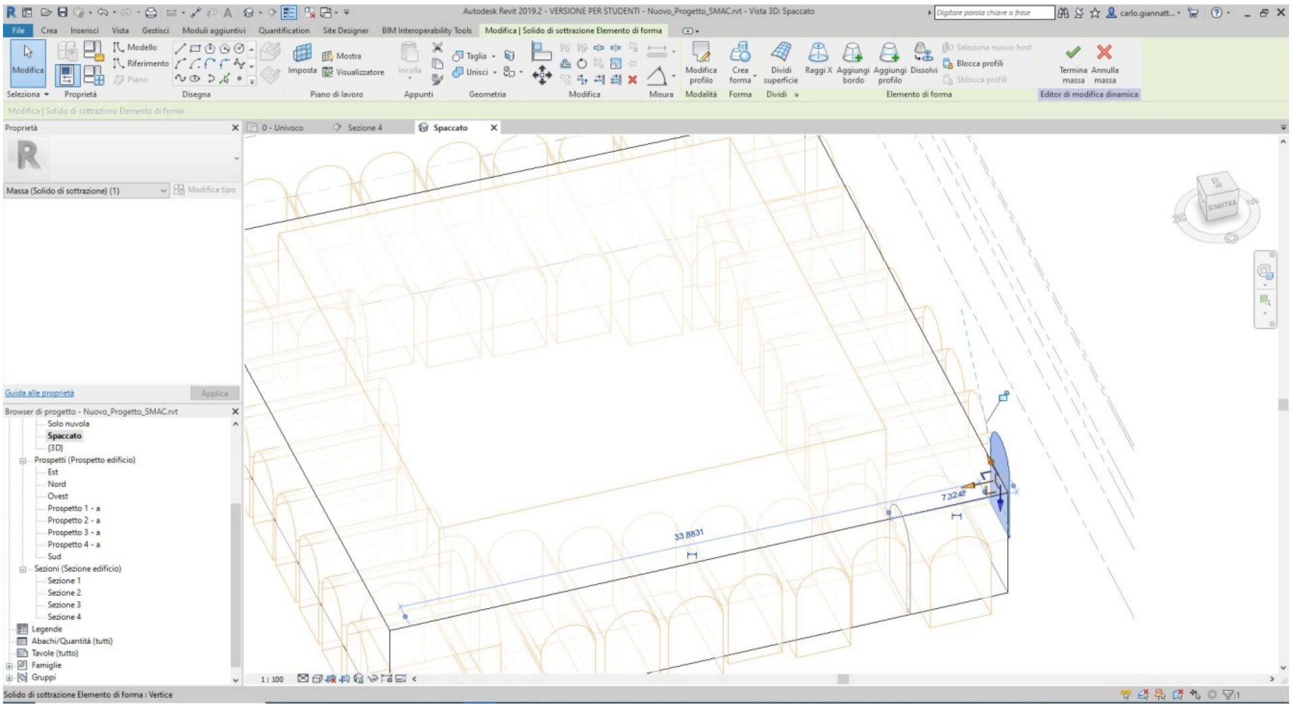

Fig. 42 - Construction of the mass object and positioning of the voids.

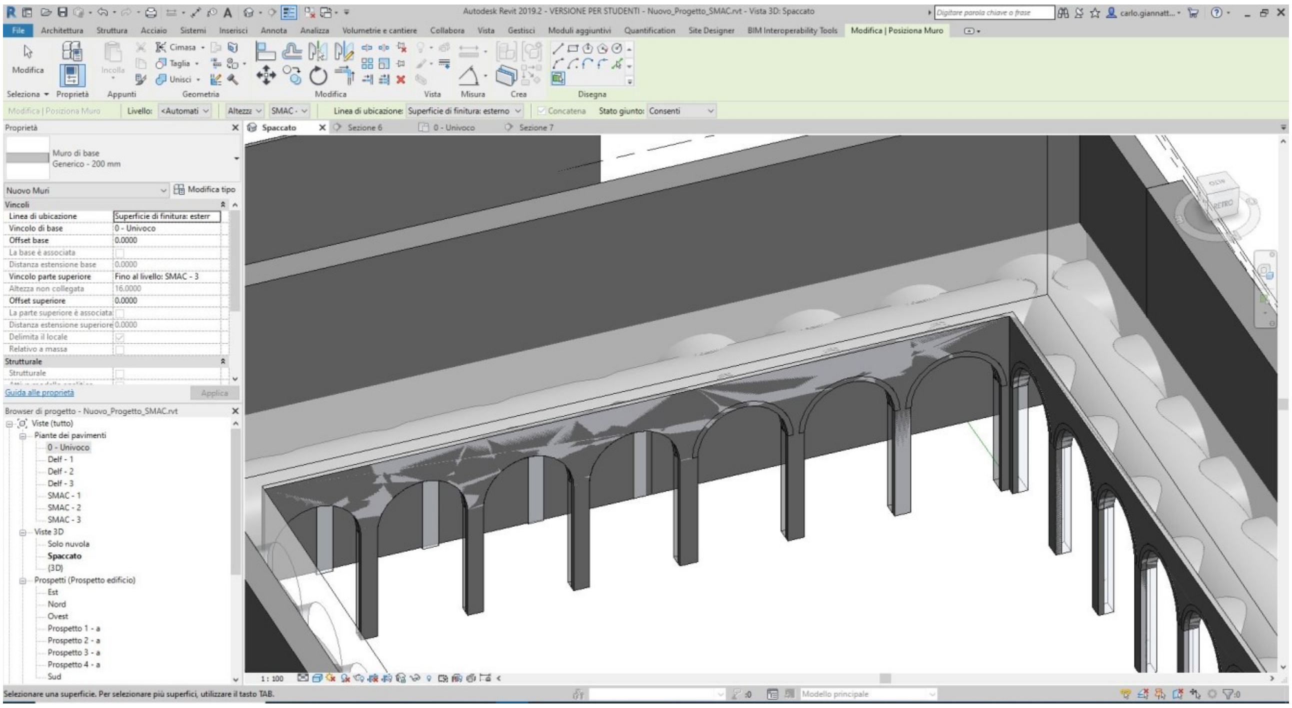

Fig. 43 - Completion of the mass and creation of the surface-based walls.

The operations continued with the construction of the interior walls. In some cases, the software reported an error message when several walls are not perfectly orthogonal to one another (Fig. 44). Local intervention was attempted but the results were not always adequate. Rather than specially recreated family objects, common objects were used for doors and fixtures, because there was not enough data for them to be modelled. The model was completed with positioning and georeferencing (Fig. 45).

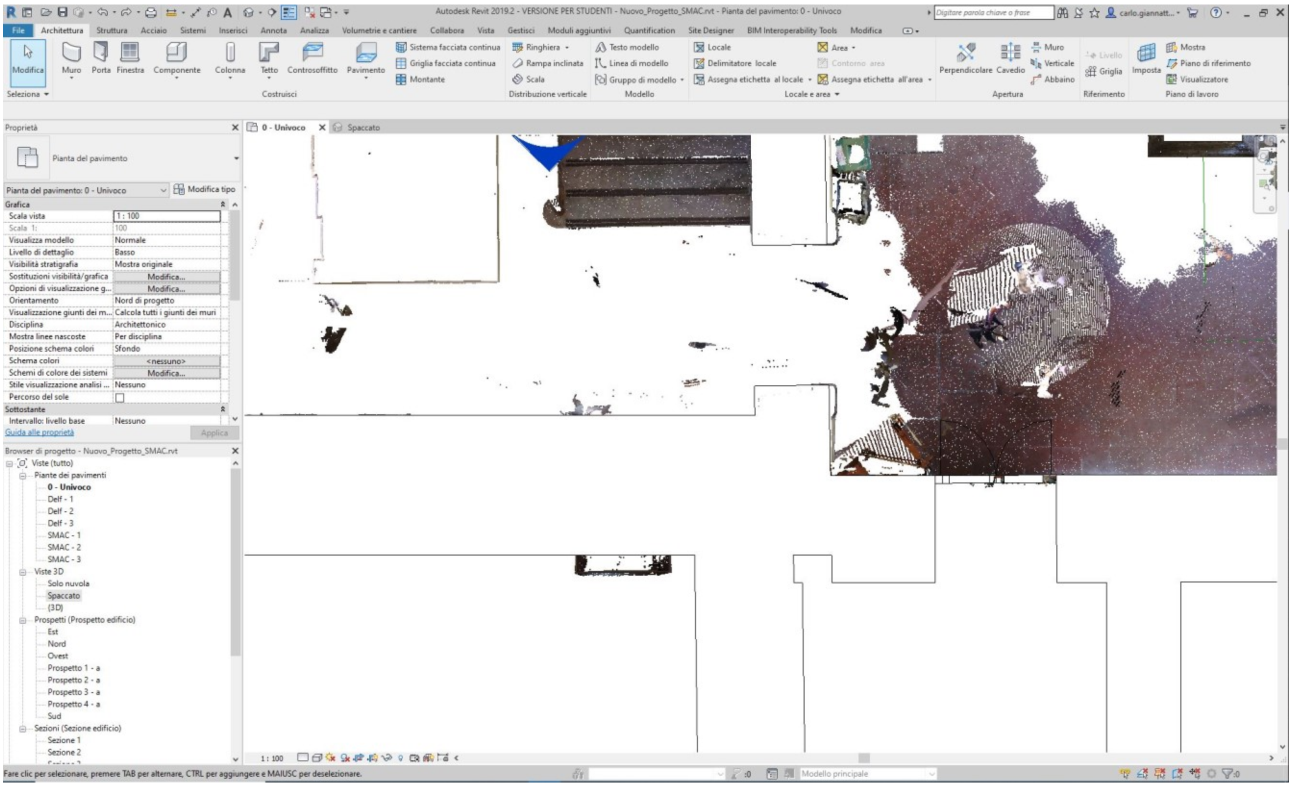

Fig. 44 - Problems with the intersection of walls.

Fig. 45 - Completed model compared with the point cloud.

ScanToBIM pattern recognition algorithm

As for CADToBIM processes, a ScanToBIM recognition pattern was defined for the detection of isolated polygonal elements that respect the Manhattan World Assumption (Coughlan & Yuille, 1999; Coughlan & Yuilla, 2000; Coughlan & Yuille, 2003). In this case, it was necessary to integrate traditional programming with algorithmic modelling. Dynamo© platform allows to run scripts with the open source language IronPython©, similar to Python© version 2.7. Then, the inputs were defined:

- the point cloud;
- the reference level;
- a height h;
- a view on which to display the result of the process.

After the point cloud is imported in Dynamo© as preliminary operation, the reduction of the points to be analysed is needed; a volumetric filter is then defined to identify all the points with a height between h ± Δh. The height h considered in the analysis is 2.40 m from the walking surface, in order not to cut the openings, and the Δh is 5 cm. The result is projected on a horizontal plane placed at height h and imported in Dynamo©. It was necessary to use the API (*Application Programming Interface*) of the Revit© software to operate on the point cloud. Then, the isolated elements must be found and distinguished from the continuous elements; for this reason it was necessary to introduce a constraint based on the proximity between the objects. Considering a specific distance value d_{lim} and a generic point P (Fig. 47), a circular neighbourhood C of radius d_{lim} is created and all other points within the set are excluded. All the circles are then intersected with each other (Fig. 48); if the generic circle C does not intersect any other circle, the element is recognised as isolated and all the points inside

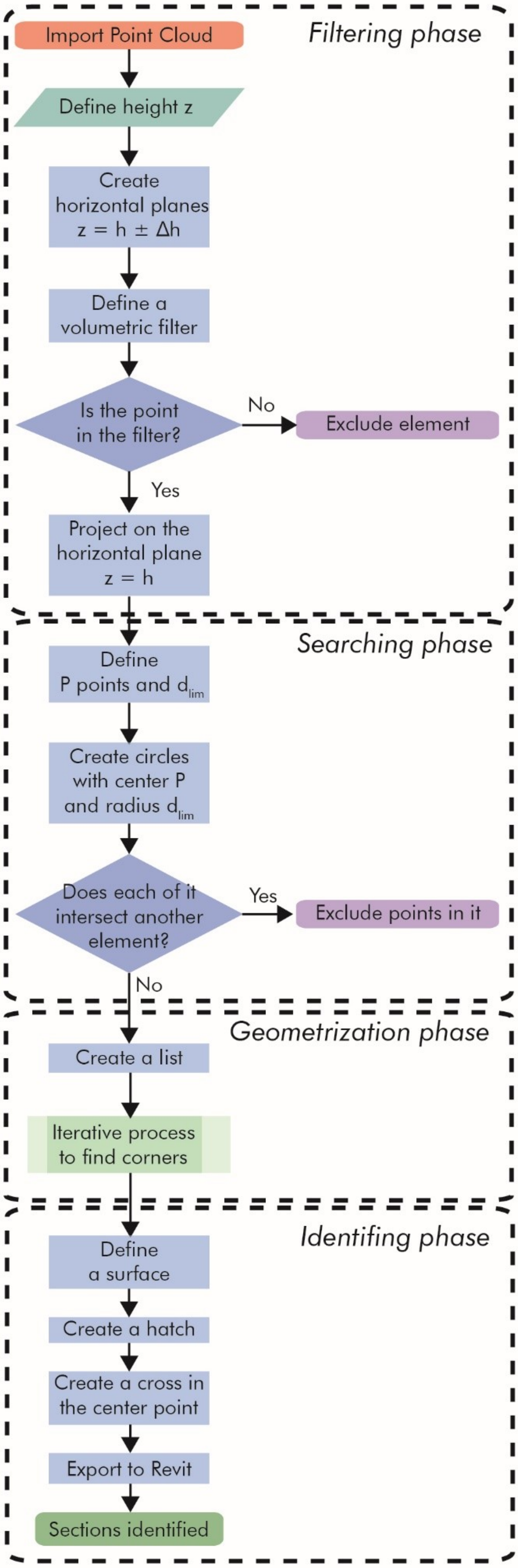

Fig. 46 - ScanToBIM algorithm for the recognition of isolated polygonal elements.

the circle C are placed in a list L (Fig. 49). In the case, d_{lim} was set equal to 1.2 m since it is greater than the distance between two pillars. An iterative process is applied to each list L for the recognition of the vertices and the creation of the geometry. The resulting section is marked with a fill and its centre is identified; the result is finally exported to Revit© (Fig. 50).

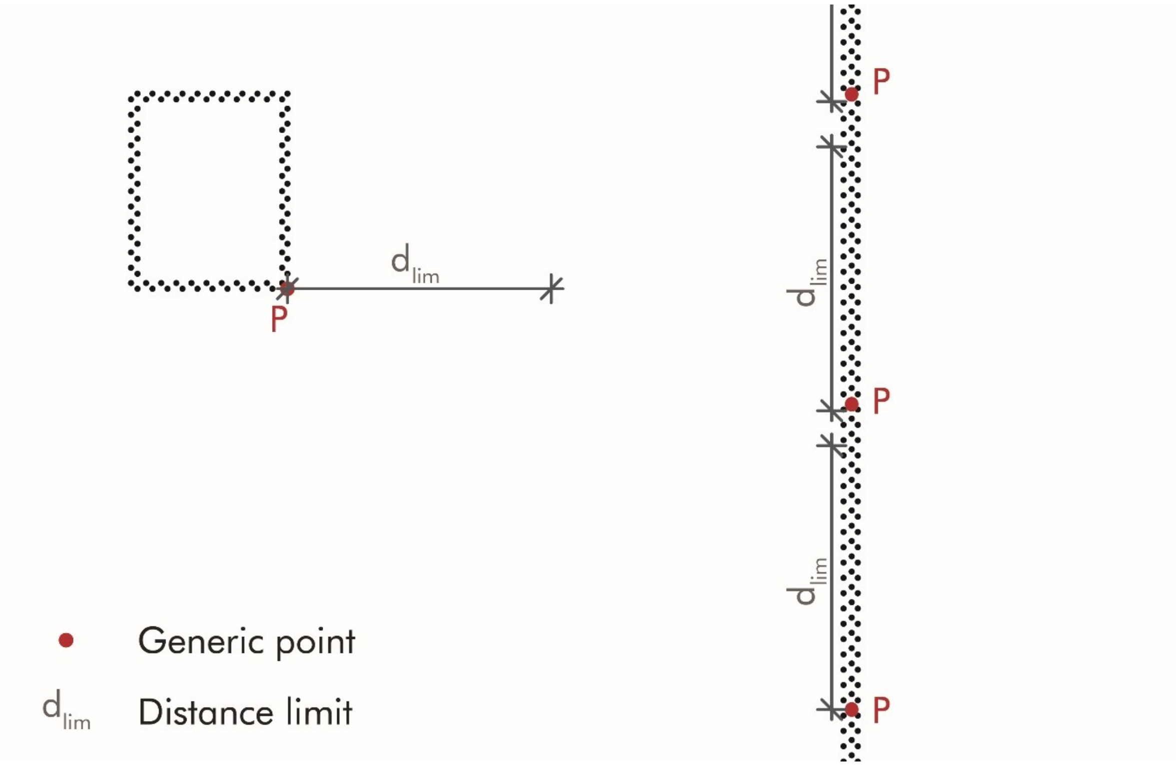

Fig. 47 - Definition of the points P and the limit distance d_{lim}.

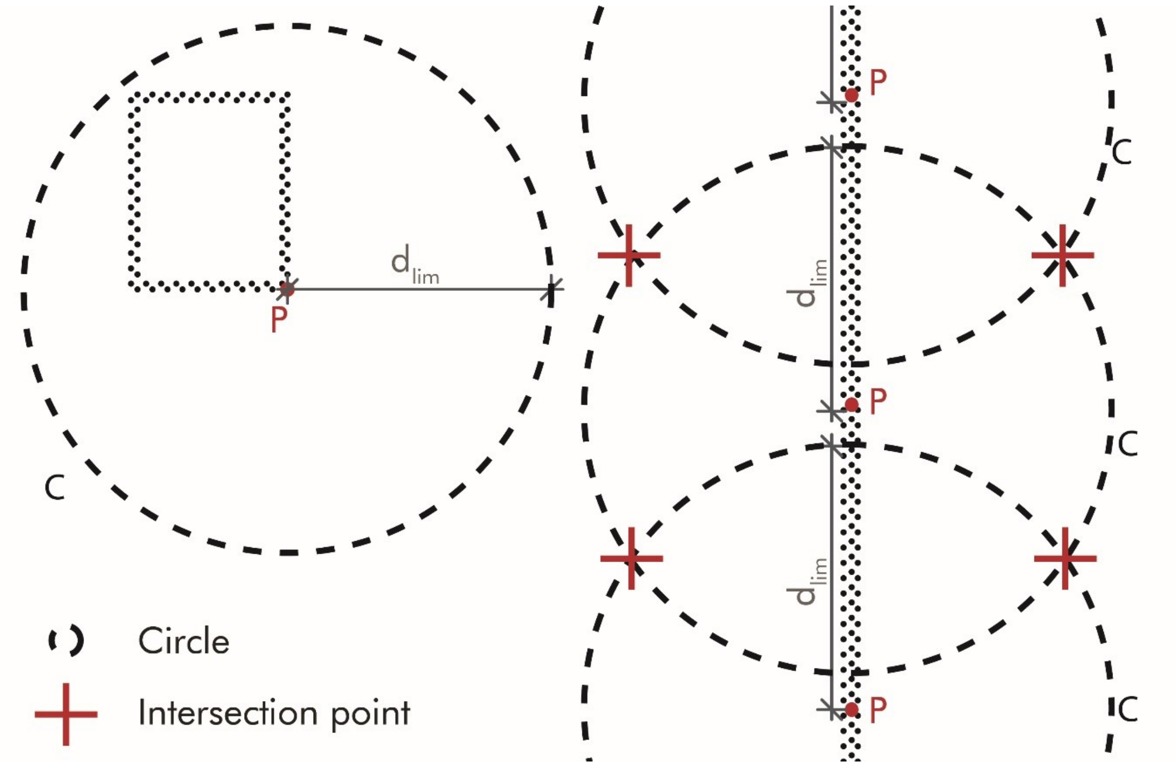

Fig. 48 - Creation of the circles C and definition of the intersection points.

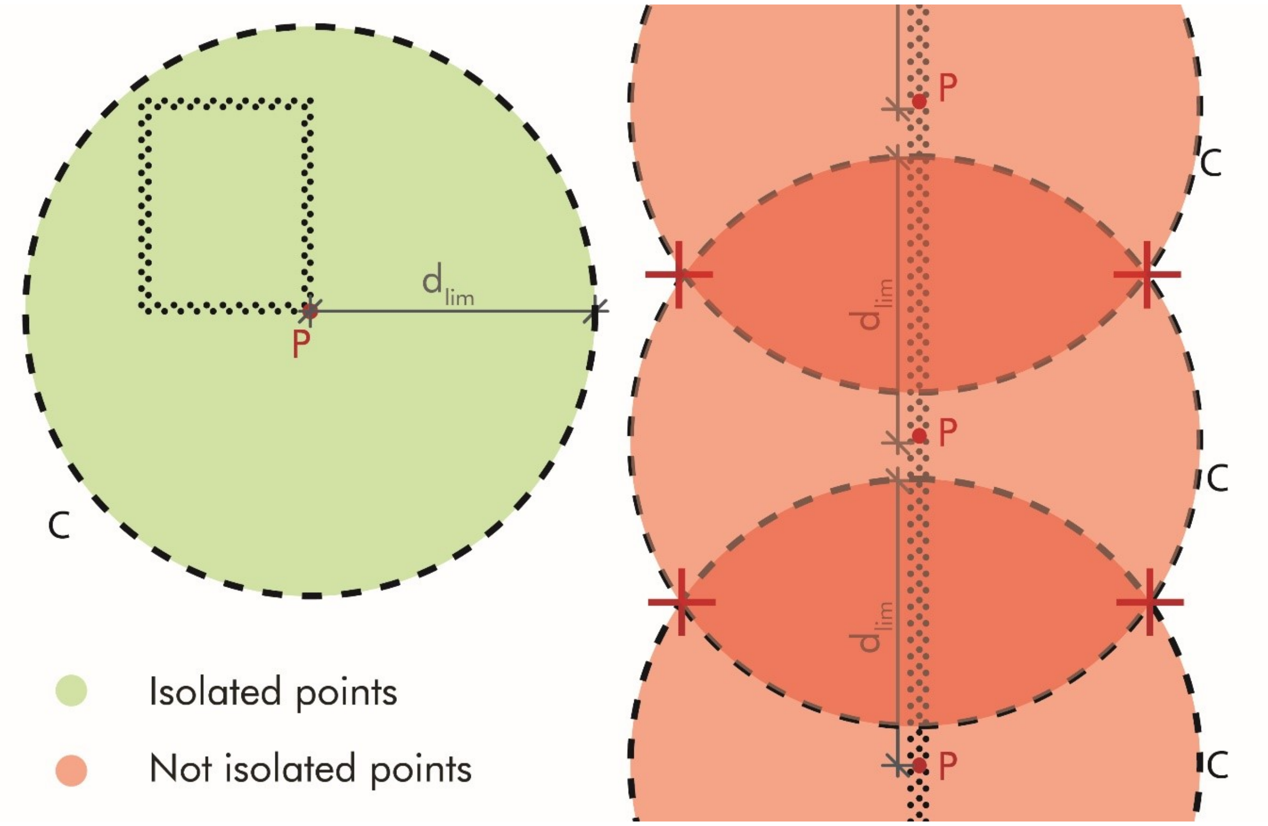

Fig. 49 - Identification of isolated elements.

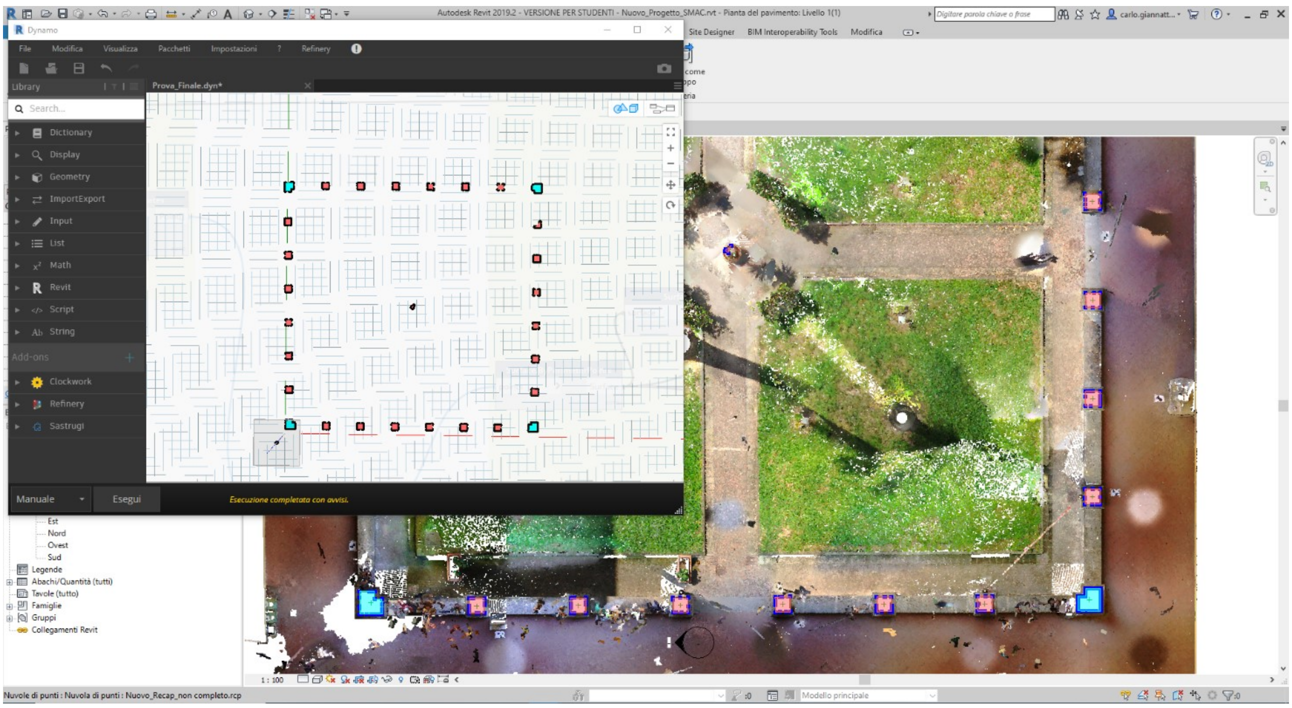

Fig. 50 - Export of results from Dynamo© to Revit© - Algorithm ScanToBIM.

Model Checking

The verification operations were facilitated by the reliability of the input data; in fact, the perfect overlap between the CAD drawings and the point cloud was noted during the model reconstruction phase (Fig. 51). However, localised checks with a laser distance measurer of the rooms were provided to ensure the correct positioning of the partition walls.

Fig. 51 - Overlapping of CAD drawings on the point cloud. The perfect match of the data can be seen.

Model Fixing

Surveys have been delayed several times due to difficulties in accessing the facilities; the presence of the professors and administrative staff involved is necessary in order to conduct the operations. In addition, the complications due to the Covid-19 have made it harder to reach the buildings and consequently to access them. No errors were found in the areas checked so far.

Data Management

Architecture of the Data Management system

The proposed data management system is based on QGIS©, an open source platform; the architecture of the database must be created before BIM models can be linked to shapefiles. First of all, a file with a WGS 84 / UTM zone 33N coordinate reference system was created. The cartographic data of the metropolitan area of Naples were then imported, previously downloaded from the metropolitan city website (Città Metropolitana di Napoli, 2020). A shapefile was then created which includes all the fields previously mentioned. In the cartography, all the elements of the building stock of the Federico II University of Naples were identified. For each building, a polygon was created and the data granted by the technical office were associated with it (Fig. 52). A field was also provided for recording the BIM model file path of the BIM model, when present. The database includes all the information collected: in addition to the archive documents, the photogrammetric acquisitions collected during the second survey for the Veterinary Faculty building were uploaded.

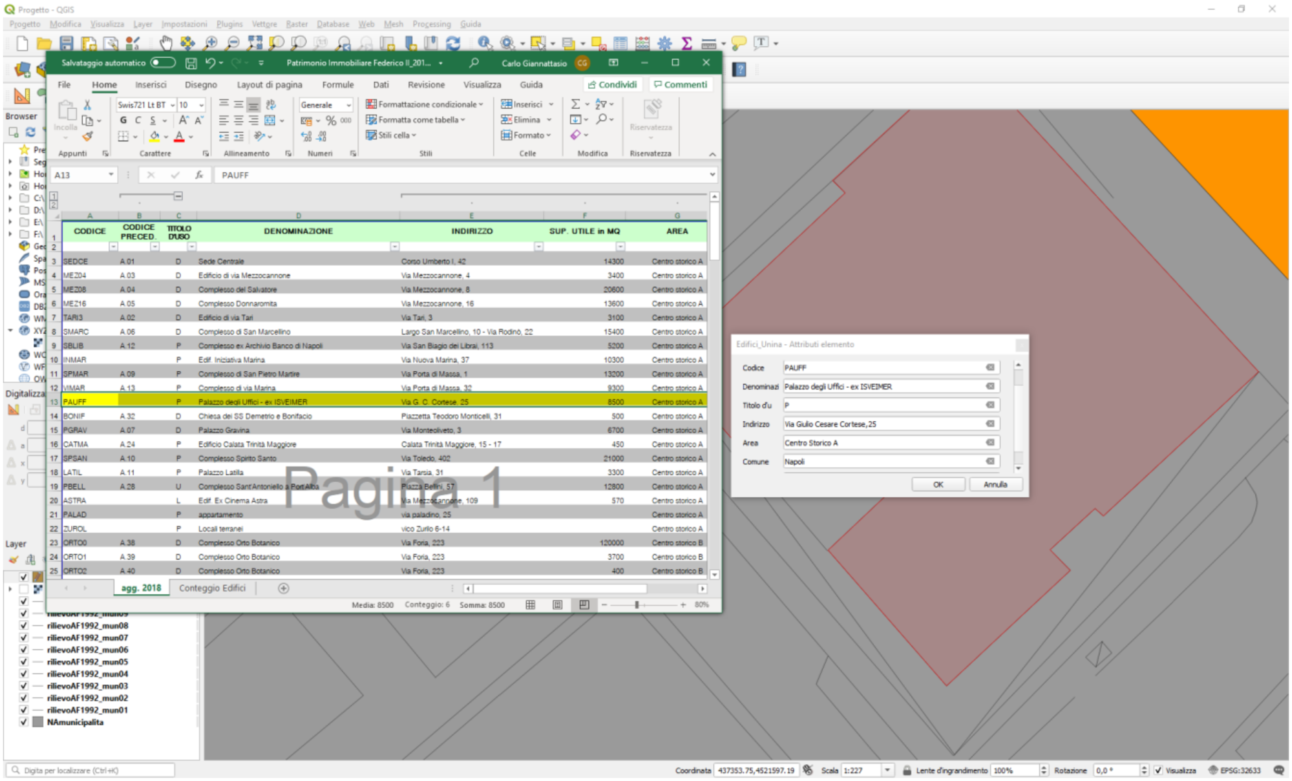

Fig. 52 - Creation of the polygons and completion of the database fields.

Verification of operation

The database was queried through the selection by common fields (Fig. 53) and a thematic map was created for the identification of the elements belonging to the different areas (Fig. 54) to test the correct functioning of the system.

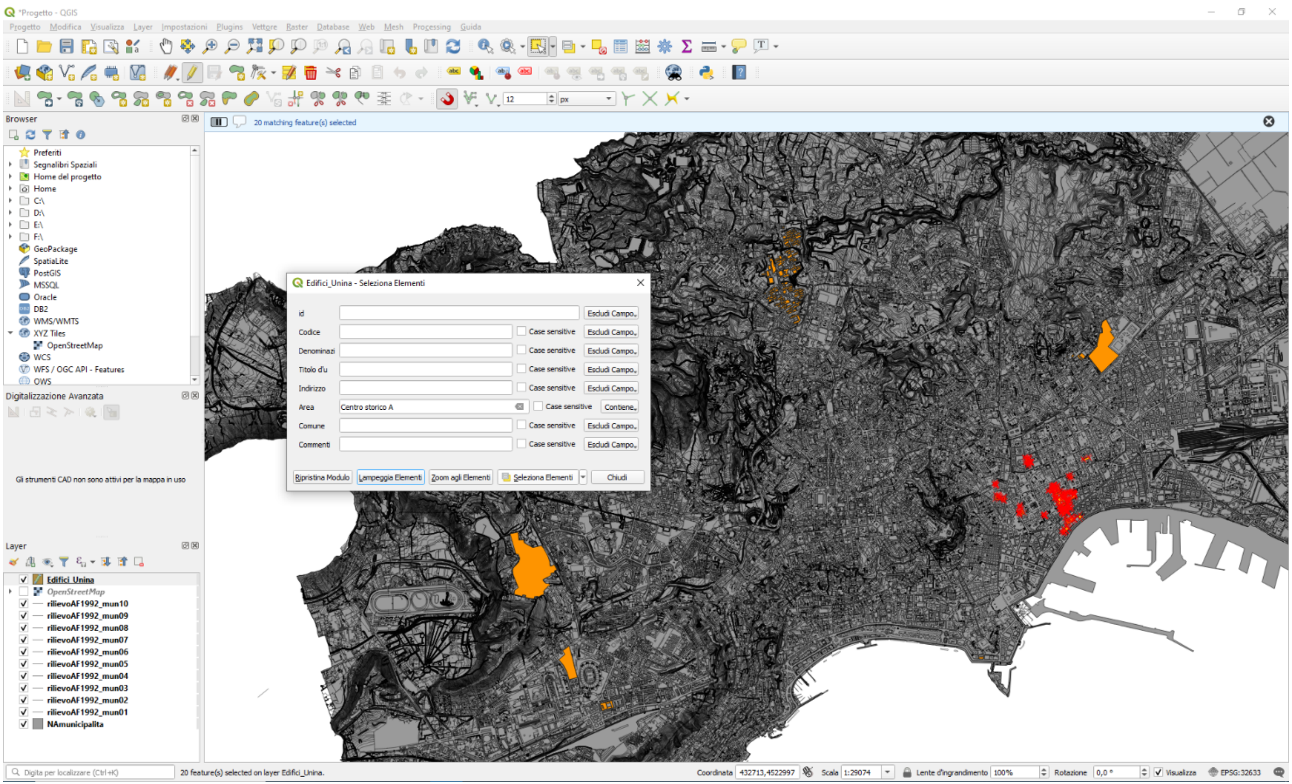

Fig. 53 - Tests of query tools.

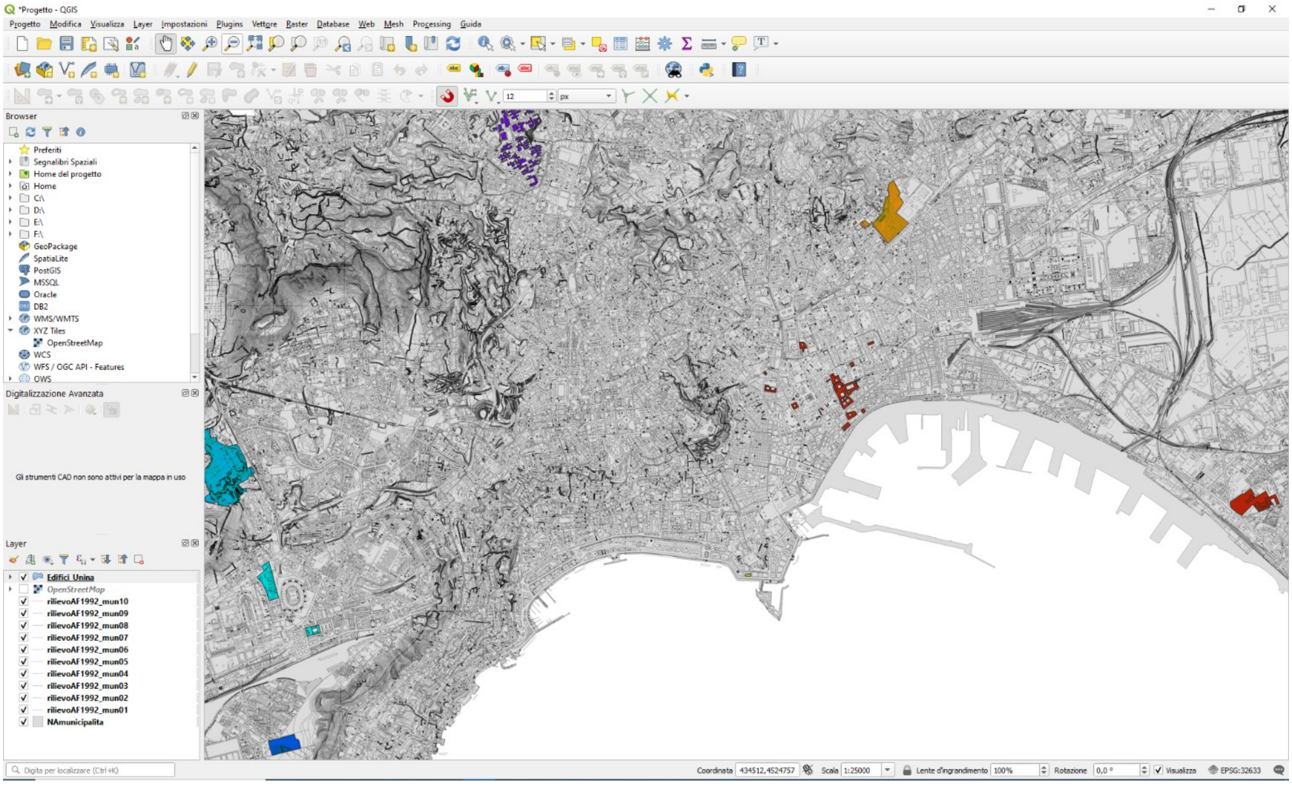

Fig. 54 - Creation of the thematic map for the identification of the areas.

Connection between GIS and BIM platforms

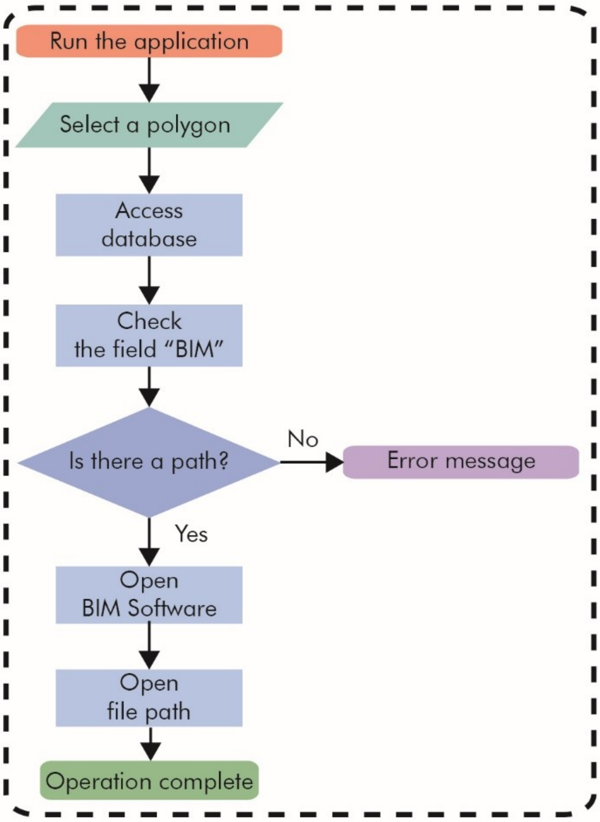

Fig. 55 - Algorithm for GIS - BIM connection.

Lastly, a first step towards BIM GIS interoperability was defined; a link between the two platforms was created since databases cannot be shared. An application was developed using the Python© programming language.

In particular, when a building is selected in QGIS©, the app checks if there is a connected BIM model in the database; if present, the associated file is automatically opened in the BIM software used (in the specific case Revit©) (Fig. 56). If there is no link connected, the application reports an error message (Fig. 57). Also in this case, it was necessary to use the API of QGIS© in order to display the notification on the work screen.

It should be noted that the structured algorithm allows access to any BIM platform or software concerned by modifying the app script.

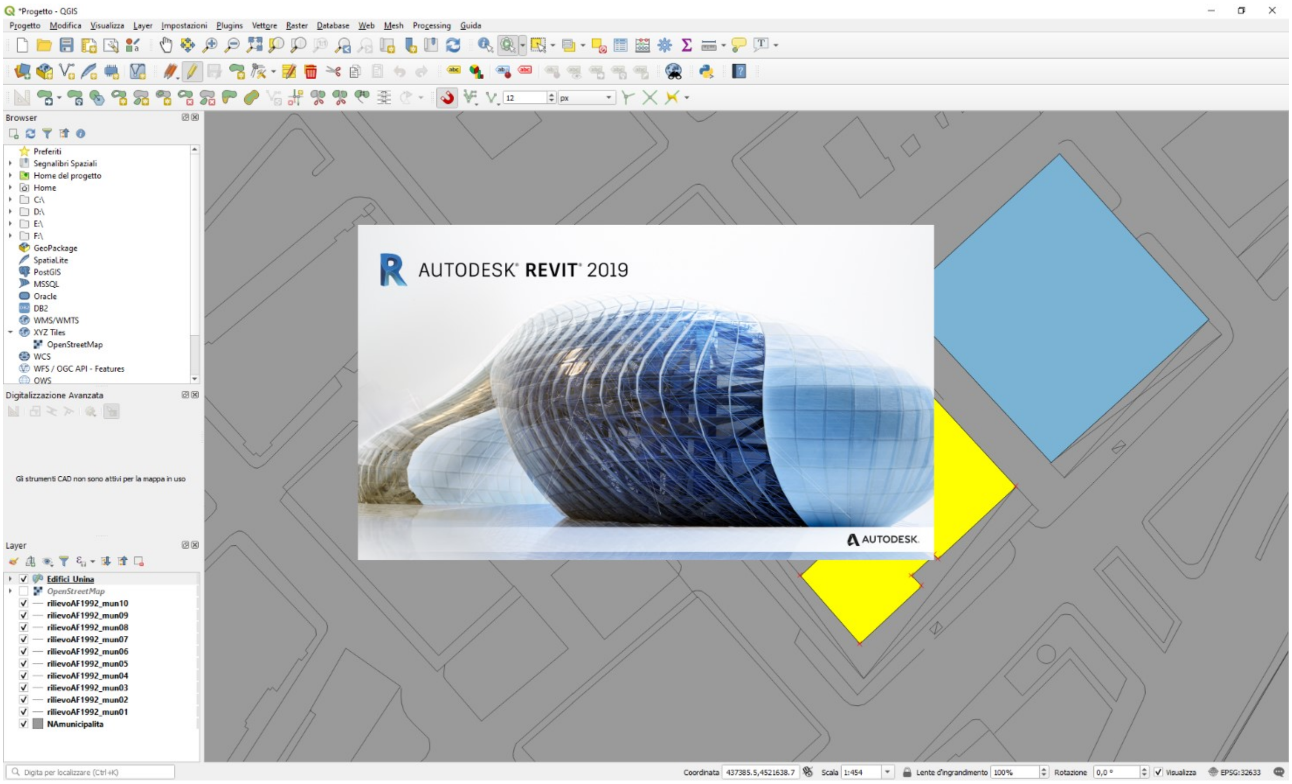

Fig. 56 - How the application works - BIM model is available in the database.

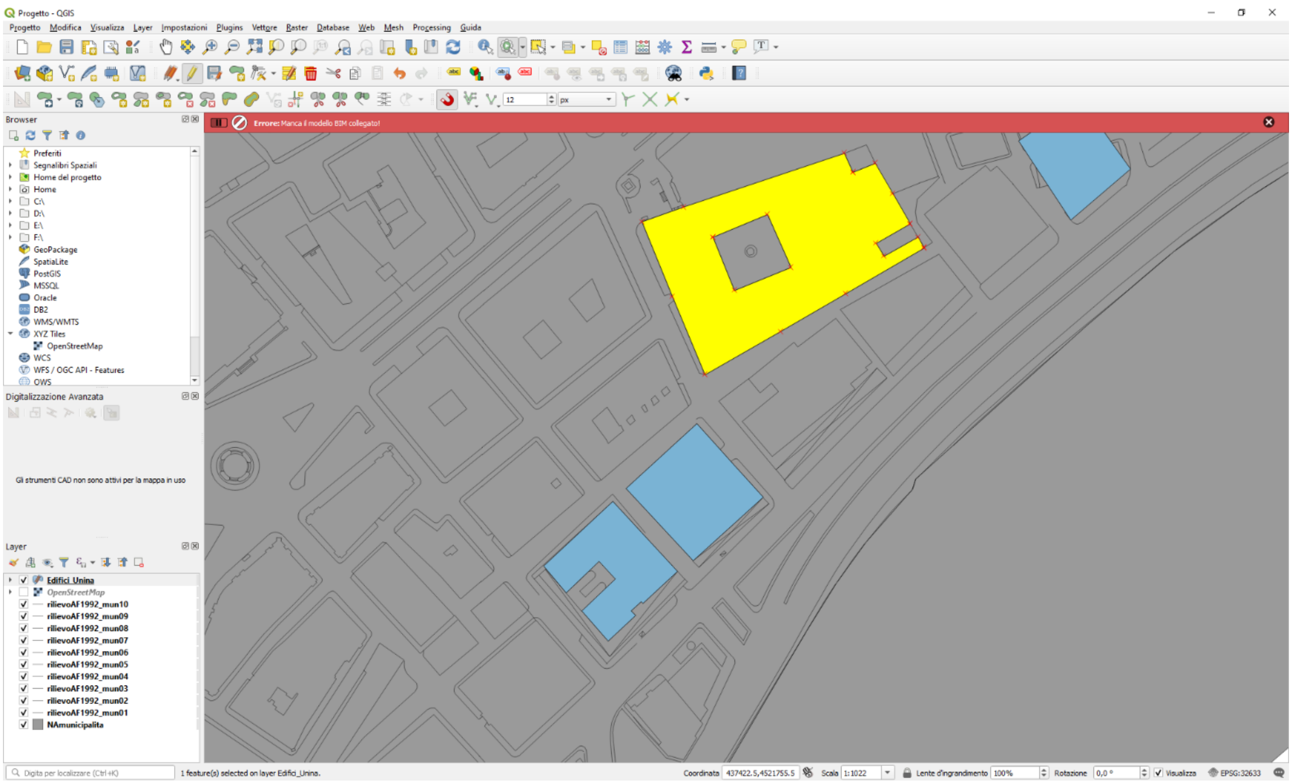

Fig. 57 - How the application works - BIM model is not available in the database. At the top, the error message in red.

Conclusions

The digital revolution is sometimes identified with innovative instruments, but it is much more than that. Our mindset on this issue is constantly evolving and the keywords of this shift are: connection, collaboration, optimisation, and automation. The new work methods that are being developed do not replace the old ones, but integrate processes and instruments better suited to new requirements. These novelties have allowed many activities to continue during the Covid-19 pandemic. Words like smart working or remote working have become commonplace and will be frequently used in future contracts, in both the private and public sector. It is now paramount to have simple, clear digital methodologies well-suited to these new needs.

This doctoral thesis focused on developing a possible work method for the digitalisation and management of existing buildings. The key objectives were the optimisation and validation of the processes and cost reduction. The first step was to share several considerations about the two hypotheses behind the methodology, i.e., the availability of resources and enough archival data to reconstruct the model.

Resources include hardware and software instruments as well as trained staff. In line with the objectives, the number of proprietary software required to verify the methodology was kept to a minimum. Where possible, integrated or open source platforms were used. Regarding the training of staff, the skills and expertise of technicians should be reassessed; today they must have the skills typically used in the *AEC* world, but also be experts in computer sciences (database programming or management). These skills, divided into necessary and secondary skills, are illustrated in detail under "Guidelines" in the appendix.

In addition, archival data has been shown to be marginally important to complete the processes: in fact, although surveying can be programmed to fill the information gap, it does increase costs. Therefore any company with input data has an unexpressed economic capital; however, input data has to be validated. On the other hand, acquisition requires an initial investment which can sometimes be rather expensive; nevertheless, it does ensure a more reliable reconstructed model. This is why the CoIN and SuRe parameters were developed; the CoIN parameter describes the reliability of the data in hand and the data required to reconstruct the model while the SuRe parameter indicates whether of not further studies are needed. These parameters provide information regarding the input data source and make it possible to control every phase of the process.

The characteristics of a GIS BIM system to manage building heritage were defined and its architecture created. Tests were performed to validate the work method and verify that the system functioned properly. University buildings were chosen as research material, in particular the building heritage belonging to the University of Naples Federico II. The results of the experiments are promising.

In addition, several pattern recognition applications for CADToBIM and ScanToBIM were developed and integrated directly into the BIM platform used in the study. Traditional and visual programming can also be used to model complex objects or the interoperability between different systems. The studies also produced another result: they demonstrated that theoretical and applied research are inseparable, especially in the industrial field. In fact, writing the algorithms required knowledge of three-dimensional geometry and linear algebra, while the development of the applications involved an in-depth review of the functioning of digital systems and current platforms.

Other considerations about BIM and its application on existing heritage are also necessary. Although it is always convenient to use it on new buildings, this is not always true for the built. Reconstructing a BIM model requires an enormous amount of input data and great skill in order to solve the operational difficulties. The result is not just a three-dimensional model or a model that can be used to automatically produce two-dimensional drawings; it is also and above all a database. A return on the initial investment exists if, and only if, it is constantly updated and used elsewhere, e.g., to manage buildings. BIM is not the ideal solution for every problem and its use should be assessed on a case by case basis. In some interventions, a collection of two-dimensional drawings or a non-parametric three-dimensional model may be enough. They can either be associated with a BIM model at a later date, or act as a basis for its reconstruction. Only when fully exploited does BIM become a real, economically advantageous resource.

As mentioned earlier, the results of the doctoral thesis were promising; they also represent a base line for future research. Developing the architecture of the GIS BIM system will lead to greater validation of the databases and comprise the sharing of geometric and information data. The applications for CADToBIM and ScanToBIM may include the automatic introduction of the objects thanks to semantic recognition of the elements. A possible research topic to achieve this goal could be to envisage the development of a specific Artificial Intelligence. Finally, the CoIN and SuRe parameters could be itemised to define the intrinsic value of the data and, at the same time, have a direct impact on professional activities.

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Appendix – Guidelines

Introduction

These guidelines are intended to optimise the digitalisation and management process of the existing architectural heritage, to the benefit of public administrations or privates. The definition of the abovementioned guidelines was developed at the end of a research project of the REMLab (Survey and Modelling Lab), Department of Civil and Environmental Engineering of the University of Naples "Federico II", in collaboration with the Technical Office of the University, the Negroni Key Engineering, and the Escuela Técnica Superior de Arquitectura of the University of Valladolid (Spain). The development of the guidelines involves:

- A reminder of the existing directives and the reference laws;
- The prerequisites that will be necessary to fully understand some aspects of the process, not to mention the optimisation step;
- The elaboration of a working methodology;
- The definition of the working tools, divided into macro-activities;
- The introduction of the procedures related to the tool used, divided into different phases;
- The description of a series of parameters to be added to a BIM model, describing the type of the incoming data.

Legislation

Existing law

The Italian regulation procedure started in 2016 with the update of the Public Procurements Code (D.lgs 50/2016) due to the adjustment required by the European guideline 2014/24/EU.

An addition was made to Article 23, "Levels of projecting for the procurements, for the building concessions, as well as the services", paragraph 1 letter h), saying

"the rationalization of the projecting activities and the relative testing phases through the progressive use of specific electronic methods and tool like the modelling software for the construction and infrastructions".

The following Ministerial Decree 560 in 2017, also known as Baratono Decree, reproduces the Public Procurements Code and defines new aspects like:

- The definition, for the Public Administrations, of a staff training plan and the acquisition or maintenance of the hardware and software apparatus for the digital handling of decisional and informative processes (art. 3).
- The mandatory use of interoperable and open source formats, "accessible without the use of commercially exclusive technological application (art. 4 par. 1)".

- The mandatory and gradual adoption of electronic methods and tools, defined by a threshold that will be reduced progressively, reaching in 2025 calls below 1 million euros (art. 6).
- Attach the technical specifications to the calls for tender, that describes the general and specific skills, including the information and parameters definition levels (art. 7).

It is important to highlight that neither the Public Procurements Code nor the Baratono Decree contain a mention of the BIM, in any sense. The existing law does not mention the informative content definition levels, which are included, instead, in the UNI standard.

Reference standard

Currently, there are two UNI standards in force concerning the digital processes in AEC (Architecture, Engineering and Construction):

- UNI EN ISO 19650 – Organization and digitalization of the information relative to the constructions and civil engineering works, including the Building Information Modelling (BIM) – Information management through the Building Information Modelling;
- UNI 11337 – Digital management of the building informative process.

It is also important to highlight that the European standard UNI EN ISO 19650 is hierarchical and contains the Italian standard UNI 11337 with all its updates even if, chronologically, the latter was approved before the European one.

All the aspects of a digitalisation process that involves BIM are being developed within the UNI 11337. A special mention should be made for Part 4 of the same standard, in which a parameter called LOD (Level of Development) is defined; this parameter will be briefly described later and may undergo significative changings with the advent of the European standard. LODs are described as the union of two components:

- LOG (Level of Geometry)
- LOI (Level of Information)

A peculiarity of this standard is that, conversely to American and English ones divided into 6 levels of object definition, they are divided into 7 levels (LOD A to LOD G), connected to a progressive improvement of the information level, whether geometric or not, and to the construction phase. They are defined as:

- LOD A = Symbolic Object
- LOD B = Generic Object
- LOD C = Defined Object
- LOD D = Detailed Object
- LOD E = Specific Object
- LOD F = Implemented Object
- LOD G = Updated Object

The UNI EN ISO 19650 update, though, is introducing a new parameter, the Level of Information Needed, which disrupts and replaces the LODs. The LOIN, thus, do not have, at the moment, a reference scale and they delineate three different components required for their description:

- A geometric one (LOG)
- An informative one (LOI)
- A documentary one (DOC)

It cannot be excluded that in a future update a reference scale could be introduced to simplify the administrative procedures. The technical staff is, therefore, urged to follow the regulatory process along with its additions and modifications.

Technical Skills

The researches on the digitalisation process and building heritage management demonstrated that the technical staff must adjust and update the competencies. Such skills involve both methodological aspects and the direct knowledge of tools and procedures.

Firstly, skills are differentiated according to their type:

- Primary or Fundamental, which are necessary to participate in the process;
- Secondary or Additional, which are not necessary to participate in the process, but can be particularly useful in order to optimise it, either in its completeness or in its parts.

Firstly, the skills are divided according to their nature (generic and specific). Following there is a detailed description of the skills

Generic Skills

The general skills represent all the knowledge that are common to all the technicians that are involved in the digitalization process and the management of the building heritage. Among the Primary Generic Skills there are:

- 3D Modelling, not only limited to theoretic aspects but expressed through the mastery of different digital platforms.
- Database management, concerning both the creation and the query of such databases.

while among the Secondary Generic Skills there are:

- Research and Development of both methodologies and tools and processes with the aim to enhance the renovation and readjustment of the single offices.
- Programming, as the basis may be useful to create applications *ad hoc* to optimise the processes.
- Statistics and Data Analysis, which are fundamental in case of a huge amount of data.

Specific Skills

They are defined as specific skills connected to one of the macro-activities of the process, namely:

- Acquisition;
- Digitalisation;
- Management

Acquisition

The term "acquisition" defines all the activities derived from the acquisition and data collection, dedicated to the geometric and informative reconstruction of the buildings.

Primary Skills:

- **Survey and topography** including survey methodologies and knowledge of the hardware and software tools and the procedures.

Secondary Skills

- **Materials** concerning tests and assays to be performed to point out the properties and the features that will be added to the digital model.
- **Restoration** to establish whether it is necessary to acquire further aspects, beside the required ones, like valuable elements or particularly degraded mode.

Digitalisation

The digitalisation activities concern all the process of reconstruction of the digital model, including all the data and parameters listed in the informative tender.

Primary Skills:

- **Building Information Modeling** aimed not only to the use of the tools but also to a deep and detailed knowledge of the field.

Secondary Skills:

- **Property Management**, useful to obtain a complete description of the building in all its physical and technological aspects.
- **Facility Management** to outline at best the managerial and functional aspects of a single building.

Management

The term involves all the management activities of the buildings and the models with the relative data.

Primary Skills:

- **Geographic Information System** meant as a methodological approach to create geospatial databases to allow and simplify the analysis and the intervention activities planning.

Secondary Skills:

- **Asset Management** to analyze the building heritage as a resource to administrate

- **Real estate** so that it would be possible to perform economic analysis to increase the value of all the buildings depending on the market.

Methodology

The working methodology was divided into 6 phases:

- **Model Definition:** when all the aspects concerning the intervention on the building are defined and, consequently, all the information related to the digital model.
- **Data Acquisition:** to acquire the information necessary to the model.
- **Model Reconstruction:** when the data previously acquired are used to reconstruct the digital model.
- **Model Checking:** when the clash detection checks and the informative aspects of the model are verified.
- **Model Fixing:** the model is updated and corrected, acquiring further information if necessary.
- **Data Management:** when the data are stored in dedicated databases and managed within an adequate platform.

These six phases can be subdivided into three macro-activities:

- **Acquisition:** that comprises all the data collection activities, geometrical or not; these activities are contained mainly in the **Model Definition**, **Data Acquisition**, and **Model Fixing** phases.
- **Digitalisation:** that comprises the parametric model construction steps; these activities are related mainly to the **Model Reconstruction**, **Model Checking**, and **Model Fixing** phases.
- **Management:** that includes all the activities connected to the data and model storage and management; these activities are mainly connected to the **Model Definition** and **Data Management** phases.

Concerning the **Model Definition**, it is necessary to stress the fact that, besides the documentation required by the standard, three aspects should be delineated:

- The Level of Development of each element category, depending on the necessity, expressed in terms of LOIN or LOD.
- The reliability of the data used to reconstruct the elements, which can be expressed in $CoIN_R$ (see "Parameters" section).
- The available information to reconstruct such elements, that can be expressed in $CoIN_A$ (see "Parameters" section).

A preliminary survey activity on the elements subject to planned interventions should be preferred to a research on the needs and of the documentation available.

During the **Data Acquisition** phase, through an investigation and survey campaign the elements lacking in information will be pointed out. This activity should be considered according to the necessities and to the available resources.

The **Model Reconstruction** phase represents the operative part of the presented method and it is focused on the reconstruction, starting from the available data, of all the elements of the building in a BIM environment.

At the end of the reconstruction, though, the model must be checked (**Model Checking**), assuring that the reconstructed elements, geometrical or informative, are solid and do not provide incorrect or confusing indications.

If any inconsistency is detected in the Model Checking phase, one must move to the **Model Fixing**, where new surveys and tests are performed to incorporate missing information; depending on the situation, the investigations may be local or general.

When the checking reports no errors, the last step is the **Data Management**, when all the data, include the generated models, are inserted into a dedicated managerial platform, updating the required field and verifying the proper functioning of the archive.

Tools

Some tools required for each macro-activity, together with a brief description and the related-use, are presented below.

Acquisition

For the equipment connected to the acquisition of internal, mechanical, or thermodynamical features please refer to the specific legislation.

The aim of this section is to present the necessary survey equipment and different methodologies.

Terrestrial photogrammetry

Terrestrial photogrammetry allows the reconstruction of points clouds and orthophoto from properly taken photographs. This tool can be used for the reconstruction of 3D geometries, but also for the determination of the conservation state or to create photorealistic views. Two key points to obtain the best results are the quality of the sensors and the created files; therefore, it is necessary to declare the precision required for the elaboration.

Aerophotogrammetry

Albeit similar to terrestrial photogrammetry, we separate aerophotogrammetry from it as the reconstruction is based on photographs taken with UAV support (drones) or other aerial support. It is usually used to build 3D geometries and characterize the context to be analyzed. The UAV systems can reach inaccessible areas and define the contextual situation, though their use is exclusively consented by specialized technicians when it involves the use of big drones or the presence of critical conditions. Like the previous case, the quality of the sensors and the created files are essential to the results; therefore, it is necessary to declare the precision required for the elaboration.

Lidar Systems

Lidar systems, which include both statical laser scanners and SLAM-based ones, allow obtaining point clouds from which orthophotos can be derived. The data collected by these systems is already scaled and require less time to be used. It is important to define a project of scan positions to simplify the alignment phase. Particular attention must be given to the minimum distance between two points along with the cloud density, which may create very large output files with consequent difficulties in several processes. Therefore, it is preferable to request both raw and post-processed data, with a reduction in the points number depending on the necessities.

GNSS System

Erroneously also known as GPS, the GNSS system allows to define the position of specific points on the globe through the connection to at least four satellites in orbit. Differently from other devices, GNNS can only work outdoor and, preferably, with clear visibility of the sky; vegetation or confined spaces may cause problems. As necessary and depending on the precision desired, two receivers may be employed to guarantee a more accurate result or only one for quicker surveys, especially if connected to a fixed station.

Total Station

The total station is the tool that obtains the most reliable metric data. On the other hand, a survey campaign with this equipment requires specific skills from expert technicians. It can precisely measure distances and angles, reconstructing 3D geometries that will be simpler than point clouds, but more precise. This tool is perfect to monitor elements or in case of precision survey analysis.

Digitalisation

BIM Platform

This type of software reconstructs parametric models of buildings; in these types of platforms, the geometric and informative data become part of a database that can be queried. This tool was meant to prototyping buildings and, because of this, it perfectly fits to the digitalisation of modern complexes. Historical buildings may be hard to reconstruct because several elements are not standardized.

Visual Scripting Platform

Frequently incorporated into the BIM platforms, these software expand the boundaries of BIM as they facilitate the creation of algorithms to solve unpredicted problems or perform tasks that cannot be carried out with the sole platform built-in commands. It is also possible to build complex parametric elements that change depending on the inputs or facilitate and automatize the import of data from other sources. It is desirable to have basic programming skills to properly use these platforms.

Programming Languages

Both BIM and visual scripting platforms use programming languages. In this way, API (Application Programming Interface) can be accessed to create new applications or plugins to respond to specific needs. It results useful also to resolve interoperability problems between software belonging to different companies. To solve these issues, skills typically outside the AEC world are required.

Management

GIS Platforms

This type of software associates data, geometric or not, to geographic coordinates; the input data can be vector, raster, strings, or numbers. In this way, a geo-referenced database is built, which can be either through fields or spatially queried, or can be analyzed in multiple ways. In detail, spatial, geostatistical or multi-field analysis can be carried out. The versatility of GIS platforms is ideal for multiple scopes, like storage, management, and analysis.

Management Platforms

These software are specifically created for the Management (Asset, Facility e Propriety) and allow the import of 2D graphs and 3D models. Particularly, depending on the software, specific plugins allow to import native BIM models, even if deprived of some characteristics. To overcome this problem, management platforms contain libraries that can directly link to the imported geometries. Moreover, it is possible to plan activities and organize spaces and facilities.

ETL (Extract, Transform and Load) Platforms

ETL software can convert and manipulate data in different formats. These platforms are not popular in the AEC field, but their use is increasing due to the different types of data deriving from multiple platforms. They are mainly used to uniform tables and databases, but commands to modify and convert CAD and IFC files are also being developed. They are particularly useful in managing documents and archives.

Processes

After defining some of the instruments involved in each activity, here are listed the principal processes in each phase of the methodology described above.

Model Definition

The activities connected to this phase are the planning and definition of the objectives. Particular attention must be paid in this phase as there is the risk of an incorrect evaluation, which may lead to an extension of the working time and a consequent increase in the costs.

Intervention Definition

First, the required intervention must be outlined; in particular, the elements affected and the way of intervention must be detailed. It is recommended to perform preliminary inspections to perform a precise evaluation of the interventions and the elements to be detailed.

LoIN/LOD and $CoIN_R$ Definition

After the Intervention definition, for each element category, the LoIN and LOD threshold must be set. The first step is the minimum level of information (graphical, informative, and documentable) required. Once LoIN/LOD are fixed, the reliability of the input data necessary to obtain the desired results must be indicated; therefore, the parameter $CoIN_R$ must be defined (see "Parameters section")

$CoIN_A$ and SuRe Definition

Once the necessary interventions, the information that the model must contain, and their accuracy are elucidated, the last step is to define the available resources with the parameter

$CoIN_A$ (see “Parameters” section). After that, it is possible to derive the parameter SuRe (see “Parameters” section) for each element category, which will give information on the required investigations. In addition, the resulting data format must be specified.

Data Acquisition

This phase contains the activities related to data acquisition, whether storage and/or the result of an investigation campaign. Below are listed the fundamental activities in every acquisition campaign; for the specific methodologies of data acquisition, please refer to the reference rules.

Authorization Request and Archived Data Accession

Before starting any field activity, it is advisable to begin the bureaucratic process to acquire the archived documents and access the area desired. Archived data may prove themselves useful during the activity planning or during their performance, even when they were not used directly to reconstruct the model.

Preliminary investigation

The preliminary access to the area is a frequently underestimated activity that, however, may highlight problems that could happen during the survey campaign. These investigations help to create a first image of the building under consideration, but also to point out the elements affected by the investigations and to understand useful aspects for their planning (building working timetable, problems, privileged elements).

Survey campaign planning

The subsequent step is to draw up a project for the investigation campaign, that must involve the elements to analyse, the degree of precision required, and the focus points. Moreover, it is advisable to add information regarding the scheduling of the activities to both estimate the working hours and reduce the time needed to acquire data in the delimited areas.

Survey campaign activity

After the planning, the actual survey campaign takes place and for the execution, please refer to the specific standards. In case the specialized technician would notice that further investigations are needed, the project can be updated and include the new acquisitions.

Data Processing

The data collected in the previous phase must be processed to assess whether they are sufficient, reliable, and consistent. After the necessary cleaning and refining procedures, as stated in the specific legislation, data are exported in the required format.

Model Reconstruction

Once the collected data are considered sufficient, they are handed to the technicians that will reconstruct the building model. The process starts with the generation of the geometrical buildings; it is preferable to characterize the informative elements at the same time. Automatizations in the shape or elements recognition are also considered in order to optimise this step and assure the best result. Moreover, filters can be applied to point out elements containing uncertainties.

Initialization

The preliminary operations concern the creation of the BIM project and the global parameter definition. Before importing the geometrical data and begin the model reconstruction, data must be divided depending on their nature as bidimensional and three-dimensional data are processed differently.

Three-dimensional geometric data import

Point clouds and three-dimensional models can be directly imported into the BIM environment and, once arranged, are ready to use. The only precaution required is to check the units of measurement of the models to avoid correcting them ahead in the process.

Bidimensional geometric data import

Bidimensional data, like CAD drawings or images, need to be processed before being used:

- Save the data in a different format (the necessary software depends on the starting format);
- For each elaboration, a corresponding BIM view must be created;
- The corresponding file must be attached to each view, paying attention to the scale used.
- Align the elaborations on the basis of known elements (fixed threads, structural elements, etc.)

Identification of the fundamental elements and construction of the supporting elements

Once imported, regardless of the format, reference elements must be identified, which will simplify the building reconstruction, like the structural or known ones. Afterwards, it is advisable to create supporting elements (points. lines, and volumes, preferably parametric) to facilitate the creation and modification of geometries (e.g. views, volumes, floors, and lines).

Vertical Elements Reconstruction

It is preferable to start from structural elements instead of the architectonic ones, as they may be more regular and uniform, especially in modern buildings. In any case, the best practice is to start with punctual elements (pillars and columns) and then move to the linear ones (rigid nuclei and staircase compartments.

External Surfaces Reconstruction

The next step is to delimitate the external perimeter through the creation of vertical surfaces. In most cases, these surfaces are regular and give an idea about the total volume of the complex. We advise not to characterize surfaces containing openings in this phase, as they will be considered later on.

Horizontal Elements Reconstruction

The general structure is then completed with the reconstruction of the floors, ceilings, and other horizontal elements, to remark the levels and evaluate the inter-floor. With the model built so far, it is possible to start evaluating roughly the volumetry and gross paved surfaces and have a preliminary idea of the backbone.

Internal diveders Reconstruction

Once the general volumetry of the building is complete, internal dividers are inserted. Where required, it is preferable to also include the data about their management.

Finishes and Vertical Connections Reconstruction

The finishes elements, like doors or windows, are placed almost at the end of the process as they are not independent elements but must be allocated inside another element (walls). Eventually, the reconstruction of vertical connections takes place, as not only the constructive (staircases and elevators) but also the auxiliary elements (hollow spaces) must be reconstructed.

Plant Reconstruction and structural characterization

The last step is plant reconstruction and structural characterization, both internal (reinforcing bars, brackets, etc.) and external (creation of new connections, junctions, etc.). In this phase, new elements are created, which need to be characterized both geometrically and informatively.

Model completion

Eventually, the model is completed placing the building onto its spatial coordinates, defining the real north. All the additional elements may be added, like the furniture and green areas. All these elements will be crucial in the maintenance and in the solar exposure evaluation. If necessary, supporting tables may be realized.

Model Checking

When the construction of the BIM model is completed, the reconstructed elements must be verified at geometrical and informative level. It is preferable to delegate this step to a technician that did not take part in the model reconstruction.

Previously Identified Elements Checking

As mentioned at the beginning of the previous phase, it is preferable to create filters or facilitate selections during the modelling step for the elements that show inconsistencies or concerns. The personnel will prioritize the verification of these elements and will evaluate, together with modelers, the solutions.

Geometries Checking

All the geometries are now assessed, by both direct analysis and using *Clash Detection*. This type of checking identifies the existing interference within the project, like mass or geometries interpenetration that do not respect previously established rules.

Informative Checking and Information Consistency

Following the geometries checking, a double-check of the informative part must be performed. The correctness of the information concerning each element and their consistency among each other must be verified. It is frequent that inconsistent information is given inside the project, like describing the stratigraphy of a wall and draw a construction with a different stratigraphy.

Model Fixing

If the model checking is not satisfied, new acquisitions are required to correct the model. If, instead, all the expectations are satisfied the staff can skip to the Data Management phase.

Definition of New Necessary Information and New Surveys

Once all the inconsistencies in the model are highlighted, it must be assessed whether new acquisition are necessary, which data must be collected and how the investigation must be carried out. It is important to determine if the investigations are punctual, concerning single elements, or a deep investigation on all the elements is required.

Survey campaign and Field Activities Planning

A new survey campaign must, therefore, be planned to fill the gaps in the informative part and correct the errors found. It is best practice to carry out these activities together with technicians who were involved in the initial phases of acquisition and digitalised the model. Once defined, the field activities take place, repeating all the steps in the Data Acquisition phase.

Data Correction and Model Checking

The joint checking carried out by several technicians and the new collected data are fundamental to the correction of the model. After examining the new acquisitions, the specific modifications that must be applied are defined. Eventually, a new checking is performed. These last two steps are repeated until the checking is satisfactory; only then the next step can be addressed.

Data Management

Once all the checking are completed, the building model is imported into the selected management platform. The activities in this phase can be divided into storage-related and management-and-accessibility-related ones.

Building records access

Before updating the database, the building records must be accessed and the relevant fields must be defined. Such records can be found both searching the database and with the spatial position of the buildings.

Model and Relative Data Import

Identified the record in the database, the fields are updated by importing the model and its data. Be careful to create new links and not simply overwrite the existing ones, as the previously stored data must be kept.

Data Analysis and Management

The imported data are now available to be reused in new projects or to be updated, but, most importantly, to perform multi-variable analysis on the building heritage or the entire context.

Parameters

Here are described some parameters that consider the reliability of the input, necessary to properly define each category of BIM elements, given a specific LoIN or LOD.

It is necessary to identify the main characteristics to be processed and the corresponding reliability of the data that must be considered. For each category of elements, four main parameters describing the different characteristics must be determined; they are:

- C_E = *External characterization*, which concerns the input data reliability required to reconstruct the external geometry of the element.
- C_I = *Internal characterization*, which concerns the input data reliability regarding the internal characterization of the element.
- C_M = *Mechanical characterization*, which concerns the input data reliability required to reconstruct the information on the mechanical characterization of the element.
- C_T = *Thermodynamic characterization*, which concerns the input data reliability required to reconstruct the information on the thermodynamic characterization of the element.

In detail, C_E is defined as a numeric value between 0 and 4.

- C_E 0 = The element is reconstructed through an existing documentation (Non-executive and unverified charts);
- C_E 1 = The element is reconstructed through an existing documentation (Executive charts) or non-executive graphs verified with contact survey;
- C_E 2 = The element is reconstructed through an existing documentation verified with a topographical survey;
- C_E 3 = The element is reconstructed through a non-georeferenced point cloud;
- C_E 4 = The element is reconstructed through a topographical-based or a georeferenced point cloud.

In detail, C_I is defined as a numeric value between 0 and 4.

- C_I 0 = Element reconstructed through existing documentation (Technical report);
- C_I 1= Element reconstructed through existing documentation (Executive graphs and technical sheets) or non-executive documentation verified with punctual indirect tests;
- C_I 2= Element reconstructed through the presence of existing documentation (Executive graphs and technical sheets) verified through a campaign of indirect spot tests on a small number of elements;
- C_I 3 = Element reconstructed through testing campaign carried out with indirect measurement on a significant number of elements, according to regulatory standards;
- C_I 4 = Element reconstructed through testing campaign carried out with direct measurement on a significant number of elements, according to regulatory standards.

In particular, C_M is defined as a numerical value between 0 and 4

- C_M 0 = Element reconstructed through existing documentation (Structural Report);
- C_M 1= Element reconstructed through existing documentation (Executive graphics and construction details) or non-executive documentation verified with punctual tests;
- C_M 2= Element reconstructed through the presence of existing documentation (executive graphics and construction details) verified through a campaign of non-destructive spot tests on a small number of elements;

- C_M 3 = Element reconstructed by non-destructive testing campaign on a significant number of elements, in accordance with regulatory standards;
- C_M 4 = Element reconstructed through testing campaign, including destructive and non-destructive tests, on a significant number of elements, according to regulatory standards.

In particular, C_T is defined as a numerical value between 0 and 4

- C_T 0 = Element reconstructed through existing documentation (Technical report);
- C_T 1= Element reconstructed through existing documentation (Executive charts, construction details and energy performance certificate (APE) or non-executive documentation verified with punctual tests;
- C_T 2= Element reconstructed through the presence of existing documentation (Executive charts, construction details and energy performance certificate (APE) verified through a campaign of non-destructive spot tests on a small number of elements;
- C_T 3 = Element reconstructed by non-destructive testing campaign on a significant number of elements, in accordance with regulatory standards;
- C_T 4 = Element reconstructed by testing campaign, including destructive and non-destructive tests, on a significant number of elements, in accordance with regulatory standards.

Defined the individual rates, a single parameter was defined that summarized the above. This is how the CoIN, (Confidence of Information Needed) was created, representing the reliability of input data needed to rebuild the element, depending on the LoIN or LOD.

$$CoIN = f\left(C_{E,}C_I, C_M, C_T, LOIN\right)$$

It is described as a vector of four elements:

$$CoIN = [n_{C_E}, n_{C_I}, n_{C_M}, n_{C_T}]$$

Where n represents the value of the specific level associated with the previously described parameter.

However, it is important to differentiate the information needed to describe the element, called $Coin_R$ where R stands for "Required", and the information held by the administration, called $Coin_A$ where A stands for "Available".

$$CoIN_R = f\left(C_{E,R}, C_{I,R}, C_{M,R}, C_{T,R}, LoIN\right)$$

$$CoIN_R = [n_{C_{E,R}}, n_{C_{I,R}}, n_{C_{M,R}}, n_{C_{T,R}}]$$

$$CoIN_A = f\left(C_{E,A}, C_{I,A}, C_{M,A}, C_{T,A}\right)$$

$$CoIN_A = [n_{C_{E,A}}, n_{C_{I,A}}, n_{C_{M,A}}, n_{C_{T,A}}]$$

We also want to highlight that Confidence of Information Needed Available does not depend on LoIN or LOD, as it represents the reliability of the data in the archive.

Conversely, the *Confidence of Information Needed Required* depends on the LoIN or the LOD requested, as it will be adapted to the type of reliability of the data to be acquired as needed.

Finally, the parameter SuRe (Survey Required) must be defined, which is a vector parameter that indicates whether there is a need for further surveys or tests to obtain reliable data for model reconstruction.

$$SuRe = COIN_R - COIN_A$$

SuRe is a vector of four elements that:

- If they are all positive, it means that it is necessary to provide for surveys and tests to describe the category in question;
- If they are all negative, it means that there are plenty of data for the required LOD or LoIN description;
- If the vector is null, it means that the requested data are exactly those present in the archive;
- If there are mixed values, it means that the characterization of some aspects will require further investigation, while others will not.

It is important to highlight that if positive values are present, the cost of the model creation will increase; if only negative values are present, investigation activities should not be included in the call for tenders.