

INTEGRATION BETWEEN BUILDING INFORMATION MODELING AND GEOGRAPHIC INFORMATION SYSTEM FOR HISTORIC BUILDINGS AND SITES: HISTORIC-BIM-GIS

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ABSTRACT:

The paper presents a novel prototype of integrated Historic BIM-GIS able to deal with multi-source, -scale, and -temporal information. It combines elements from the cartographic scale to a more detailed level of detail towards the building. It can be defined as a 3D virtual environment with an associate (geo)database able to encapsulate heterogeneous data not limited to products derived from the geometric survey, notwithstanding digital recording and its deliverables play a fundamental role. The system also provides a good interoperability level so that BIM and GIS software can exchange information, avoiding the implementation of functions and tools already available in other software packages. The example proposed in this contribution is related to the system of fortified structures around the city of Sondrio. Here, a single 3D environment was developed to encapsulate information from the cartographic level in an area of more than 135 km² to the scale of 1:1 for specific architectural elements.

1. INTRODUCTION

Nowadays, projects based on the integrated use of BIM (Building Information Modeling) and GIS (Geographic Information Systems) are becoming more popular especially at the scale of the infrastructure. The combination of parametric modeling tools directly used in a georeferenced space, as well as the integration of different information (the "I" in both acronyms BIM and GIS), has a natural role in projects related to several infrastructures such as roads, railways, bridges, ports, airports, dams, and tunnels, among the others (Wang et al., 2019; Barazzetti et al., 2020; Karimi and Jordanova, 2021). Different authors have faced problems related to HBIM (Historic BIM, Murphy et al., 2013), and several scientific papers have introduced different methods for HBIM generation in the case of complex buildings, often facing the "rigidity" of modeling capabilities available in commercial software when applied to the irregular geometries captured by laser scanning or

photogrammetry (Barazzetti et al., 2015; Fassi et al., 2015; Tommasi et al., 2016; Brookes, 2017; Macher et al., 2017; Banfi et al., 2018; Bruno and Roncella, 2019, Reina Ortiz et al., 2019).

GIS has also been widely exploited in different projects related to heritage. The reader is referred to Xiao et al. (2018) for more details on the relationship between geoinformatics and cultural heritage.

This paper aims at demonstrating that the integrated use of BIM and GIS can be extended to historic buildings and sites. An integrated Historic BIM-GIS (H-BIM-GIS) is here defined as a 3D georeferenced digital environment able to (i) encapsulate elements at both cartographic and building levels, (ii) provide parametric modeling capabilities, (iii) connect databases and geodatabases, and (iv) exchange data with BIM, GIS or other software such as CAD, photogrammetric and laser scanning packages (Figure 1).

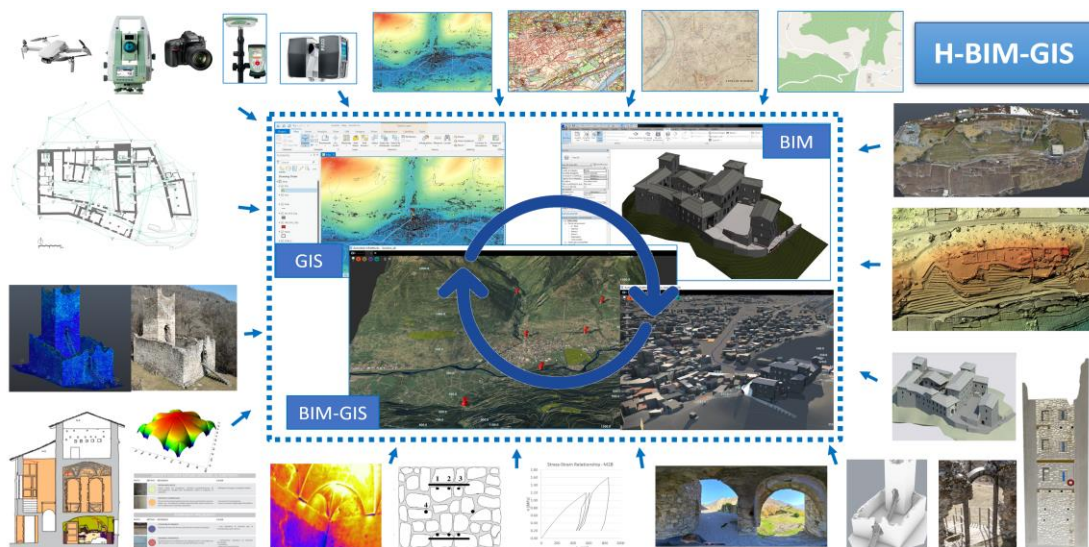


Figure 1. The proposed H-BIM-GIS integrates multiscale information shared among three engines.

The focus on cultural heritage has a direct impact on the information stored in such an environment, which is not limited to digital documentation for restoration and conservation processes. It must support management and design activities with the production and exchange of new information, as well as heterogeneous data produced by different specialists involved in the project.

The example proposed in the paper is related to the fortified structures around the city of Sondrio and its neighboring municipalities (Italy). Such an example tries to show how heterogeneous data sources can be integrated into a historic BIM-GIS. The idea is not only the creation of a digital repository for deliverables but also the use of the 3D environment as a productive tool where new information can be created. For instance, georeferenced point clouds can be imported and used as a reference to generate additional products.

Moreover, the H-BIM-GIS environments can import cartographic data in both raster and vector formats. Such information is usually already georeferenced notwithstanding transformations between different reference systems could be necessary. The direct import in the H-BIM-GIS of geospatial databases is feasible at different scales. Multiple layers (buildings, roads, etc.), digital terrain and surface models (both TIN or grid) or contour lines, orthorectified images (including multi-spectral) are just a few examples. Historic maps available only as scanned images can be preliminary georeferenced and imported. Existing reports and documents can be linked assigning a specific geographic location to facilitate data access and retrieval.

Information produced during a restoration or conservation project, such as maps with materials, construction technologies, and condition assessment, preliminary and detailed design drawings or 3D products, reports, tables, and photographs can also be linked to the system. The deliverables produced by multiple specialists (architects, historians, archeologists, engineers, geologists, etc.) could be accessed through an integrated system that combines all digital information following a multi-source, -scale, and -temporal approach.

The disadvantages are related to the limitations of actual technology. Current BIM-GIS software are not specifically developed for historic buildings and sites, thus a single software package for all operations is not available. Most BIM-GIS applications are related to modern infrastructures, resulting in a rather rigid system in the cultural heritage domain. Heritage objects are often characterized by complex geometries, heterogeneous materials and construction technologies, and they were built in different stages with continuous modifications over time. In this sense, the detailed representation required in digital documentation projects based on modern surveying instruments must face the lack of flexibility offered by BIM-GIS software, requiring novel solutions and approaches.

Such issue is not new to specialists that have worked in the field more related to Historic Building Information Modeling (HBIM), in which different authors have developed methods able to deal with the precise and detailed information encapsulated in point clouds, which reveal the geometric complexity of historic constructions. Modeling tools available in BIM software (Autodesk Revit, ArchiCAD, etc.) could not be sufficient to deal with such a level of detail.

GIS also received special attention in cultural heritage projects, demonstrating to be a valid tool in several projects. However, a pure GIS approach (including 3D GIS) cannot be sufficient especially in the case of 3D architectures.

The H-BIM-GIS proposed in this paper was developed considering the pros and cons of BIM and GIS solutions when they are used independently, and possible integration into a

single environment with the previously mentioned limitations. It is the author's opinion that an integrated H-BIM-GIS cannot rely only on a software. The system must simultaneously exploit the advantages of BIM, GIS, and BIM-GIS software, which can be interconnected and can also dynamically exchange information. Specific operations would remain in the domain of specific software, e.g., advanced geospatial analysis tools already available in GIS does not need to be reimplemented in the BIM-GIS software. What must be available is an efficient exchange of digital information, possibly based on cloud services. The proposed example was carried out using combining three software engines: ArcGIS Pro, Autodesk Revit, and Autodesk InfraWorks, which have procedures able to provide an efficient exchange of digital information.

2. THE MULTI-SCALE APPROACH: THE CARTOGRAPHIC LEVEL

The paper describes the developed prototype based on an integrated H-BIM-GIS for the fortified structures in the city of Sondrio and its neighboring municipalities (Italy). The area considered is about 135 km² notwithstanding the approach could be easily extended to larger extensions. Sondrio is located in the Alps and the difference in elevation in the model is about 2000 m. A view of the 3D model is shown in Figure 2 and was generated in Autodesk InfraWorks using the Model Builder tool, which can retrieve a set of cartographic layers using different data sources available on the web (Figure 2).

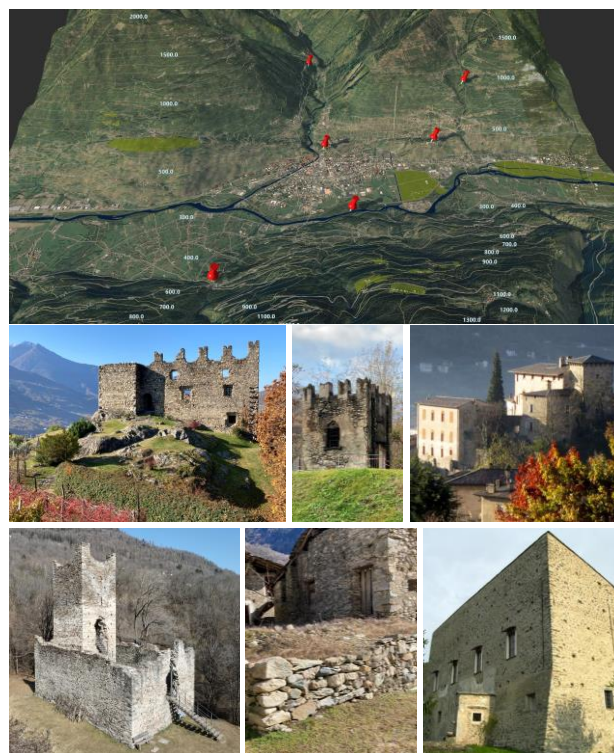


Figure 2. Top: the considered area and the preliminary H-BIM-GIS model with indicated the fortified structures: Castel Grumello, Torre del Castelletto, Castel Masegra, Castello di Mancapane, Torre di Gualtieri, Torre Paribelli.

The visualization is directly tridimensional: a DEM provides the geometry, and an orthophoto (from Microsoft Bing Maps) and different geospatial vector layers (from OpenStreetMap) are draped on the DEM. The description provided on the Autodesk

website states "terrain data for the United States and its territories uses USGS 10 meter DEMs from the National Elevation Dataset (NED). Between -60° and $+60^{\circ}$ latitude, we use SRTMGL1 30m DEM data. Between $+60^{\circ}$ and $+83^{\circ}$ latitude we use ASTER GDEM v2 30m DEM data". The vector layers retrieved from OpenStreetMap are buildings, roads, railways, and water bodies.

The location of the different fortified structures considered in this paper are represented with the red icons and correspond to Castel Grumello, Torre del Castelletto, Castel Masegra, Castello di Mancapane, Torre di Gualtieri, Torre Paribelli (Conti et al., 1991). A point shapefile was generated in ArcGIS to identify the geographic location with an additional field related to the building name. Figure 2 shows the shapefile imported in InfraWorks and customized as a point of interest.

The output of Model Builder is considered a preliminary result in this work. Cartographic datasets of the city of Sondrio are available in web repositories at national, regional, and provincial levels, as well as the level of the different municipalities, leading to the creation of the refined model shown in Figure 3.

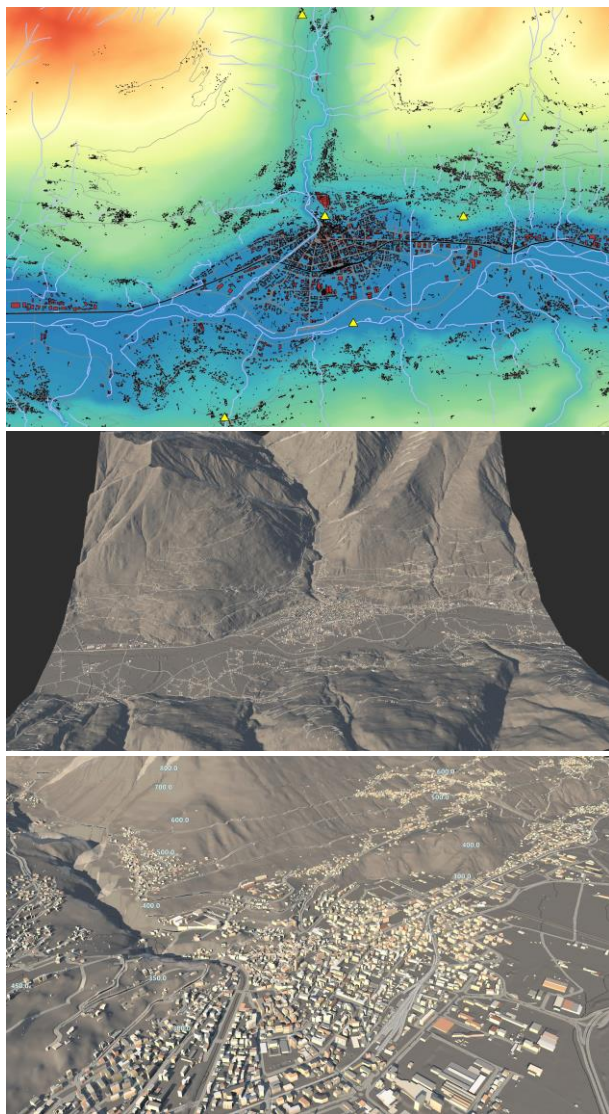


Figure 3. The refined model with cartographic layers available at the regional and provincial levels.

Such data are accessible on the web and can be downloaded and integrated into the 3D environment. It has been decided to set the project using the reference system UTM-WGS84 - zone 32N so that Cartographic coordinates (East, North) are available instead of latitude-longitude coordinates. This decision is motivated by a simple use also considering the different specialists that could be involved in the project that are usually more familiar with metric units instead of angles. The elevation used is the orthographic one, which is provided according to national specifications for the Italian territory. This is an important consideration: working in different countries with different cartographic conventions requires knowledge of the adopted specifications. More in general, the user must be aware that global geoid models (such as EGM96) automatically included in software could be just an approximated solution.

The digital terrain model used was retrieved from the geoportal of the Lombardy region. The edition of 2015 was used and it features a resolution of 5m x 5m. Information about buildings, roads, railways, and rivers was instead recovered from the geospatial database of the Province of Sondrio. Data are available online and were downloaded as shapefiles.

Figure 3 shows the refined model in InfraWorks, in which all the different layers were automatically draped on the DTM. Buildings were turned into 3D elements using the value of the height of the roof stored inside the shapefile table.

3. THE MULTI-SCALE APPROACH: INTEGRATION OF DATA ACQUIRED ONSITE

3.1 Reliable georeferencing via GNSS

One of the advantages of the multi-scale approach available in the proposed H-BIM-GIS environment is the opportunity to work with cartographic layers already georeferenced as well as the possibility to import data acquired on different sites. Georeferencing of the different products of a geometric survey (e.g., point clouds, orthophoto, CAD plans, 3D models, BIM) is possible with a centimeter level-precision using GNSS measurements. In this work, measurements with a GNSS receiver were taken using Real-Time Kinematic (RTK) with an Internet connection to the network of permanent GNSS stations SPIN3 GNSS (<https://www.spingnss.it/>). The reference system used is ETRF2000-RDN, 2008.0. The city of Sondrio hosts one of the stations. The use of static GNSS acquisition technique and the following adjustment using RINEX files (downloaded for the Sondrio station) was necessary for just one of the sites (Castel Mancapane). Here, the area was densely covered by vegetation and prevented the use of RTK. Figure 4 shows some images of the points acquired with the GNSS antenna.



Figure 4. Data acquisition on-site (left) and the reference GNSS station of Sondrio used for RTK.

Nowadays, the use of GNSS allows one to georeferenced surveys at a global level. The survey described in the paper exploited the availability of regional correction services. Besides, a subscription to commercial services can also be purchased in different countries (e.g., HxGN SmartNet). Other solutions, such as Precise Point Positioning (PPP) or RTK-PPP are also available for those areas without a reference network.

3.2 Laser scanning, total station, and photogrammetry for an integrated H-BIM-GIS

One of the advantages of the integrated H-BIM-GIS environment is the opportunity to handle photogrammetric and laser scanning point clouds (Figure 5). It is well known that point clouds are very popular solutions for the digital documentation of heritage buildings and sites. They provide accurate metric support for the generation of products in both raster and vector formats. Point clouds can be produced from different platforms operating at different elevations: satellites, airplanes, drones, and at the level of the ground.

In the case of the different fortified structures, photogrammetric data acquisition was carried out using a drone equipped with a digital camera as well as terrestrial photogrammetry. The survey was always georeferenced thanks to GNSS points, some of these points were directly measured with the GNSS receivers (e.g., flat targets placed on the ground and visible from a drone), whereas additional geo-referenced targets were measured combining GNSS and total station measurements. Point clouds from laser scanning were also georeferenced with some checkerboard targets measured with the same strategy.

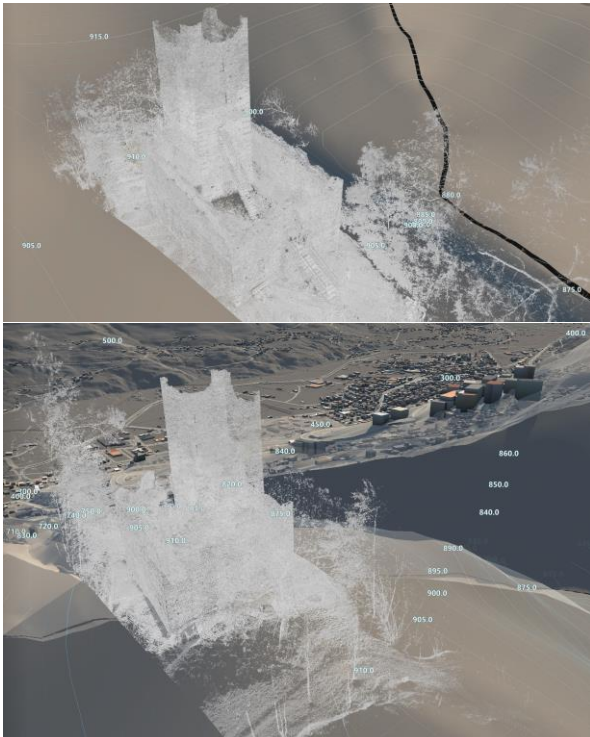


Figure 5. Examples of a georeferenced point cloud of Mancapane Castle imported in the H-BIM-GIS system. The city of Sondrio is visible at the bottom of the valley.

The transformation from local cartesian coordinates (e.g., to total station measurements, laser scanning point clouds) to the UTM system requires a correction for distances (which is variable depending on the location). It was decided to avoid such

correction when the survey is conducted at the level of a building, which is essentially rigidly translated and rotated in the cartographic reference system. This choice was motivated by the need to preserve the measured distances, which would change by a few centimeters by applying the scale factor of the UTM. In fact, in the case the operator decides to apply the correction for distances, the different specialists involved in the projects, (such as architects, engineers, geologists, restorers, archeologists, historians, etc.) could find inconsistency in the comparison of the H-BIM-GIS measurements and traditional measurements taken with simple tools like measuring tapes or disto-lasers.

In other words, at the level of a single building, georeferencing is carried out with a 3-parameter transformation (1 angle, 2 translations) between local (x,y) coordinates and cartographic coordinates (East, North). The conversion between the vertical z coordinate and the orthometric elevation H is instead calculated applying geoid undulation evaluated.

In the case of data capture on larger areas, the use of orthometric elevations calculated with a geoid model is essential. The expert in digital documentation must be aware and inform the other specialists about the transition from a local Cartesian reference system to a cartographic one, especially when the survey is conducted in large areas in which the different cartographic "effects" cannot be neglected.

3.3 Orthophotos and DEMs

Orthophotos and digital elevation models generated using the cartographic plane (East, North) can be automatically imported into the H-BIM-GIS environment. For example, data produced with drones find in the H-BIM-GIS a natural environment because procedures will be completely automatic (Figure 6).

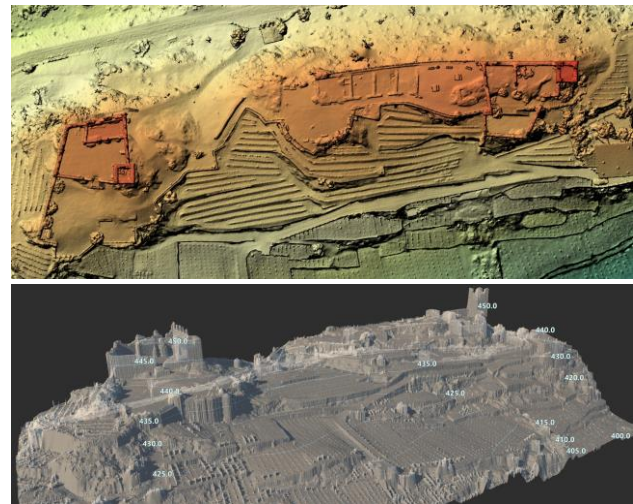


Figure 6. Top: shaded relief in GIS. Bottom: DEMs and orthophotos generated using the cartographic plane imported into the H-BIM-GIS.

The case of DEMs and orthophotos not produced in the cartographic plane requires a different approach. Heritage sites are 3D and therefore orthophotos are often needed for walls, arches, vaults, frescoes, or other surfaces that require the creation of a local reference system that depends on the geometry of the considered elements. Such orthophotos are added to the H-BIM-GIS using a link to specific points of interest placed in the 3D space.

It is also important to consider that orthoimages could be more useful for other specialists if they can be imported into software

for additional operations. For instance, a restorer could be interested in using the image in software for condition assessment. As clarified in the next paragraph, the aim of the H-BIM-GIS is not to reimplement and replace those functionalities already available in other software. In some cases, it must guarantee simplified access to the information.

3.4 Georeferenced meshes, CAD, 3D models, and BIM

Different types of 2D and 3D products can be imported and used in the H-BIM-GIS. Although 2D CAD drawings can be imported and draped on the DEM, the real advantage of the virtual environment is the opportunity to import 3D models in various formats, including geometric surface or solid models as well as BIM. Figure 7 shows the BIM of Castel Masegra imported into the H-BIM-GIS environments.

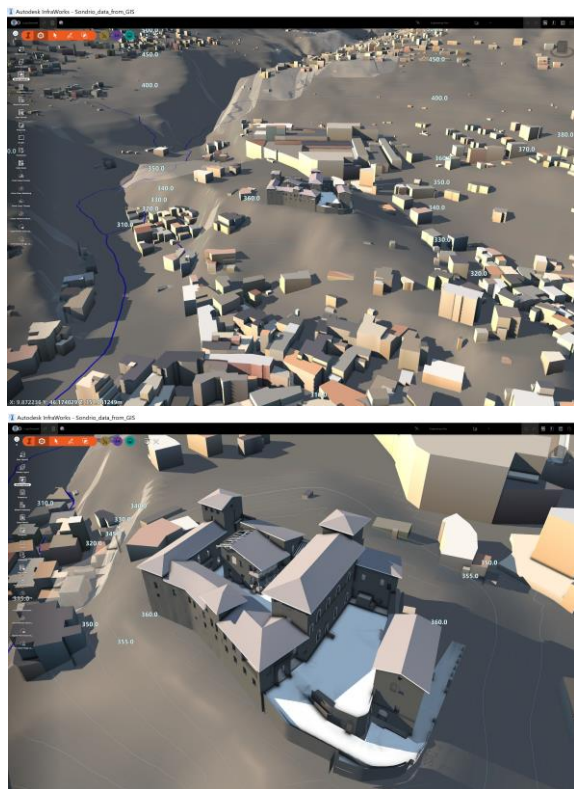


Figure 7. The HBIM of Castel Masegra was added to the refined InfraWorks project.

More details about the production of such HBIM model are illustrated in Barazzetti et al. (2015). Georeferencing was carried out using GNSS techniques. The model in InfraWorks includes the cartographic layers with the buildings extruded using the vertical height of each building, which is stored using the attribute table of the shapefile. The simplified reconstruction of the castle was not completely removed from the project. It was decided to add another proposal to the same project; thus the BIM replace just the corresponding shapefile polygons. The user can activate different proposals to work with more refined models. From this point of view, the H-BIM-GIS does not only include data stored on layers but also in project proposals offering automatic transitions between multiple versions of the same project.

4. INTEGRATION OF ADDITIONAL INFORMATION

4.1 Overview

Digital recording of historic buildings and sites is not only limited to the geometrical survey. Information can be available in different formats, sometimes without the opportunity of a “direct” connection to a geospatial database. For instance, existing texts and reports could be digitized and stored in a way that their content is accessible via the H-BIM-GIS notwithstanding they do not cover a specific geographic area. This problem could be avoided by creating point-of-interest object layers with a link to the data source.

This section shows just a selection of heterogeneous information integrated into the H-BIM-GIS model of the fortified structures around Sondrio. The aim is to show that specific ad-hoc solutions can be used depending on the considered information.

4.2 Virtual tour based on spherical images

360° images, also called spherical images or panoramas, can be acquired with 360° cameras usually equipped with multiple lenses able to look in different directions. Images are then merged into a single equirectangular projection that gives a 360° visualization of the scene around the camera. Multiple 360° images taken from different locations form a virtual tour of the site. Figure 8 shows the different locations of the 360° images acquired in Castel Grumello. The user can access the corresponding image by interacting with a 3D map.



Figure 8. Top: A point shapefile generated in the GIS with a link to the different 360° images included in the attribute table. The shapefile can be imported into the H-BIM-GIS to allow direct access to the panoramas. Bottom: one of the panoramas.

Virtual views can also be created using the digital model. In this sense, the H-BIM-GIS is used to produce new data, which can be shared on the web. Such functionality is particularly interesting when accurate 3D models are integrated into the environment. For instance, the creation of multiple proposals also allows the transition from the current state captured with the on-site survey to the visualization of virtual future configurations after restoration.

4.3 Diagnostic information, materials, and condition maps

Digital documentation produced by the different specialists involved in a conservation project can be added to the H-BIM-GIS. An example of thermographic image, double flat-jack test (with the associated numerical data), and condition assessment file is shown in Figure 9. They can be linked to the model using points-of-interests so that the user can access them by simply selecting the icons in the 3D view.



Figure 9. Thermographic image revealing hidden cracks in the vault, double flat-test, condition map with the identified degradations.

4.4 Historic cartography

Historical maps are a valuable source of information that is usually processed in GIS software. Scanned maps can be georeferenced using control points, i.e., points visible in both the historical map and more recent maps able to provide a set of cartographic coordinates used as a reference. After georeferencing, the historical map can be imported into the H-BIM-GIS environment and draped on the DEM. Figure 10 shows the result for the 1844 map showing the city center of Sondrio.



Figure 10. Left: An historical map georeferenced and imported into the virtual H-BIM-GIS environment. Right. The continuation of the same image with the modern buildings and streets from the geospatial database.

The method can also be extended to other products that could require georeferencing. Examples are old aerial photographs not acquired considering photogrammetric requirements for data processing, i.e., multiple images with good overlap.

4.5 Satellite images

Nowadays, a huge number of images taken from satellites are available. Such images feature different spatial, temporal, and radiometric resolutions and were already exploited by different authors for conservation projects, opening new opportunities

and linking the field of parametric BIM-GIS modeling with remote sensing.

The use of remotely sensed data for heritage has been discussed by different authors. The reader is referred to Agapiou et al. (2020) and Hadjimitsis et al. (2020) for a review and some applications. As remotely sensed optical images are usually orthorectified, they can be imported into the H-BIM-GIS. Often preliminary processing is required in GIS or remote sensing software to generate a 3-band image that is recognized as a more traditional orthophoto. Figure 11 shows some results using a Sentinel-2 image acquired on 2020-08-09 and imported in InfraWorks as traditional false color and classification map, and NDVI.

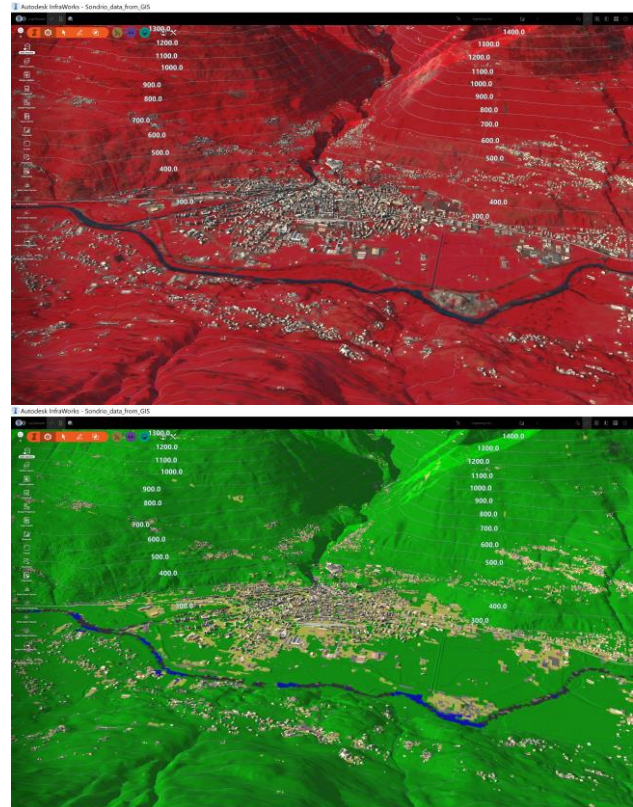


Figure 11. Remote sensing products (false color Sentinel-2 image and classification map) can be added to the H-BIM-GIS project.

4.6 Many other products: considerations

Different products could be available in a heritage project. The work has listed some typical information (including sources already available or newly generated with planned data acquisition and processing campaign), but the proposed list is not exhaustive. Data produced by other specialists can also be encapsulated into the H-BIM-GIS. However, interoperability issues must be faced. The system could be quite rigid when some typologies of datasets are used. Besides, BIM-GIS software were not developed for historic buildings and sites, which often feature unique characteristics.

Interoperability problems are already well-known when more traditional BIM or GIS software are used (independently). Future work and new applications would require the development of protocols, methods, and procedures to face interoperability problems (see next section).

5. BIM, GIS, AND BIM-GIS: INTEROPERABILITY AND PRODUCTION OF NEW INFORMATION

The experience carried out during the digital documentation project and the creation of an integrated H-BIM-GIS that handles different digital information has revealed pros and cons. The first important consideration is the need for multiple software, especially when specific operations must be carried out.

GIS engines have advanced geospatial tools operating on heterogeneous data. The use of ArcGIS Pro (desktop solution) has allowed advanced operations to produce additional results, which can be then imported into InfraWorks in essentially two ways: (i) the creation of new files (import/export) or (ii) a more direct and interoperable connection using ArcGIS Online. This interaction works in both ways, so the InfraWorks work can be published in ArcGIS Online, in which users can directly explore and make modifications.

An example is the reconstruction of the path on the mountain that connects the main road to Castel Mancapane. The path is about 600 m long and was measured with kinematic GNSS obtaining a shapefile shared on ArcGIS Online and imported in InfraWorks using Connector (Figure 12). The line is parametrized as a street object and draped on the 5 m DEM. The transformation into a component road enables advanced editing operations. The figure also shows the vertical profile with the associated slope.

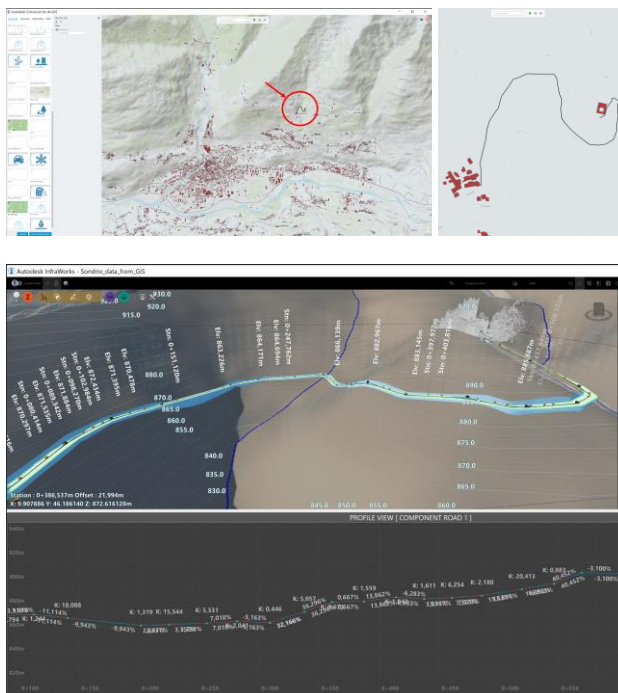


Figure 12. The path on the mountain between the main road and Castel Mancapane. The path was surveyed via GNSS, added in ArcGIS Online, retrieved using Connector, and parametrized as a street object in InfraWorks.

Data exchange is also feasible between Revit and InfraWorks, as shown in section 3.4. For instance, a specific portion of the InfraWorks model can be imported in Revit. Alternatively, the BIM model produced in Revit can be added to an InfraWorks project. Revit offers the opportunity to define a survey point, i.e., a very simple and intuitive solution that allows the user to georeference the BIM. As mentioned, the use of GNSS points

with centimeter-level precision provides all the necessary information for georeferencing.

Finally, interoperability between ArcGIS Pro and Revit is also available. ArcGIS Pro can directly read Revit BIM, providing instruments for additional refinement of georeferencing. The procedure used was the direct georeferencing in Revit using a point with known cartographic coordinates (East, North, orthometric elevation) as well as the azimuth (angle to the North).

An additional projection file (.prj) with the same name of the Revit file was stored in the same folder. This allows direct import into ArcGIS Pro. Elements of the BIM are recognized as feature layers and can be used like 3D GIS information, enabling operations such as queries or more advanced analysis (Figure 13). Also, GIS data can support modeling activities in BIM. For instance, vector contour lines generated in GIS provide the shape of the terrain to start modeling operations in BIM.

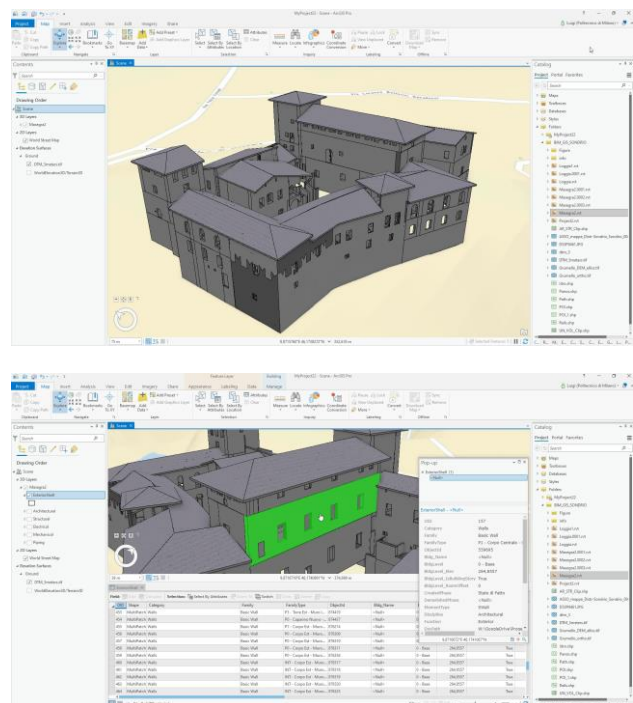


Figure 13. The HBIM was imported in ArcGIS Pro in the correct location after georeferencing via GNSS. The information stored in the BIM is available as feature layers.

The opportunity to switch between different software in both directions allows the user to take advantage of the tools of each software. The idea is not to replicate or find a way to reimplement tools already available in another software. For instance, the production of a BIM considering the constructive elements of the building will be carried out in Revit, which is specifically designed for this purpose. The model can be moved to InfraWorks if a larger area must be considered. Other buildings in the surrounding area can be added with a level of detail depending on the requirements of the applications.

Additional information can be produced using a combination of different packages. This is also necessary considering the multiple specialists involved in the process, who can provide existing data and also generate new information. From this point of view, the H-BIM-GIS approach is not only a "container" of information. It becomes a productive tool where new information can be created and shared. Interoperability between software is the key, and this aspect still must face the lack of

tools or the rigid procedures and algorithms available, which were often not developed for the special case of heritage sites featuring complex characteristics that are not replicable for other sites.

6. CONCLUSIONS

The paper presented and discussed the creation of an integrated H-BIM-GIS system, in which multiple heterogeneous data sources were encapsulated starting from the cartographic scale to the different buildings and their constructive elements. The 3D capabilities and the possibility to georeference digital information provide a unique multi-scale environment that connects BIM and GIS. One of the outcomes of this work is the need for interoperable tools that can facilitate the exchange of digital information among multiple software. BIM, GIS, and BIM-GIS engines must be simultaneously exploited because each software provides unique advanced functions and tools. Data interoperability becomes a fundamental factor to ensure a smooth workflow to produce new information. In this sense, the proposed software already have methods able to exchange digital data and run specific tools. Some of the proposed solutions are also quite dynamic being hosted on cloud services (e.g. ArcGIS Online and Connector).

It is the author's opinion that an integrated H-BIM-GIS could have remarkable potential for preventive conservation (Della Torre and Pili, 2019) because it extends the advantages of current BIM and GIS technology, fulfilling two fundamental requirements: (i) better survey and documentation, and (ii) long term storage, access, and production of digital information.

On the other hand, different limitations were found. The intrinsic characteristics (such as the complex geometry) of heritage sites must face the rigid structure of software not specifically developed for heritage objects.

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