

Article

A Scan-to-BIM Methodology Applied to Stone Pavements in Archaeological Sites

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Abstract: The transition from Building Information Modelling (BIM) to Heritage Building Information Modelling (H-BIM) is intended to pursue an adequate knowledge of the artefact that is to be preserved, progressively replacing the traditional methods of restoration and structural reinforcement projects with new tools for the management of both existing information and new interventions. The aim of the paper is to show the application of the H-BIM method to a stone pavement road located in the Archaeological Site of Pompeii. In detail, starting from a laser scanner-based survey, juxtaposed with coordinated points georeferenced through a total station, point clouds were handled by means of several BIM-based tools to perform the road design process, starting from the digital elevation model (DEM) and proceeding to the corridor representation. Subsequently, a visual programming application based on Python language was adopted to update the corridor information by means of the object property set. As preliminary results, a tool, complete with graphical and non-graphical information, is proposed to be used in conservation, maintenance and restoration projects.

Keywords: heritage-BIM; stone-paved road; procedural modeling; VPL scripting; CAD; point cloud



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1. Introduction

Digitization and computerized processes are an effective answer to cost reduction and production time issues, and therefore BIM, defined as “a process involving the generation and management of digital representation of the physical and functional characteristics of a facility” [1], represents the best-fitting result of the continuous search for new methods and approaches to increase process efficiency in the Architecture, Engineering and Construction (AEC) industry. BIM is recognized as the most appropriate methodology for the undertaking of building and infrastructure projects [2,3], having revolutionized the field of architecture and construction for some years now [4], being both a technology and a methodology [5]; even though it remains a challenge for the AEC industry, as it requires a shift to a new way of working, there is a strong legislative endeavour to flatten any differences in its adoption level among the various EU states [6].

The increasingly widespread adoption of BIM for new projects has been accompanied by the application of the BIM methodology to reverse-engineering processes of existing civil works. In the case of buildings with historical or cultural value, this approach is known as H-BIM, defined as “a new way of modeling the existing structures, generating intelligent models that can contain and manage information, and concern all components of the project, including their geometric and identification information described in detail” [7].

The reverse engineering process mentioned, yielding a three-dimensional (3D) geometric model enriched with semantic information, comprises three fundamental steps, including acquisition, segmentation, and modeling [8]. Remote sensing technologies—such as Terrestrial Laser Scanning (TLS) [9], Unmanned Aerial Vehicle (UAV) photogrammetry [10],

Mobile Terrestrial LiDAR Scanning (MTLS) [11] and Structure from Motion (SfM) [12]—are a fundamental part of the process itself, as they allow for the smart geometric surveying of historical sites. SfM photogrammetry employs overlapping images acquired from multiple viewpoints. It is a low-cost technique which can be carried out with cameras within the reach of everyone, including smartphones [12]. TLS operates by emitting a laser beam and calculating the distance from the object detected by measuring the round-trip time of the laser pulse itself [9]; it is a more expensive technique that also requires more experienced staff. MTLS applies LiDAR technology installed on moving terrestrial vehicles [11]. UAV represents perhaps the most elaborate technique, involving vehicles that move by remote control, such as aerial drones [10].

Many studies in the literature have focused on such techniques, and on methodologies—often used together [13]—which are intended to achieve digital information models of heritage assets from intelligent surveying systems [14,15].

The experience in the architectural field is well consolidated. Indeed, many case studies have been carried out to develop systematic approaches to historical-cultural heritage sites, such as for the Cathedral of Parma and the Ducal Palace of Mantua (Italy) [16]; the Pisa Charterhouse (Italy) [17]; the House of Pilatos in Seville, Spain [18]; St. Bernard's Chapel in the Plasy Monastery (Czech Republic) [19]; the Porticoes of Bologna (Italy) [20]; the Cathedral of Christ the King, in the municipality of Huejutla de Reyes (Hidalgo, Mexico) [21]; and St. Herakleidios Monastery in Cyprus [22].

For example, Moyano et al., (2020) evaluated the accuracy of SfM point clouds against TLS for large architectural spaces with a symmetrical configuration, with the main courtyard of Casa de Pilatos in Seville, Spain, as a case study [23]. Four representative cases of different urban facades' typologies were selected in the historic center of Santiago de Compostela by Peña-Villasenín et al. [24], focusing on the photoshoot arrangement.

A key issue that characterizes this field of research is that of the creation of libraries of objects [25], because the elements of the models tend to be quite peculiar and often unique. Murphy, among others, has led many research efforts on the topic [26], integrating H-BIM with a Geographic Information System (GIS) [27], considering the dynamic construction of parametric objects to constitute an architectural heritage purpose library [28].

In order to obtain libraries of parametric objects, the possibility of using automation tools was also explored [29].

As important aspects in H-BIM, the appropriate level of detail depends on the intended use of the model itself and the type of analysis to be performed [30].

In this sense, the level of graphic rendering of the objects inserted into the intelligent digital model also depends on the LOD, and the designer will have to assess which technique to apply, considering that in the field of digitization in the service of cultural heritage conservation, research has defined methodologies based on increasingly refined algorithms and methodologies [31].

The level of information can be highly varied, and may not relate only to architectural aspects [32]. The H-BIM also provides a tool to support structural analysis, through the BIM-to-Finite Element Model (FEM) process. The latter defines an FEM, starting from a surface mesh obtained by BIM, and allows us to consider the loads, material quality and geometric variability of the resistant sections [33,34]. Other interesting case studies have proven that H-BIM is also suitable for infrastructure, such as the Giorgini Bridge in Castiglione della Pescaia (Grosseto, Italy) [35]. The authors addressed the problem of the geometric simplification of as-built model. The Carlo III Bridge of the Carolino Aqueduct (Benevento, Italy) [36], was also examined by integrating the use of laser scanning, photogrammetry, and traditional survey methods to maximize the effectiveness of the data acquisition phase. The Azzone Visconte Bridge (Lecco, Italy) [37] was modeled with H-BIM as well, and the authors tried to overcome some limitations of commercial BIM software packages with parametric algorithms.

H-BIM is also suitable for the development of Virtual Reality (VR) and Augmented Reality (AR) projects, serving to create digital worlds which are able to represent recorded real

places, enabling the improvement of new immersive experiences faithfully and accurately for experts and non-experts [38–44].

Considerable efforts are currently underway to develop the automatic reconstruction of geometry and information models from laser-scanned point clouds of cultural heritage elements [45], and also through the use of Deep Learning (DL) techniques based on Convolutional Neural Networks which are able to implement automatic segmentation to help us to recognize historical architectural elements [46]. Among these developments, the process has also been applied to analyses of stone pavement patterns [47,48] in order to retrieve precise measurement data on irregular surfaces, such as those of historical paved roads, with a high degree of automation [49]. Most of historical urban areas in western countries are paved with stone elements [50]; in particular, the Italian road network is among the world's greatest heritage complexes, given that Italy has the highest number of UNESCO Heritage Sites. Examining these in the case study of Via Duomo, the main cardo of the ancient Neapolis, an H-BIM approach considering road infrastructure was developed [51]. Some cases of H-BIM approaches for archaeological sites are the following, which were used to examine the Hierapolis in Phrygia (Turkey) [52] and Curium (or Kourion, Cyprus) [53], where Laser Scanning and UAV technology were combined, as well as Staffarda Abbey (Cuneo, Italy) [54] and the Crypt of St. Sergius and Bacchus Church (Rome, Italy) [55], where the authors performed the inclusion of stratigraphic analysis in an H-BIM workflow to overcome the 3D modelling limitations of BIM software with a free-form modeler based on a NURBS algorithm.

Referring more in particular to archaeological roads, the work carried out in the archaeological site of Pompeii by Biancardo et al. [56] realized H-BIM focusing on the modular elements of the road pavement section of the Via del Vesuvio. This workflow process began with data acquisition by photogrammetry, and only later involved modeling via point clouds.

From the review of the literature given above, it may be observed that H-BIM is a topic of strong interest in the fields of engineering, remote sensing, and IT technology. While it seems that the technique and research favor the architectural domain, some exemplary case studies have been performed on linear infrastructure. Nonetheless, reverse-engineering operations tend to find very peculiar results when examining historical and archaeological road pavements. In fact, the high irregularity that characterizes ancient historical pavements raises important questions about the suitability of the currently available software, and involves additional difficulties related to the remote sensing work phases.

Therefore, this study aims to address this gap by establishing a workflow for the implementation of an H-BIM methodology by means of non-conventional data association, and using automatic algorithms for semantic enrichment. In order to validate the proposed workflow, we applied it to a stretch of an archaeological road in the Archaeological Site of Pompeii.

BIM is a methodology which has been successfully used in the different life phases of architectural and infrastructural works. The multidimensional model supports professionals in the planning, design, operation and disposal of the work, providing a continuous flow of information, made dynamic by the possibility of being continuously updated by professionals with different skills. The question arises: can BIM play the same role in archaeology?

By their nature, archaeological finds are not affected by the planning, design, construction and disposal phases. Indeed, conservation agencies are entrusted with the task of managing archaeological assets and safeguarding their preservation. Still, research is focusing on the ways in which BIM can be exploited for the asset management phase, as well as a basis for the development of further analysis. A perfect example is the work of Garagnani et al. [57], which focused on the case study of the Etruscan temple of Uni in Marzabotto.

This work falls into line with other previous research, such as that of Bosco et al. [58], which focused on the case study of *insula* 4–6 in Paestum (Italy), and it showed how the

Archaeological BIM approach provides a complete system which is useful for different purposes, from documentation to interpretation and management.

The main novelty of this research work is that it would like to bring to general attention the archaeological road artefact, pointing out H-BIM (or ABIM) as a tool to support agencies in their aims, specifically for the management of the archaeological roads, as well as a tool for sharing information related to materials and ancient construction techniques that still exert fascination for experts and non-experts.

2. Methodology

The research study aims to define a new approach to the use of the H-BIM methodology for the analysis and the management processes of archeological sites, focusing on the terminal part of Via Stabiana on Porta di Stabia in the Archaeological Site of Pompeii.

The pivotal methodology shown in Figure 1 is built around the so-called Scan-to-BIM workflow, which allows for the generation of a 3D BIM from a point cloud, involving two main work phases: 3D surveying through a laser scanner and the processing of the information surveyed with several pieces of BIM-authoring software.

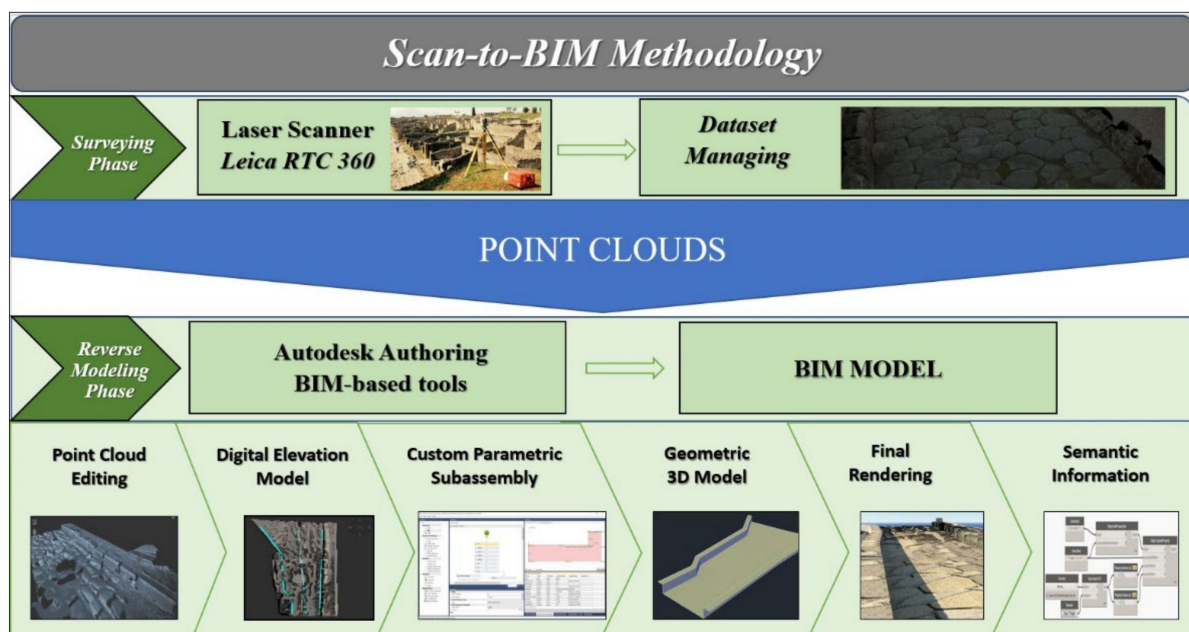


Figure 1. Methodology workflow.

The surveying phase of the Scan-to-BIM process relies on Terrestrial Laser Scanner (TLS) technology, electro-optical instruments capable of surveying the surface of any object by mapping the points in 3D.

In order to perform the reverse engineering of 3D objects using a CAD program, both polygon mesh and Non-Uniform Rational Basis Spline (NURBS) algorithms have been previously implemented to address the representation and conservation of heritage assets [37,54,59]. While polygon meshes are easier to model, they also provide rougher images compared to NURBS, and are highly dependent on the degree of simplification of the mesh itself [60]. In the present work, the road surface was modelled through a mesh. Due to the extreme irregularity of the stone-paved surface under analysis, a comparison between the geometry obtained from the point cloud survey and that of the final rendered model is discussed in Section 5.

The final step of the 3D modeling was the assignment of customized textures to the mesh surfaces using source images taken during the survey, allowing use to obtain a more realistic simulation. Once the model of the three-dimensional surfaces had been recreated

on the trace of the point cloud, it was possible to manage the information of the model itself and interrogate it using tools which are able to develop semi-automatic algorithms.

Autodesk BIM-based tools were used to ensure the 100% interoperability and perfect success of the Scan-to-BIM methodology just described: (i) Recap Pro, for survey data management; (ii) Infracore, for the BIM creation preparation phase and final render; and (iii) Civil 3D, to create the BIM, for which it was necessary to create from scratch a customized typological road section with its add-on Subassembly Composer, and to develop algorithms by means of its add-on Dynamo.

3. Case Study

3.1. Pompeii Case Study

Once a thriving and sophisticated Roman city, Pompeii was buried under meters of ash and pumice by the catastrophic eruption of Mount Vesuvius in 79 AD. Pliny the Younger, an eyewitness to the eruption from his family's villa in Miseno, described the pyroclastic mushroom as a "prodigious pine tree, here shining white, there soiled with gray from the ashes and the raised earth" [61]. Because the ashes protected the structures from historical processes of destruction, Pompeii is one of the best-preserved Roman cities. Therefore, Pompeii is one of the most important archaeological sites in the world, attended by major scholars of international renown. As the excavations continue, new discoveries are still found, such as the Thermopolis of Regio V [62].

Because any H-BIM application should include an informed preliminary analysis of the construction criteria, previous research works were investigated in order to obtain an in-depth picture of the knowledge on the case study [63], such as for Roman road building technologies and practices [64], and their design criteria [65]. Particularly significant is the study conducted in the archaeological site of Pompeii by Poehler and Crowther (2019) [66] on the paving techniques hypothesized from the surveys carried out.

Pompeii stands on a buttress about 40 m high, formed by the flow of lava from Vesuvius in prehistoric times. The land on which the city was built is therefore considerably irregular, with a steep slope towards the south. The roads, almost all straight and crossing at right angles, are divided into main arteries, corresponding to the cardines, with directions from north to south, and to the decumans, with directions from west to east, and in secondary arteries, of variable width; they are flanked by more- or less-high sidewalks, made with construction waste and paved by private individuals [56].

The H-BIM workflow was applied to the terminal part of the Via Stabiana on Porta di Stabia in the Archaeological Site of Pompeii (Figure 2). It is a road stretching 12 m long, with a 5.20% average slope that guarantees the outflow of the water into an underground canal on the right side (North–South direction) and then outside the walls, thanks to a change of the road's cross-slope.

3.2. Surveying Phase

A Leica RTC360 model laser scanner was used to perform the survey. After setting the resolution parameter, connected to the precision and scanning speed, a single 360° scan was performed in one minute and 50 s, obtaining a point cloud composed of 2 million points. Each point position was identified by coordinates [X,Y,Z], that were the distance of the point from the instrument, the inclination angle formed by the conjunction of the point and the instrument with respect to the vertical axis of the instrument itself, and the azimuth angle formed by the conjunction of the point and the instrument with respect to a horizontal axis taken as the reference.

A TLS survey process should be supported by multiple scans, to survey the same objects from different perspectives. Indeed, a common problem is that of "laser beam occlusion", or the inability of the laser beam to overcome opaque obstacles, which results in some areas of shadow in which the cloud is devoid of points. It is therefore good practice to perform multiple scans to overlap the resulting clouds, thus obtaining a final one without shadowed areas. We performed several scans of the same object produced as a result

overlapping data, which were later manipulated with a dedicated software package, Leica Cyclone. This software was used to view and check every scan, to coordinate several scans into one, to georeference the project in the Gauss–Boaga system, and to export the project to a common format file to ensure its interoperability.

Because the area subject of this study was not excessively wide or irregular, three scans was found to be the satisfactory.

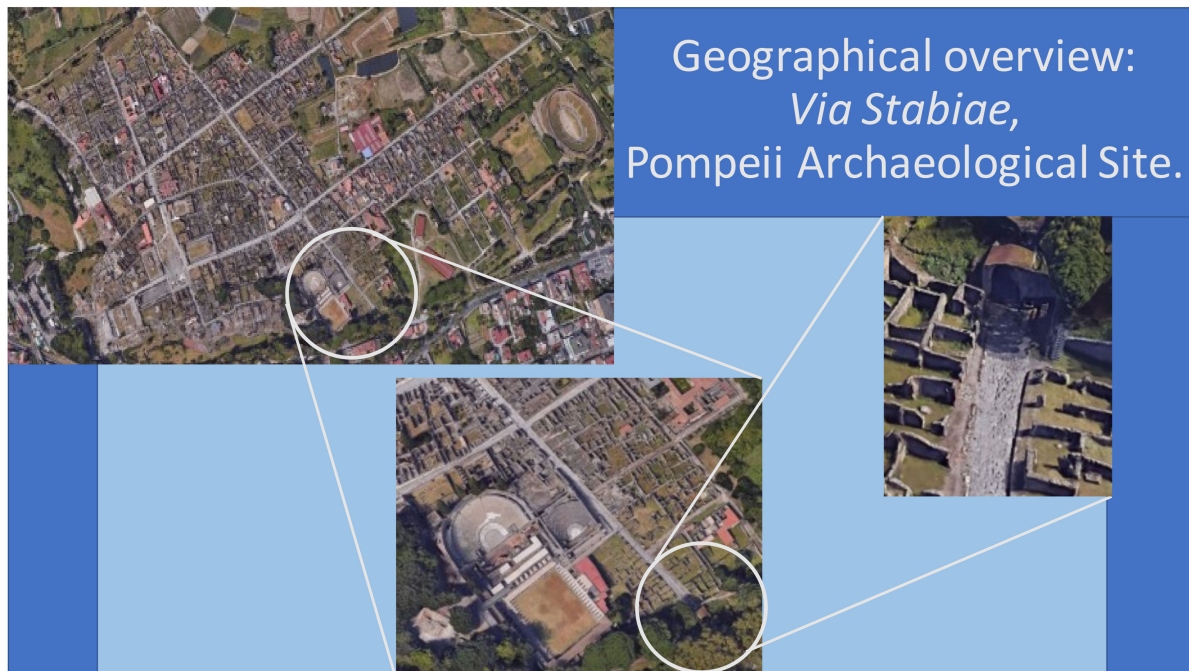


Figure 2. Geographical overview.

3.3. Database Managing and Point Cloud Editing

The management of the scanned point cloud database was carried out within Leica Cyclone. When finished, a single point cloud derived from the coordination of the three scans performed was exported to a PTX format to import it into Autodesk Recap Pro. The latter was then leveraged to clean up the cloud and export it to an RCP file format in order to enable it to be used by Autodesk InfraWorks.

3.3.1. Leica Cyclone Database Management

The first operation in Cyclone was to add and configure an empty database, to which the data derived from the RTC360 laser scanner was subsequently associated.

The software allowed us to automatically align the different scans through the built-in smart alignment function; subsequently, ambiguous, mixed-pixel, and overloaded points were removed.

Once the import process was completed, each scan was referred to as a *scanworld*, denoting a visualization environment of a single scan, isolated from the others and with a fixed viewpoint corresponding to the position of the scanner at the time of the survey. Eventually, it was possible to merge the three scans into a unique registration.

In order to georeference the project, a Control file was used, i.e., a text file in which some Ground Control Points, surveyed by means of a total station, were identified by their ID and their coordinates (latitude, longitude, altitude). Once imported, the Control file was processed as a scanworld. In order to georeference all of the scans, it was necessary to set the Control file as the home scanworld. A new final registration was carried out after the georeferencing.

Finally, the project was exported as a PTX formatted file.

3.3.2. Autodesk Recap Pro Point Cloud Segmentation

Recap Pro, from Autodesk, was used for the segmentation of the point cloud.

Once the file to import had been selected, a filter was applied to adjust the density and range; moreover, the geographical coordinate system was specified among hundreds of options available, but the operation was eased by the automatic detection performed by the software itself. Then, a decimation grid was set, which is a parameter that imposes the minimum points' mutual distance. In Cyclone, the points scanned were at a mutual distance of the order of 1 mm, and the dimension of the points was set at 0.5 mm radius; thus, the points perfectly covered the space on the surfaces, giving to the human eye the exact perception of the objects surveyed. This level of detail is not needed anymore in the modelling phase, so the decimation grid was set at 5 mm, obtaining a lighter database.

In order to perform the segmentation, Color Setting and Selection Tools were leveraged, allowing for the changing of the background color and the simulation of illumination (Figure 3), and allowing us to define a point selection by means of a rectangular window, a closed polygon, a plane or a limit box. The segmentation consisted in the identification of the area that was strictly necessary to the modeling process, to cut the superfluous elements and make the model even more streamlined, optimizing at the same time the performance of the machine and the graphic rendering.

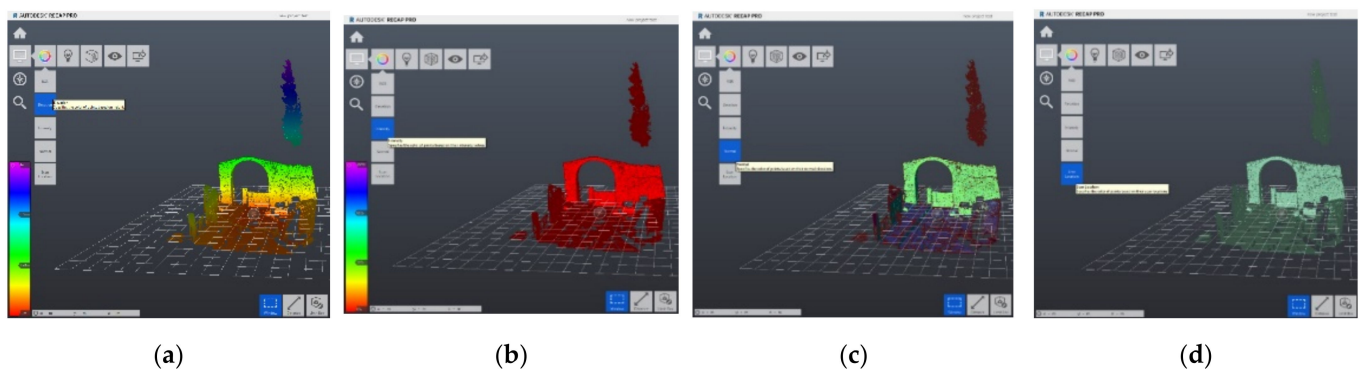


Figure 3. Colorization options: (a) Elevation; (b) Intensity; (c) Normal; (d) Scan Location.

3.4. H-BIM Process

The H-BIM process was accomplished through a series of Autodesk codes, used in a synergistic and versatile way to optimize the resources, and results as shown in Figure 4.

The segmented point cloud was imported into Infraworks to generate the Digital Elevation Model. The output of this part of the process is represented by some three-dimensional polylines, which trace the DEM, i.e., the very heterogeneous road surface under study. These polylines were transformed into Feature lines in Civil 3D, used as Baselines of the Corridor. At the same time, through Subassembly Composer, an extension of Civil 3D, a parametric section consistent with the information found in the literature [66] was modeled. The association of this subassembly with the baselines has led to the production of the Corridor in Civil 3D, on which a 3D surface with custom material was modeled. To the geometric model thus obtained, a series of information was added using Dynamo, another Civil 3D extension, which works through VPL scripts.

3.4.1. Infraworks DEM Creation

Recap Pro was also fundamental to ensure interoperability with the other software used; indeed, it was used to convert the original file with a PTX extension to a file with an RCP extension, in order to import it to Autodesk Infraworks.

Starting a new project within Infraworks, the geographical coordinate system was set accordingly with the one used in the georeferencing phase. The RCP segmented Point Cloud was imported and configured as the dataset.

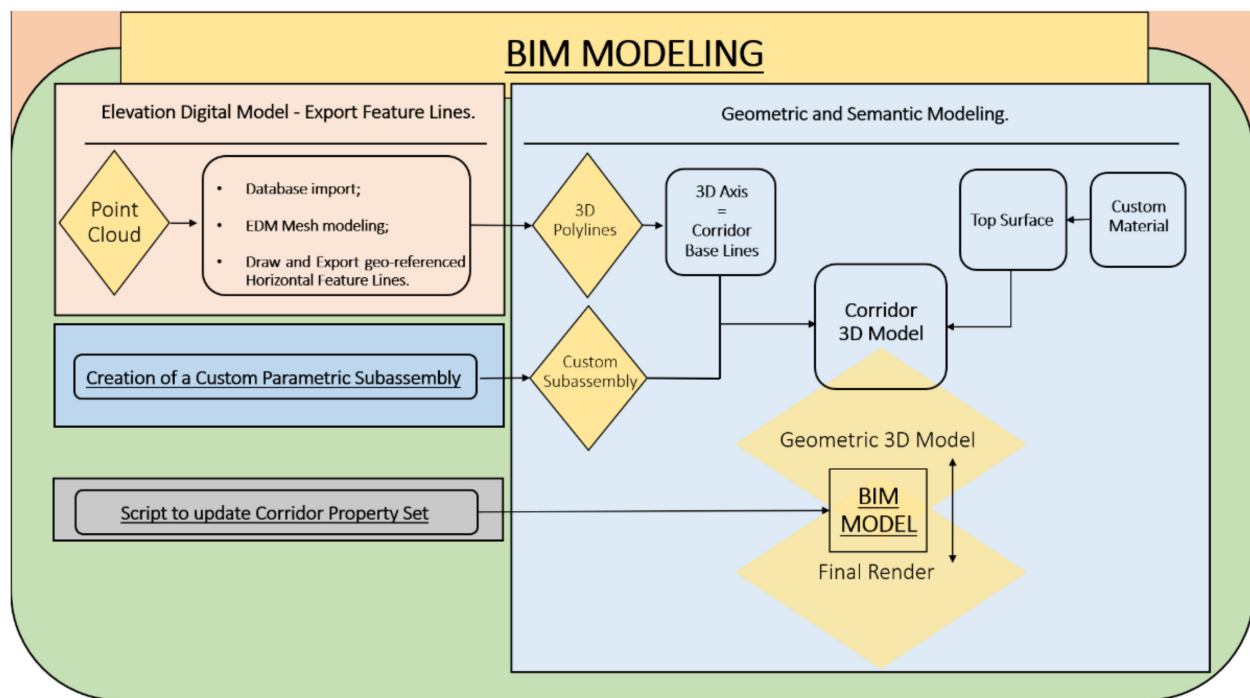


Figure 4. BIM Workflow.

After the import process had been completed, Infraworks was used for the creation of the DEM. In this step the processing rules were defined, i.e., the level of detail of the terrain, and the linear and the vertical features to be associated to the process.

The next step was to extract linear features from the resulting DEM by manually drawing characteristic lines directly onto the DEM surface in correspondence with the road axis, road margins, and sidewalk edges, in order to coordinate the horizontal and vertical information.

Then, they were exported in a SHP file format that contains the X, Y and Z, coordinates of the lines' vertices, which correspond to latitude, longitude, and altitude.

In this way, 3D and geo-referenced feature lines were obtained, ready to be imported into a BIM tool, such as Autodesk Civil 3D. These feature lines were the base to develop the H-BIM itself.

3.4.2. Subassembly Composer Custom Subassembly Modeling

Civil 3D has a well-stocked default library of structural and functional elements, but the assembly of the ancient Roman road does not correspond to any of those available, as these ones follow principles and materials of modern conception; thus, it was necessary to build it from scratch using Subassembly Composer, which is automatically bundled with the Civil 3D license and is an extremely useful tool for the customization of typological road sections.

In order to create the geometry, one must proceed by selecting from the Toolbox the necessary elements, i.e., nodes, links, and the surfaces enclosed by them, and add them to the Flowchart section. The position of the points in the section plane can be set from an initial point, by default the origin, by means of Delta-X and Delta-Y, or by imposing a slope combined with a Delta-X or a Delta-Y. Links are defined by indicating the starting and ending nodes. Shapes are defined by indicating the links that constitute their edges. For each element, point, link or shape, it is possible to associate a code, which is of vital importance for subsequent operations in Civil 3D, which happens to be a strongly hard-coded piece of software. As the geometry is formed, the preview of what has been coded is obtained.

By defining the parameters in the Input/Output Parameters section, it was possible to use them to characterize the geometry and thus make the section parametric. For example, by defining the “width” parameter, encoded as “LaneWidth” because, as mentioned, Civil 3D is strongly hard-coded, this can be used to define the distance between two points within the geometry (the Delta-X or Delta-Y mentioned previously). In the same way, it is possible to define parameters such as the material and its characteristics, through string-type parameters, or the cross slope through the “CrossSlope” parameter of the grade type, or a percentage.

Due to the peculiar conformation of the infrastructure and the variable horizontal-vertical trend of the three-dimensional polygonal lines used as the reference, it is essential to set targets among the other parameters of the typological section itself.

Once the subassembly is ready, it is saved in a .ptk format, a kind of compressed file that contains all of the information related to the Subassembly Composer process. Then, it can be imported into Civil 3D and used to complete the corridor modeling.

3.4.3. Civil 3D Corridor Modeling

The 3D model of the road was obtained using Civil 3D. Usually, the corridor is obtained by extruding an assembly along an alignment, drawn on a topographic surface and made three-dimensional by the coordination with a design profile. In this case, the three-dimensional axes were obtained differently (cf. Section 3.4.1), resulting in 3D polylines tracing the point cloud (Figure 5).

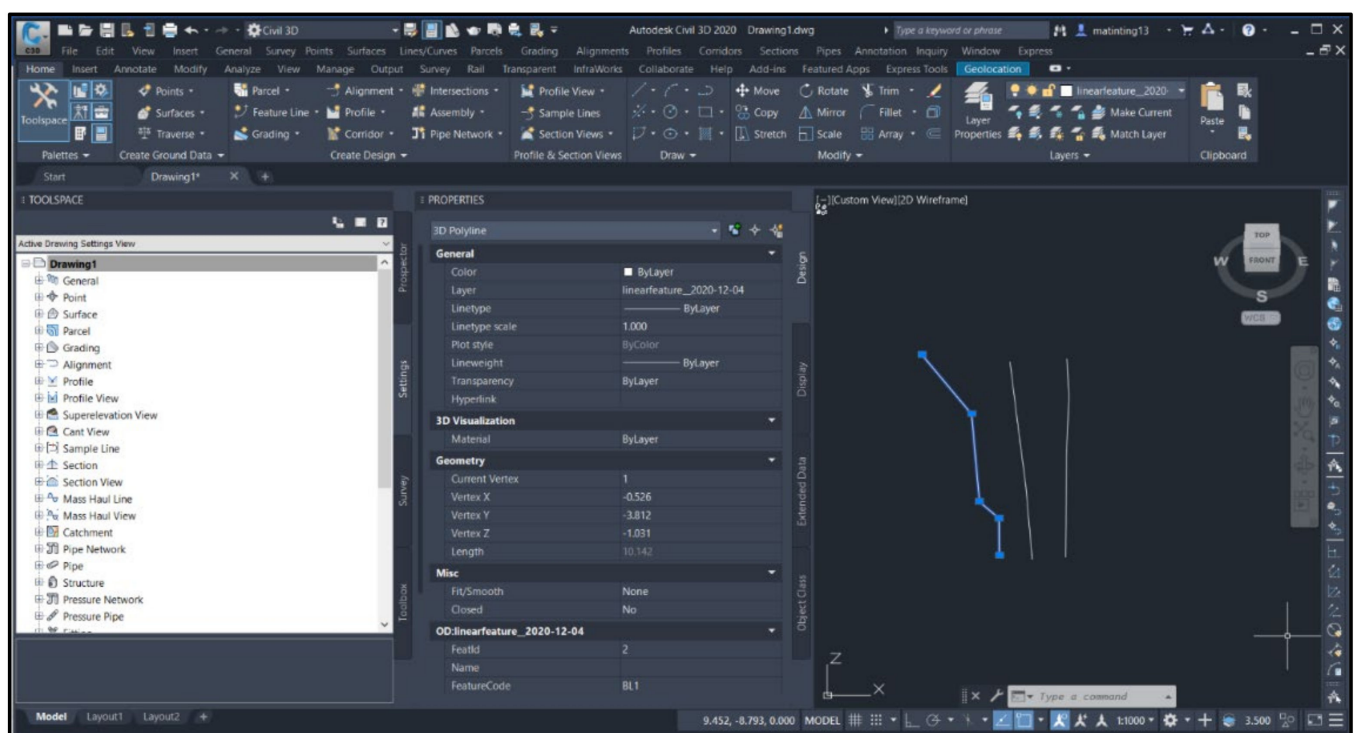


Figure 5. 3D polylines' property visualization.

Next, the corridor was created as shown in Figure 6: the 3D polylines were turned into feature lines; the central one was set as the road axis, while the external ones were set as edges by associating them with the target types “Width or offset” and “Slope or elevation”.

To complete the corridor model, the extrusion surfaces and solids were made, and finally materials for the render characterization were associated with them.

The Corridor represents the geometric frame on which the data structure of the BIM is supported. In order to add informative content to the Corridor, the so-called “property sets” were leveraged, which are sets of various types of information that can be customized

by the designer. Four different Property Sets were created and added to the corridor manually, each one matching a supposed layer of the roman road, namely: Nucleus, Rudus, Stratumen, and Summa Crusta. The properties added were basically the material properties, such as the shear modulus and density.

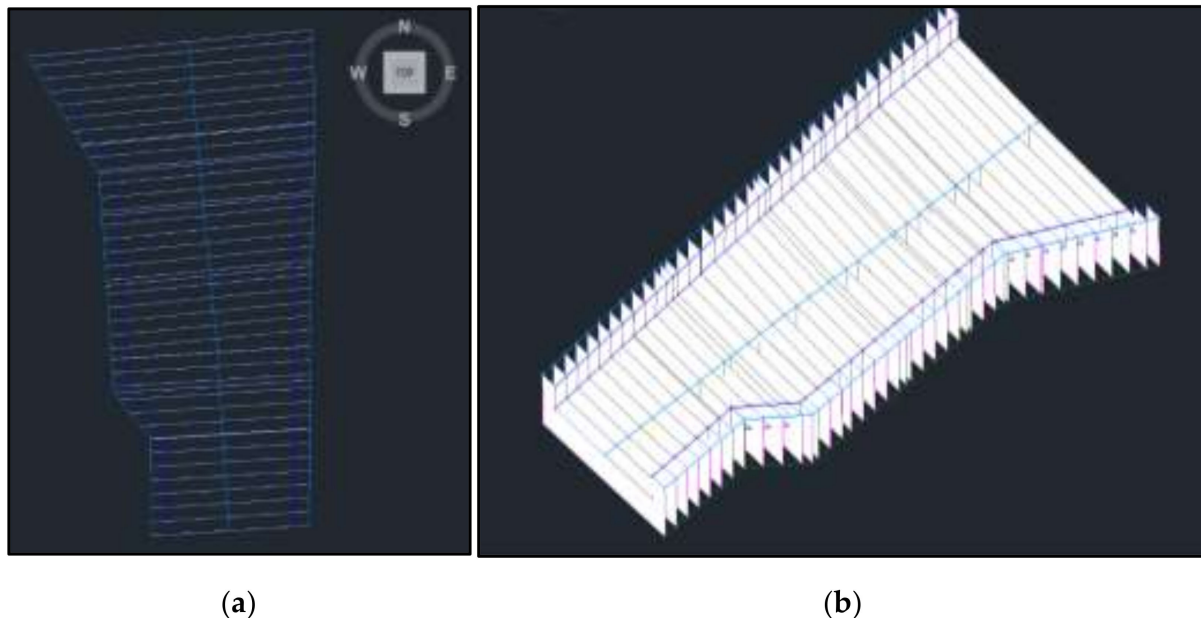


Figure 6. Corridor visualization: (a) drawing view; (b) object viewer mode.

3.4.4. Infracore Rendering

The Civil 3D model was exported from and reimported into Infracore in order to visualize the renders.

In order to control the appearance of the coverage areas of the rendered model, style rules of the coverage areas—first in Civil 3D, and later in Infracore—were modified, creating a custom coverage area style rule.

After that, the Top Surface and Materials were imported from Civil 3D to Infracore.

3.5. Algorithm Scripting through the Visual Programming Language Environment within Dynamo

Finally, a Dynamo script was developed to update the Property Set attached to the Corridor Model. Dynamo is based on a VPLE (Visual Programming Language Environment) which consists in a logic graph, the nodes of which represent functions that have inputs and outputs. The output of a node can be used as an input for other nodes. Nodes are connected by means of links. Nodes can be selected from among the hundreds contained in the Dynamo Nodes Library.

The script developed for this case study is as essential as it is effective (Figure 7): the main operational process is led by the “Object.UpdateProperty” node, which updates the properties of the Property Set attached to an object. As inputs, the user must indicate the object, the Property Set name, the names of the properties to be updated, and the values to update them with. The object was directly extracted by the current Civil file indicating the name of the object (“Corridor”) and the name of the Property Set (“Summa Crusta”). Property Names could be indicated with strings, manually introduced by means of the “String” node, and values could be indicated by means of a “Block” node; in this case, the names and values were imported from a .CSV formatted file, where the first line provided names and the second provided values, by means of the node “File Path”, allowing for the selection of the input file and “Boolean”, which enabled the default setting of the “Data.ImportCSV” node, which transposed the rows and columns to be changed.

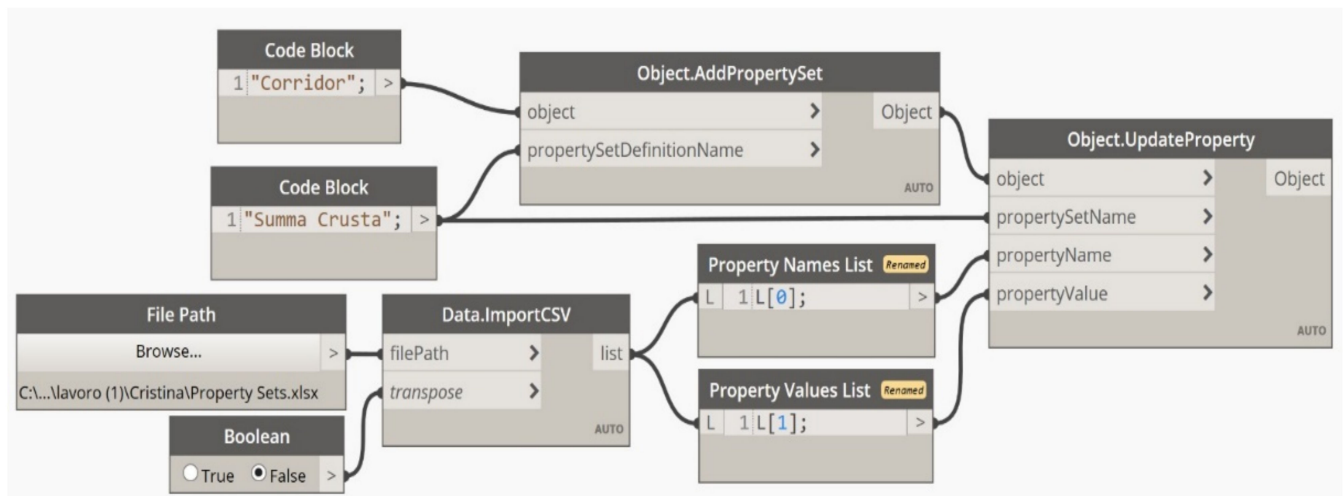


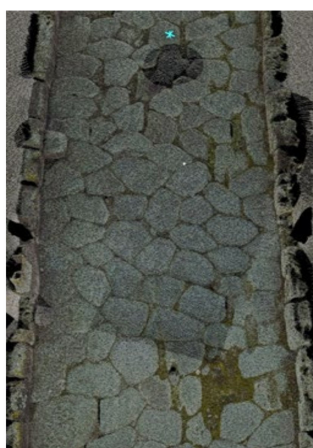
Figure 7. Dynamo visual script to update the corridor properties.

4. Results

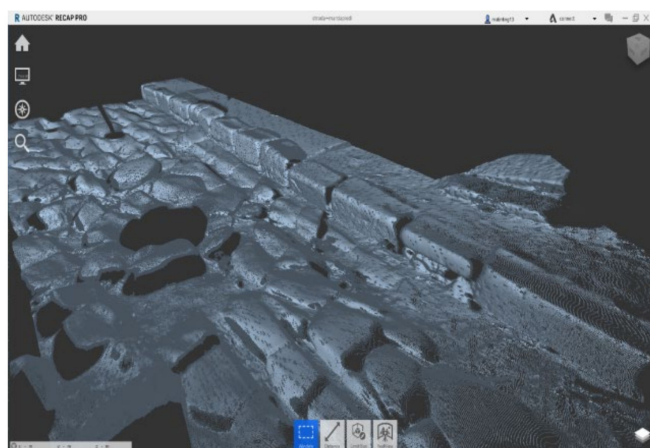
In the present work, Leica Cyclone was used to manage a geographic database, i.e., a large amount of data collected in the field using a terrestrial laser scanner. In Cyclone, the point cloud is shown at a very high level of definition: color gradients, and the slightest depressions and differences in level can be easily appreciated, and one can obtain an idea of the degree of the macro-roughness of the paved surface (Figure 8a). These features make it a useful tool for visualization and project orientational exploration.

Recap Pro was subsequently used to operate the segmentation of the original point cloud (Figure 8b), and for reasons of interoperability with the other software used in the following phases of the workflow.

After being processed within Recap, the Point Cloud file was exported as an RCP-formatted file to be imported into Infraworks (Figure 8c), and a DEM was developed. Feature lines were drawn on the DEM (Figure 8d), and data related to the coordinates of their vertices were extracted.



(a)



(b)

Figure 8. Cont.

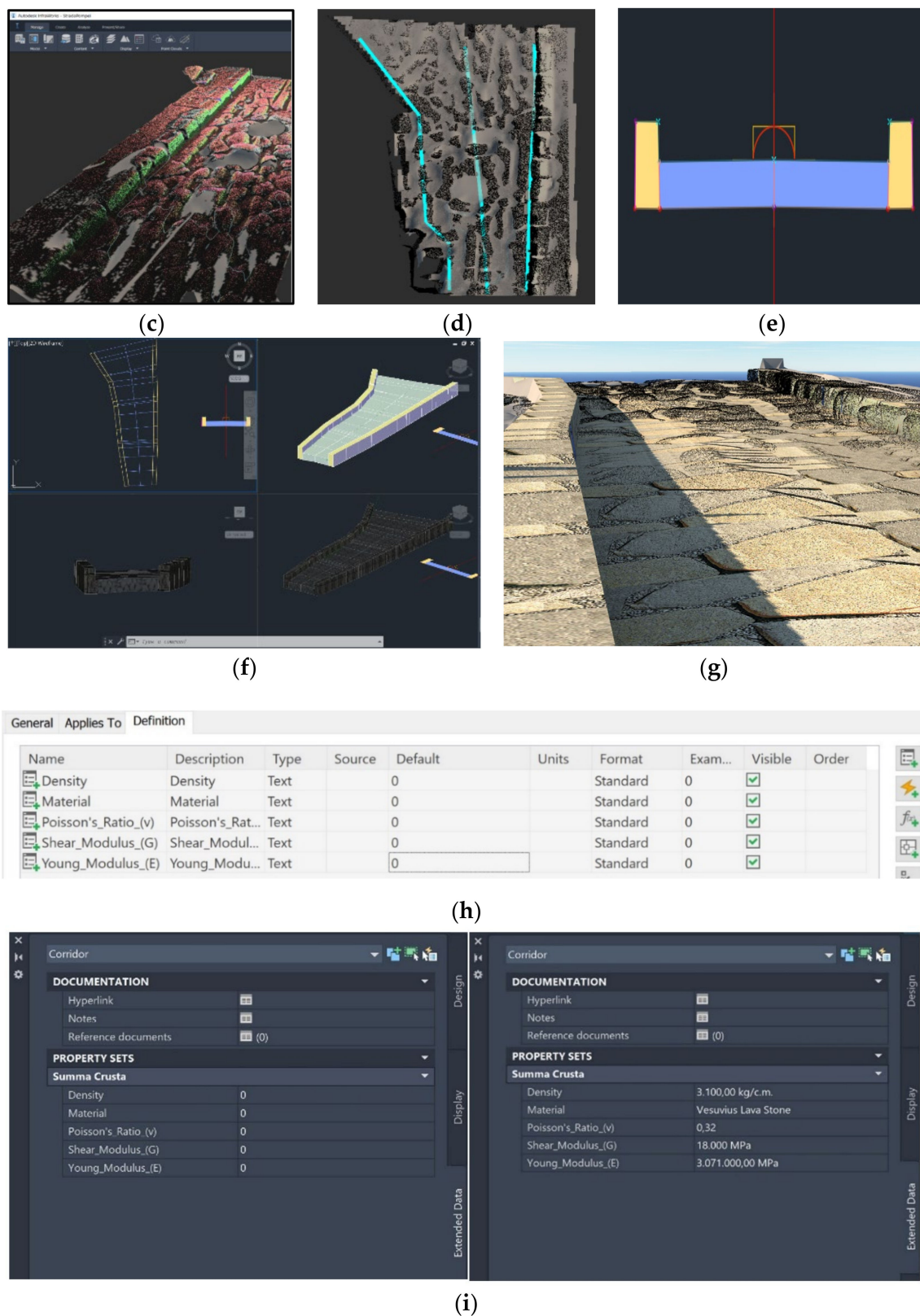


Figure 8. Results: (a) Leica Cyclone view for registration. (b) Recap Pro view for segmentation. (c) Infravorks view for Digital Elevation Modeling. (d) Infravorks view for Linear Feature lines extraction. (e) Subassembly Composer typological section view. (f) Civil 3D view for Corridor modeling. (g) Infravorks view for the pavement render. (h) Civil 3D property set for information associated with the Corridor model. (i) Properties before and after the dynamo script application.

The tools made available by Subassembly Composer were exploited to create a typological section (Figure 8e) that was as consistent as possible with the studies carried out on the typological section of urban Roman roads [66]. Moreover, the use of this tool has been fundamental for the definition of the parameters characterizing the section itself. Among these, a logical-geometric parameter is that of the “targets”, which allowed us to adapt the section to the horizontal–vertical alignment of the three-dimensional axes imported in Civil 3D and previously produced in Infraworks, which precisely follow the trend of the DEM and therefore the data obtained from the laser scanner survey.

This is an element of unquestionable innovative value that demonstrates how the reverse-engineering technique can be applied to infrastructural elements of complex and non-standardized geometry.

Once the process was completed in Subassembly Composer, it was possible to complete the construction of the 3D model in Civil 3D, extruding the customized typological section along the three-dimensional line corresponding to the central axis of the road, and adapting the horizontal–vertical alignment to that of all of the three 3D lines imported from the previous work carried out in Infraworks for the geographical orientation of the surveyed data (Figure 8f). A top surface was then modeled on the corridor thus formed, to which a custom material corresponding to Vesuvian lava stone was associated (Figure 8g).

A BIM project is characterized by the association of technical information with a three-dimensional geometric model.

For this reason, the BIM was completed with the creation of a Property Set that reports the information related to the mechanical behavior of Vesuvius Lava Stone [67], which can be viewed in the corridor properties (Figure 8h).

Dynamo was then used to fill in the empty Property Set created in Civil 3D with data imported from a .csv file (Figure 8i).

5. Discussion

The results obtained showed the suitability of the workflow set up for the production of the BIM of a stone-paved archaeological road, although the IT tools used were not originally designed for this purpose. The implemented methodology allows us to manage and process the data collected during the survey phase.

The use of the latest technologies of topographical surveying allowed for the accumulation of a huge geo-spatial database consisting of point clouds defined by millions of points. Leica Cyclone software has been critical to the management of this database and its geo-referencing, while Recap Pro proved its efficiency in the segmentation operational phase. The subsequent use of Autodesk applications for the creation and management of projects in the BIM environment allowed the processing of the data and the obtaining of a BIM representative of what was surveyed in the field.

It is perhaps necessary to point out that, in the transition from a detailed mesh obtained with techniques that faithfully trace the point cloud obtained during the survey with TLS, to the simplified digital model, there is a loss in terms of precision in the geometric representation. However, the advantage of using a Building Information Model lies in the “I” of the acronym. The information contained in the model is the keystone that holds the very meaning of applying BIM to archaeological heritage.

The correspondence between the model created and the actual geometric distribution of the surveyed surface was verified using Cloud Compare, an open-source software program for the manipulation and comparison of point clouds. In Civil 3D, the volume of the model was measured as the volume of the solid extracted from the corridor. The volume measured in Cloud Compare was obtained by creating a reference plane positioned below the point cloud, at a relative height equal to the thickness of the cross-section created in the model. We executed Cloud Compare’s “2.5D Volume calculation” algorithm, which compared the volumes between two-point clouds, or between a point cloud and a plane of reference. Mesh transformation operations into point clouds and repositioning were

performed in order to execute the algorithm, which also makes it possible to interpolate the data and homogenize the areas which are useful for calculation.

The two volumes deviate by 3.78%.

Civil 3D and Infracore are industry-leading tools for the delivery of infrastructure projects; it is much rarer to find their applications in H-BIM, and even less so in archaeology. In this, the work described in this research brings an element of innovation, given that the features of these pieces of software, conceived to optimize the infrastructural design from scratch, have been exploited for the reproduction of unique artifacts with an immense historical and cultural value, which are part of an important UNESCO archaeological site such as Pompeii.

The possibilities offered by the integration between the tools for the writing of calculation codes have been exploited using Dynamo—which leverages the visual programming environment to open the doors of the programming world to the widest possible user base—to manage the semantic heritage of the created BIM, ensuring the possibility of updating its content from external databases and surveys of architectural, structural, geotechnical types.

6. Conclusions

In this research work, IT tools were leveraged to apply techniques and methodologies that have previously been successful for infrastructure projects. The desire to find workflows that are functional in the process of the reverse engineering of existing artifacts is not new, but our goal of being able to coordinate technologies and software designed for the BIM approach for linear infrastructures was ambitious, given the shortcomings in the application of BIM to linear infrastructures of historical value. Hence, the present work was able to take another small step in the right direction to achieve this end, including the results obtained in the broader context of historical and cultural heritage conservation, creating another precedent for the application of Heritage-BIM to archaeological heritage, i.e., the implementation of BIM in Archaeological-BIM.

However, the work carried out did exhibit some criticalities related to the limitations of commercial software conceived for the ex-novo design of linear infrastructure. In fact, these involve the use of standard parametric elements, which are geometrically very simplified and homogeneous. Attempting to fit the model to the field reality has been an operation characterized by limits and simplifications. Although Civil 3D allows users to operate on the meshes, the computational complexity makes this software poorly suited for this type of operation. In addition, the modeling of the pavement surface texture was relegated to the visual field, associated to a photographic image obtained in situ, which was repeated modularly along a smooth surface.

Other limitations derived from the uniqueness of the site in question included the fact that the archaeological protection regulations prevent the possibility of carrying out intrusive tests on the road pavement, and that the high irregularity of the surface surveyed accentuated the problem of laser beam occlusion, leading to program errors and the necessity of repeating the survey operations.

Moreover, the need for patterns and templates to structure the data to be associated with the geometric models is emphasized in order to obtain BIM models for which the consultation rules are clear and defined.

Future research should go further in the direction of the digitalization of Europe's immense cultural heritage, strengthening the knowledge of processes and methodologies to simplify and improve the performance of methods for the analysis and the conservation of the architectural–infrastructural heritage, with a focus on stone paved roads, which constitute most of the historical roads in urban centers.

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