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BIM approach for stone pavements in Archaeological Sites: The case study of Vicolo dei Balconi of Pompeii

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ABSTRACT

At present, ecological and technological transition policies encourage the improvement of efficiency of engineering processes; this is the background for new methods for the digitalization of engineering works. The methodological approach of Building Information Modeling (BIM) brings a great wave of innovation, probably destined to replace previous approaches to the designing, maintenance, and management phases. The aim of this paper is to propose a methodology to apply BIM to the archaeological field (Heritage BIM - HBIM), with a focus on stone paved roads. It addresses the case study of a stretch of stone paved road located in the Archaeological Site of Pompeii in Italy. For the development of the digital model, several BIM-based tools have been used, starting from a laser scanner-based survey, which led to a point cloud that was subsequently coordinated with certain referenced points to achieve a correct geo-referenced point cloud. The corridor design process was performed by developing a Digital Terrain Model (DTM) of the paved surface and customizing the cross-section. Meanwhile, a visual programming application based on Python language was used to enrich the usability of the model itself with further operations. As result, a tool is proposed to be used in maintenance, management and restoration projects, for archaeological assets.

Introduction

In recent years, digitisation has played a key role in the AEC (Architecture, Engineering and Construction) industry (Gu and London, 2010). Indeed, the issue of the development of new methodologies is in full swing (Ma et al., 2020a; Ma et al., 2020b). The aspiration underlying this new approach is the improvement of the processes, the reduction of time and costs, and the increase of the overall quality of the projects (Abbasnejad et al., 2021).

BIM, which stands for Building Information Modelling, improves the quality of projects by addressing the need to reduce construction costs resulting from lost time due to unforeseen events and design errors. BIM navigates a three-dimensional geometric model made up of a multitude of objects, grouped by families, which are easy to interrogate. In fact, the BIM designer can provide each instance with information of any kind, e.g., materials and labour required, costs, construction times, technical qualities in terms of mechanical resistance, fire and chemical actions, etc. BIM is therefore not only a design tool, but also an information storage tool, making it very useful, if not essential, in the subsequent phases of management, maintenance and decommissioning (Oreto et al., 2021) and to implement benefit-cost analysis (Biancardo et al, 2022; Cantisani et al., 2022).

The clear potential of BIM has been of interest to research circles for years. The starting date of research on BIM is traditionally stated by Eastman in 1975. Eastman imagined that an ideal representation of a building would combine the positive aspects of both drawings and physical models: "it would incorporate 3D information in an easy-to-read format and would require any change to be made only once for its full effects to be revealed" (Eastman, 1975).

He was the first author to postulate that computer graphics would lead to this achievement, but BIM has come a long way since this early mostly geometrical definition. Indeed, with the development by various

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companies of dedicated software, as Autodesk, Bentley, Graphisoft, and Acca, BIM has become more and more inclusive in all aspects of the design and management of an engineering project, as for example for modelling levelling, embankments and earthworks (Santamaría-Peña et al., 2021) and for geotechnical and numerical modelling of a conventional tunnel excavation (Fabozzi et al., 2021). Bentley software has been involved in many applications, including the railway sector (Biancardo et al., 2021a; Biancardo et al., 2021b; Liu, 2019). The most widely used Graphisoft software for architectural BIM is ArchiCAD, as witnessed in several publications (Dore and Murphy, 2014; Li et al., 2018; Sampaio et al., 2021; Tse et al. 2005). ACCA, the Italian leader in software for construction, architecture and engineering, on its official website, claims to be the company with the largest number of IFC certified BIM software in the world, and many researchers are using them for their applications (Musella et al., 2021; Ramirez, 2021). BIM has effectively evolved into an extremely multidisciplinary tool (Jin et al., 2016; Sackey et al., 2015; Sandberg et al., 2019; Welle et al., 2011; Zanni et al., 2020), involving structural engineers, architects, plant engineers, logistics managers, administrative planners, etc., with categorized relationships that are both horizontal and vertical. This has advanced modelling well beyond the third dimension (Charef et al., 2018).

The multidisciplinary of BIM is only guaranteed if all BIM-based tools used by the professionals involved in the work are able to 'talk to each other'. This translates into the need for a common file format to ensure interoperability between different software. As defined by Peter Wegner in 1996, "interoperability is the ability of two or more software components to cooperate despite differences in language, interface, and execution platform" (Wegner, 1996). The file format for BIM software interoperability is IFC, standing for Industry Foundation Classes, a registered platform-neutral open-source standard owned by buildingSMART International. The IFC, composed by four levels (domain, interop, core and resource) (Bormann and Liebich, 2016), allows to store any kind of information (buildingSMART, 2016). In 1994–1995, with first agreements between several US industrialists, investments started to be made on open format for interoperability. Then, by the end of 90', IFC began to be promoted internationally and in 2005, the alliance of companies changed its name in buildingSMART, covering in a few short years the needs of vertical architecture professionals. To also meet the needs of horizontal engineering, several projects were undertaken, such as IFC Road, IFC Bridge, IFC Tunnel, IFC Port, and IFC Airport (China Railway BIM Alliance, 2015). Today, bSI has defined the IFC Infra Overall Architecture project to define the general principles to be followed by all extensions of infrastructure standards (Golparvar-Fard et al., 2010). The latest official IFC standard is 4.0.2.1, published in October 2017 and ratified by ISO 16739-1:2018, while the latest in development, is the standard candidate 4.3 (BuildingSMART, 2021a, BuildingSMART, 2021b, BuildingSMART, 2021c).

Development of the IFC reflects the determination, at all levels, and in ever more numerous technical communities around the world, to embrace the BIM methodology and make the most of its advantages (Kassem and Succar, 2017; Succar and Kassem, 2015). Indeed, the wide diffusion of BIM has been supported by the regulatory efforts of many countries. In Europe, countries such as Finland and Sweden have pioneered a general trend towards the adoption of BIM systems for major infrastructure. Then, the European parliament introduced the Public Procurement Directive 2014/24/EU and European countries started to implement the adoption as mandatory (European Parliament, 2014).

The spread of BIM as an increasingly common tool has been paired with the appearance of several innovative technologies that have changed the way of performing surveys. Examples are laser scanners, both fixed terrestrial (TLS - Terrestrial Laser Scanner) (Fröhlich and Mettenleiter, 2004), mobile (MLS - Mobile Laser Scanner) (Stal et al., 2021) and aerial (Unmanned Aerial Vehicle) (Achille et al., 2015). The synergy between the BIM methodology and advanced technologies has led to the advent of a further novel approach to the design and management of engineering works, such as the case of VR (Virtual Reality), that allows the operator to fully immerse himself in the work that has been previously scanned and modelled (Banfi et al., 2019; Brumana et al., 2019). Interesting developments in indoor navigation research are to be found within this framework (Isikdag et al., 2013). The world of university engineering education has also shown interest in students developing VR skills (Alizadehsalehi et al., 2021).

Quickly evolving into the versatile and reliable tool it is today, BIM has been applied in several fields, to design new buildings, especially if characterized by the assembly of prefabricated parts (Bataglin et al., 2017, Liu and Zou, 2021, Ma et al., 2020a; Ma et al., 2020b), both for vertical architectures (Quiñones et al., 2021) and for horizontal structures (Bensalah et al., 2018; Chong et al, 2016, Kurwi et al., 2017; Vignali et al., 2022). When BIM is applied to transport infrastructure, it takes the name of I-BIM (Infrastructures-BIM), or Heavy BIM (Arena et al., 2021; Bosurgi et al., 2021). Notable research has been conducted in the area of integration between geometric and structural modelling, implemented within the BIM method. Thus, on the basis of a geometric model, it is possible to simulate the mechanical response of an object subjected to load-stress (Tang et al., 2020). The BIM approach has also made great progress in synergistic applications in reverse engineering, which in the case of AEC is the attempt to recreate the functional scheme (architectural, structural, plant engineering, etc.) of a currently existing building, starting from a more or less sophisticated survey operations and using deductive logic (Vignali et al., 2021). When the object of the model has historical value, BIM can be broken down into H-BIM (Heritage BIM) (Baik, 2017; Biancardo et al., 2021a; Biancardo et al., 2021b; Logothetis et al., 2015), or to Archaeo-BIM if it is an archaeological asset (Bagnolo et al., 2019; Bosco et al., 2020; Garagnani et al., 2016).

What scientific research has explored about BIM and its applications is in the general interest of promoting methods and technologies that can optimize engineering processes, leading to the progressive elimination of design errors, document discrepancies, management difficulties, and a general lack of information, which are crucial for the efficient maintenance of works (Akbarieh et al., 2020; Costin et al., 2018; Karimi and Iordanova, 2021; Obrecht et al., 2020; Wang and Meng, 2019). A still relatively unexplored but very promising field is that which we can call Archaeo-Horizontal-BIM, i.e., BIM concerning ancient archaeological roads. This is focus of the present research paper, with the aim of deepening and expanding the knowledge of the field explored in previous works (Biancardo et al., 2020; Intignano et al., 2021). Furthermore, the study is part of the debate on stone road pavements and the use of the latest technologies for their analyses (Garilli et al., 2021a, Garilli et al., 2021b).

The aim of the research is the development of a framework in BIM for the management of historical road. In fact, the digital information model can store huge amount of data, always updateable and verifiable. The model and its information can be surfed and easily checked solving long-standing problems related to the complexity of archives. Moreover, the graphic representation of the archaeological asset is an added value, a starting point for further interesting developments in digital cultural tourism.

The research is in line with the aims of the general vision of Pompei Archaeological Site Management Body of digitizing the entire site for dissemination purposes. Indeed, with the "Grande Progetto Pompei" (Pompei Archeological Site, 2023) first, a research project started in 2016 for the digitalization of the entire site "for the purpose of ensuring that present and future generations can take advantage of virtual visits to the site" (Osanna & Picone, 2018), and the PRIN 2017 "Stone pavements. History, conservation, valorisation and design" (20174JW7ZL) financed by the Ministry of Education, University and Research (MIUR) of the Italian Government, great interest is rising about historical-archaeological sites management methods involving digital tools.

This research shows how the BIM methodology has been implemented on a section of an ancient Roman road in the archaeological site of Pompeii: the case study aims not only to show a BIM application, but also to show how BIM can be a useful tool for the purposes of archaeological conservation and protection agencies. A further scientific value of this work lies in the information content of the digital model, consisting of the results of complex non-invasive survey operations, which have made it possible to hypothesise a specific road stratigraphy and construction techniques (Autelitano et al., 2022).

Methodology and tools

The research work was conceived with the aim of defining a general methodology for the implementation of BIM in horizontal infrastructures in the world of archaeology. To this end, a case study was addressed, namely the realisation of the digital model of a section of *Vicolo dei Balconi*, in Regio V of the Archaeological Site of Pompeii, near Naples, Italy.

The methodology developed is shown on a chart in Fig. 1.

Key words are: I-BIM, because the modelled object is a road; H-BIM, because the road has historical and cultural significance; Archaeo-BIM, since the road is located within an archaeological site; Reverse Engineering, intended as an engineering technique that involves recreating the model of an existing artefact; Scan-to-BIM, i.e., informative digital modelling on the basis of geometric surveys carried out using laser scanners (Stanga et al., 2019). The first three relate to the type of model obtained, the other two to the technique used to obtain it.

As far as the procedure is concerned, four successive phases follow one another: a data collection phase, consisting of a geometric survey campaign using Lidar (Light Detection And Ranging) (Reutebuch et al., 2005); a data management phase for the alignment, coordination and geo-referencing of the scans in a single reference system; a point cloud editing phase for the transformation of the data into a single segmented and ready-to-use point cloud; a final modelling phase, in which, using different dedicated software, the model of the roadway was created, including costumed information sets; eventually, scripts were written in a visual programming language environment to automate some operations on information stored in the model.

Several BIM-based tools were used to apply the methodology to the case study. For the first data management phase, Leica's own Cyclone software was chosen, in line with Leica's guidelines, available on Leica official website, which recommend its use in conjunction with the TLS model used – Leica RTC 360. For the subsequent phases, on the other hand, it was decided to use the Autodesk software suite in order to ensure the highest level of interoperability: Recap Pro was used for the point cloud segmentation operations; Infraworks for the creation of DTM (Digital Terrain Model) and Horizontal Feature Lines; Civil 3D for the actual modelling of the road corridor, with the aid of Subassembly composer, an extension of Civil 3D, for the definition of a customised section type that best corresponded to the surveys carried out; and finally Dynamo, another extension of Civil 3D, for the creation of some scripts in VPLE (Visual Programming Language Environment) for the updating of the information content of the model.

Case study

Architectural and infrastructural works of an archaeological nature preserve the historical memory of the greatness of the past and therefore constitute a heritage to be protected. This is the case of the archaeological remains of the Site of Pompeii, one of the best-preserved cities of the Roman Empire and, for this reason, the subject of study by researchers all over the world.

The subject of the case study is *Vicolo dei Balconi* (Balconies Alley) (red framed in Fig. 2), which has recently (2018) emerged from an area of excavation in *Regio V* (black edged in Fig. 2) (Ansa, 2018; Osanna,

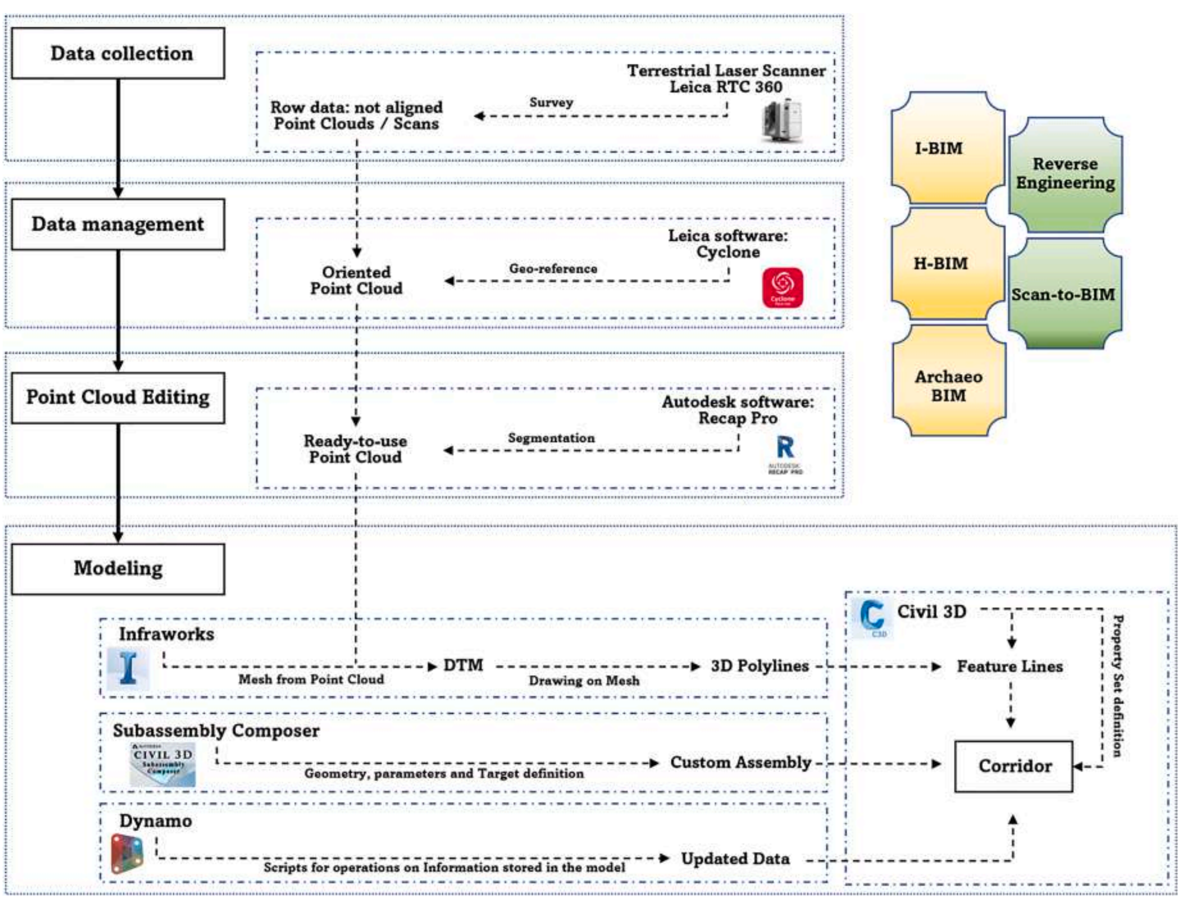
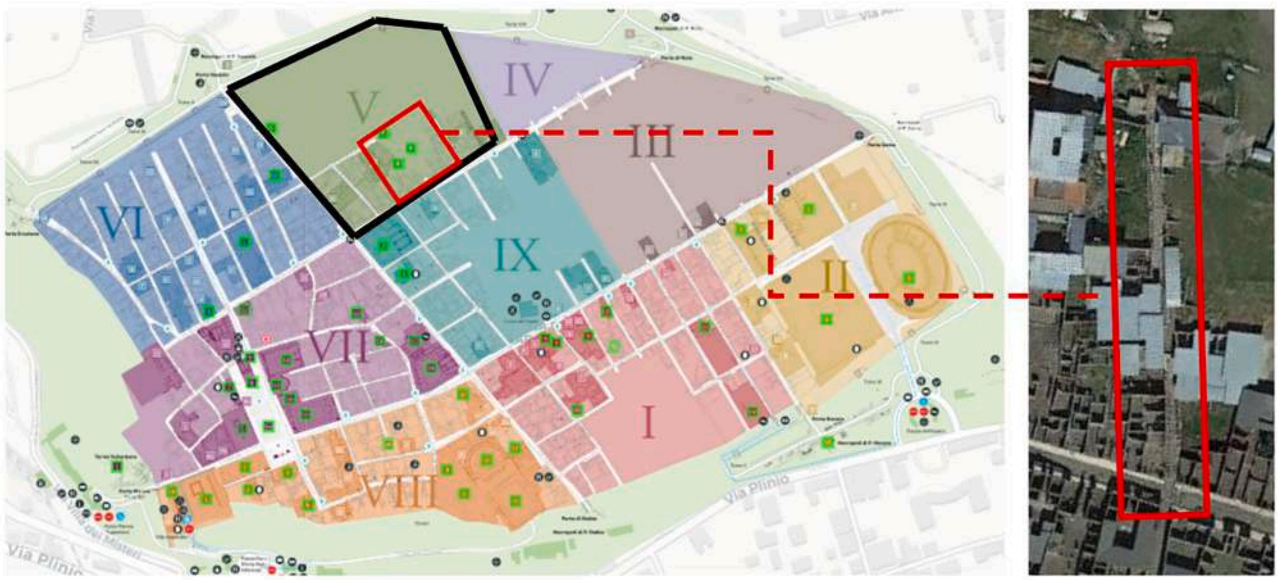


Fig. 1. Graphical Abstract of the Methodology.



-a- -b-

Fig. 2. Vicolo dei Balconi overview: (a) Pompeii map from https://pompeiisites.org/pompei-map/; (b) Aerial view from Google maps.

2019): the archaeological findings have yielded many artefacts: amphorae, a thermopolium with valuable frescoes (even the remains of a man crushed by a large stone block (Archaeology News Network, 2018), some houses where daily life objects, furniture and jewels were found, as *Casa del Giardino* (Garden House) and *Casa di Giove* (Jupiter House) (Ferro et al., 2020). The alley connects *Vicolo delle Nozze d'Argento* (Silver Wedding Alley) with *Via di Nola* (Nola's Street), the important *decumanus superior*.

The most interesting aspect for our study, is that at the time of the eruption, the road was undergoing work, presumably resurfacing. In fact, the alley is paved along the northern half only, where the flagstones are laid and preserved in good condition; the southern half, on the other hand, presents the uncovered subgrade: this is of amazing interest because it allows a direct observation of the characteristics of this otherwise inaccessible portion of the road structure. Fig. 3 displays a rather specific overview of the mentioned section, with a North-South direction point of view and a zoom on the step between un-paved and paved road stretch.

From the evidence of recent excavations in *Regio V*, the hypothesis is that the repaving of *Vicolo dei Balconi* was part of a broader urban planning project that included the repaving of a series of parallel streets tributary to *Via Nolae* (*Vicolo di Lucrezio Frontone*, *Vicolo dei Gladiatori* and probably others yet to be discovered).

Results

Findings in surveying phase

In the first phase of the work, a geometric survey was carried out using a Leica RTC 360 Terrestrial Laser Scanner model, which made it possible to obtain "raw" data, i.e., a point cloud for each scan performed. It is needed to undertake a lot of scans to avoid the phenomenon of "beam occlusion", i.e., the formation of shadow zones due to obstacles between the detection instrument and the object detected. A total of 61 scans were carried out; some of these were eventually eliminated because they were not considered useful. On the contrary, they made the resulting file heavier, causing an excessive slowing down of the operating machine.

The laser scanner survey and the subsequent modelling of the resulting point cloud (an operation that will be described later), made it possible to define the geometric layout of the road as far as can be observed on the surface, i.e., the width of the section and its variation

-a- -b-

Fig. 3. Detail of the road section where paving work stopped at the moment of eruption: (a) Photo overviewing the alley, direction N—S; (b) Detail: photo of the section between the paved and the un-paved stretch of the alley.

along the alignment, the planimetric and altimetric course. With regard to the reconstruction of the cross-section layout, several observations made on site were taken into account. First of all, along the entire length of the route, the curbs of the pavement adjacent to the road were studied. The curbs are aligned consistently: in the paved stretch they protrude from the line of footfall by about 20 cm on average, in the unpaved section by more than 40 cm. This implies that the thickness of the flagstones laid, considering only the emerging part, is around 20 cm, as can also be directly observed on site and as shown in Fig. 3.

The road stretch to the south, the one that is not paved, features a more or less compact surface of material that at first glance appears to be unbound, covered by some debris driven by the rainwater. Since this surface constitutes the bottom of the archaeological excavation, it also constitutes the main limit to the degree of knowledge of the constitution of the lower layers of the road structure. That's why, for deeper understanding, two dynamic procedures were performed, namely a penetrometer test (Dynamic Cone Penetrometer – DCP (Paige-Green and Du Plessis, 2009)) and a deflectometric test (Light Weight Deflectometer – LWD (Elhakim et al., 2014). Both tests are modern sophisticated procedures based on the soil response to mechanical inputs, probably never applied to archaeological roads. These procedures were intended to deepen the knowledge about the subgrade structure, whether it is composed of one or more layers, to assess the materials used, their characteristics, the composition and compaction degree, the possible use of hydraulic binders for the improvement of soils and granular mixtures.

The DCP consists of a steel rod ending in a conical tip. At the top of the rod, an 8 kg hammer is dropped and travels 575 mm before stopping. The recoil is reflected in the remaining meter of the rod at the end of which is the tip. The rod is flanked by a vertical scale by means of which the sinkage of the tip into the ground is measured. The result of the test is the DCPI (DCP Index), i.e., the sinkage of the tip, expressed in mm, per blow.

By analysing the DCPI obtained, it was possible to assume the presence of 5 successive layers of different consistencies. In fact, each layer is characterized by consecutive DCPIs that are very similar. Table 1 summarizes the evidence of the test in one of the three locations where the test was carried out: 5 layers for which the average DCPIs, and thicknesses, are reported. Note that L4 thickness is due to the bottom limit of analysis, that is 500 mm.

The LWD test consists of measuring the deformation at the centre of a plate, which is impacted by a mass dropped from a certain height. In this case, a Dynatest 3031 portable LWD was used: a mass of 10 kg was dropped from a height of 84 cm to generate a stress of 100 kPa on a circular plate with a diameter of 300 mm. In addition, by means of two other geophones, the deformation undergone by the soil was also measured at 350 and 550 mm from the centre of the plate in axis with the falling weight rod.

From the combination of the deformations measured with the LWD and the layer thicknesses estimated with the DCP, it was possible to formulate a hypothesis about the composition of the stratigraphy of the road structure.

DCPI can be related to CBR by means of the ASTM D6951/D6951M-18 standard. CBR, acronym standing for California Bearing Ratio, is defined by the ASTM D1883-16 as the percentage ratio between the material resistance or the unite load (pressure) on the piston for 2.54 mm or 5.08 mm of penetration and the standard unit load for well graded crushed stone (that for 2.54 mm is 6.9 MPa and for 5.08 mm is 10.3 MPa). Then, the CBR test is a simple strength test that compares the bearing capacity of a material with that of a well-graded crushed stone (thus, higher the quality of the tested material, higher the CBR, that will always be minor than 100). Through LWD was possible to calculate the surface modulus using the Boussinesque elastic half-space theory. Considering that CBR and stiffness modulus are relatable (Powell et al, 1984), using the Unified Soil Classification System (Yoder and Witczak, 1975), it was possible to estimate the material type for each layer: L_0 is rich in organic material, probably material transported by rainwater following the excavation and discovery of the road; the assumption for L_1 is that it is composed of well graded (GW) or silty sandy gravel (GM); the second layer (L_2), it is possibly uniformly gravelly sand (SW) or clayey sand (SC); with regard to L_3, it could again be well graded gravel (GW) of high consistency, not excluding the possibility that the material may have a slight bonded structure developed through hydraulic binder or through the action of heat transmitted during the eruption; the deepest layer that could be analyzed, L_4, is similar to the second, but given the instructions of the archaeological site superintendence to limit the tests to a depth of 500 mm, it was not possible to carry out further tests, which are probably necessary to confirm the hypothesis.

Regarding the last two layers, L_3 being again a very hard and compact layer, while the subsequent L_4 has similar characteristics to L_2, it was thought that the combination of these two layers could be, in truth, an old pavement covered by the new one.

To analyse the upper surface of the stone pavement, another non-invasive sophisticated engineering instrumentation was used. In fact, a skid resistance tester, also known as the British Pendulum Tester (BPT) (Hall et al., 2009), made it possible to determine the qualities of the materials in terms of resistant friction.

The BTP test consists of letting a mechanical arm swing in a pendulum motion with a rubber pad at the end of the arm to rub the road surface to be tested. The test measures the loss of energy experienced by the pendulum, i.e., the difference in height reached by the pendulum as it rises after free fall. The mean of five consecutive swings describes this loss of energy that is labelled as PTV (Pendulum Test Value). The tool used is a TRL (55) rubber slider (76 mm × 25.4 mm × 6.35 mm), which is intended for measuring the slip resistance of a surface for natural stone according to EN 13036-4 and EN 14231. The instrument was used on different elements of the pavement, oriented according to the road axis. The flagstones on which the test was carried out were previously cleaned and moistened (as was the slider). The test was carried out on 12 stones, 6 in the newly paved road stretch of *Vicolo dei Balconi* and 6 in the road stretch near the intersection with *Vicolo delle Nozze d'Argento*. In conclusion, both the tests carried out on the old pavement and the tests carried out on the newly laid flagstones gave very similar results, with PTV averaging 47. This is justified by the nature of the material making up the flagstones, namely Vesuvius lava stone, a mineralogical igneous and holocrystalline stone (Langella et al., 2009; Piovesan et al., 2019).

Table 1
Number of layers and thicknesses assumed following DCP test results for location-test 1.

Layers [ID]	DCPI [mm/blow]	Thickness [mm]
L_0	41,97	87
L_1	3,02	146
L_2	16,68	145
L_3	2,13	46
L_4	9,52	76

Point cloud managing and editing

The following phase focused on managing the visual data acquired (Fig. 4): the various scans were recorded together, to obtain a single file containing all the point clouds, aligned according to a single reference system, by means of the Leica software Cyclone. The aligned and oriented point clouds were geo-referenced with the aid of a text file containing the coordinates of certain reference points, known as Ground Control Points. The geographical coordinate system used as reference is the Italy East Fuse Gauss-Boaga system, based on the European Datum 1950.

Next phase consisted in a segmentation process, i.e., a selection of points was made, retaining those belonging to areas of interest for the study and eliminating the others. This operation removes unwanted objects, such as human figures, vegetation, and roadside encumbrances.

Fig. 4. Point cloud representation in Leica Cyclone of the step between the un-paved and the paved road stretch.

To do so, Autodesk software Recap Pro was used; in particular, view and selection tools were leveraged (Fig. 5).

Digital model process

With a ready-to-use point cloud, it was possible to start the modelling. The point cloud was imported into Infraworks (Fig. 6.a), where a Digital Terrain Model (Fig. 6.b), i.e., a mesh on the trace of the points contained in the cloud, was created. The mesh is much lighter than the original point cloud, which makes it a much more manageable object to allow subsequent operations. In fact, 3D polylines were drawn with the vertices belonging to the mesh itself (Fig. 6.c). In this way, these 3D polylines represent the road axis (in orange in Fig. 6.d) and road edges (in purple in Fig. 6.d) and their vertices retain the spatial information contained in the mesh, i.e., in the DTM, and previously in the point cloud.

In order to achieve greater precision and to reduce possible inconsistencies, a section-by-section check of the course of the axes was

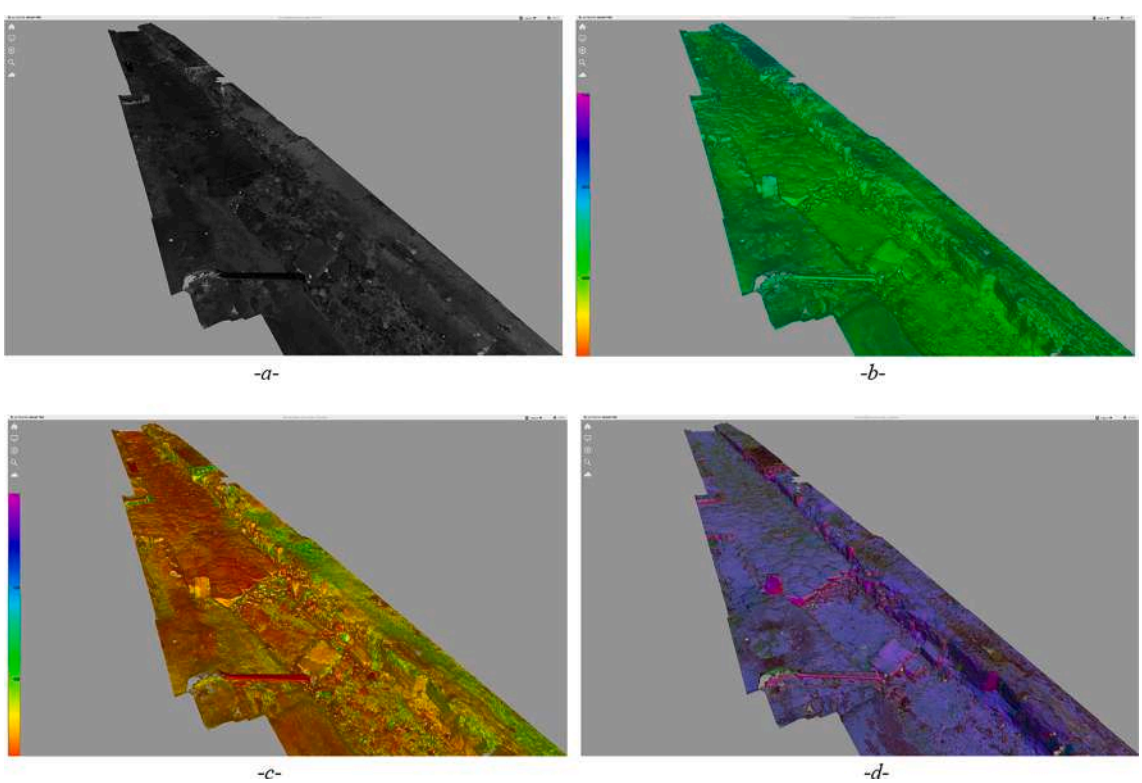


Fig. 5. Segmented Point Cloud visualization in Autodesk Recap Pro: (a) Grey scale; (b) Elevation; (c) Intensity; (d) Normal.

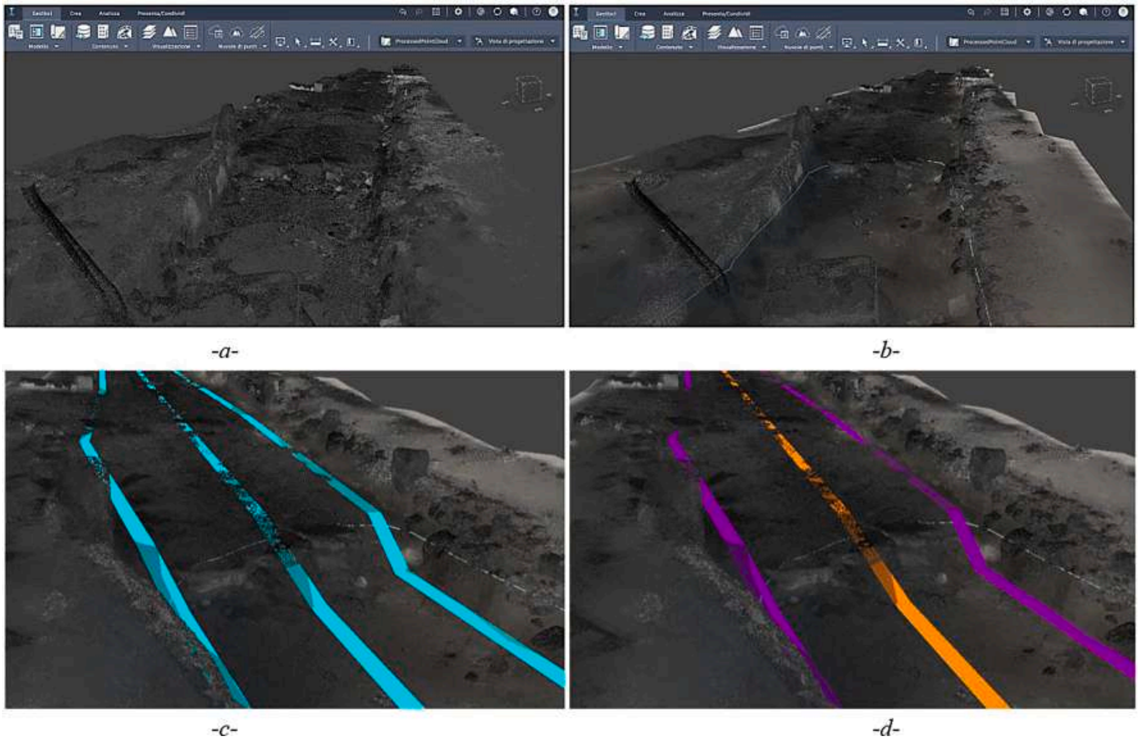


Fig. 6. Working in Infraworks: (a) The imported Point Cloud; (b) The mesh surface (DTM) overlaps the Point Cloud; (c) Horizontal Feature lines have been drawn manually; (d) Feature lines get different colours depending on the type: Axis, Edge.

also undertaken (Fig. 7).

When satisfied with the result obtained, the polylines were exported in Shapefile format so that they could then be imported into Civil 3D as vector elements. Here they were transformed into Feature Lines, essential for the development of the road corridor model. Two types of feature lines were created: Axis (for the road axis) and Edges (for the left and right edges).

Civil 3D allows the creation of a road corridor, surfaces, and solids (also for the purpose of calculating backfill volumes, determining watershed and water flow directions, etc.), from the extrusion of a cross-section along an axis. The axis can be defined from the correlation of 2D axes i.e., alignment and profile, and a surface, usually that of the ground. In fact, the third spatial dimension of the road axis is obtained by coordinating these three elements. Otherwise, the software allows for the use of any Feature Line as a 3D road axis. This paper has exploited this possibility, directly using the 3D polylines, obtained as explained above, and transformed into Feature Lines.

At the same time, the cross-section must be defined for the construction of the corridor. Due to the special nature of this case, it was necessary to use Subassembly Composer, Civil 3D add-on, to create a

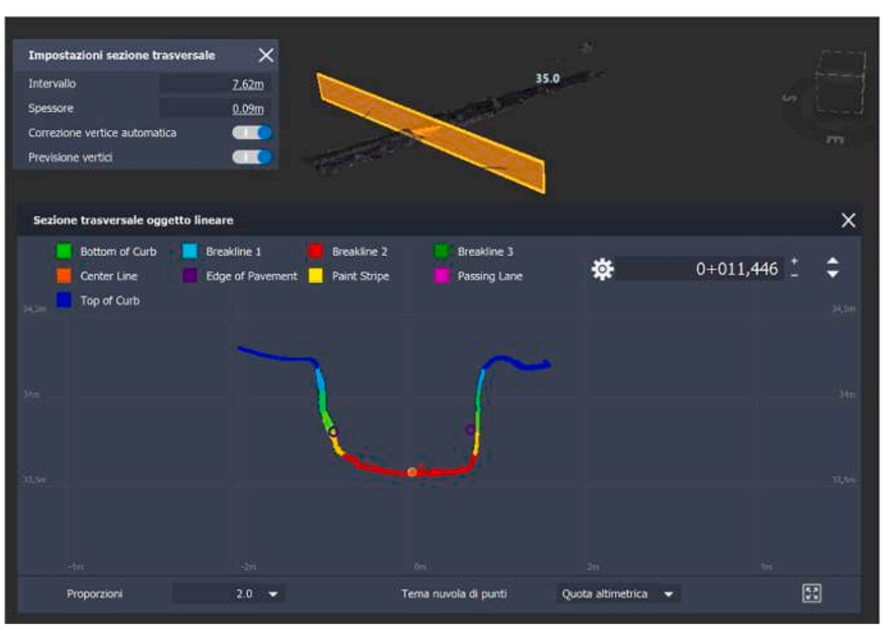


Fig. 7. Infraworks operative tool for Horizontal Feature Lines check.

customized cross-section, i.e., one corresponding with the observations and measurements made on site.

According to the surveys carried out on site using non-invasive technological instruments, it was possible to determine the stratigraphy of the road under study. The flagstones are about 20 cm thick (as can also be seen in the photographic evidence – Fig. 3.a), not including the wedge-shaped part embedded in the subgrade. The subgrade is composed of 5 layers: L_0 is mostly made of organic terrain and 87 mm thick; L_1 is 146 mm thick and made of well graded or silty sandy gravel; L_2 is 145 mm thick and made of uniformly gravelly sand or clayey sand; L_3 is 46 mm thick and made of well graded gravel of high consistency (not excluding the presence of hydraulic binder); L_4, similar to L_2, is made of uniformly gravelly sand, but its thickness of 76 mm is limited to the maximum testing depth imposed by the archaeological site superintendence.

In view of the evidence, two types of cross-sections were created in Subassembly composer, one for the paved (Fig. 8.a) and one for the unpaved (Fig. 8.b) part of the road, with the difference, therefore, that one will be composed only of the subgrade while the other will also have the presence of flagstones. The subgrade was conceived in this way: layer L0 was ignored, as it was almost certainly not foreseen by the Roman builders, but formed after the archaeological excavation operations; L1 was increased from 146 mm to 150 mm, as was L2, from 145 to 150 mm; L3 and L4 were joined, considering that they probably formed a single system being an old pavement covered by the new one, for a total thickness of 150 mm.

While it is true that the thicknesses are well defined, the cross-sectional pattern is anything but regular. In fact, we frequently find the street is frequently slightly narrowed or widened, and the sidewalk is higher or lower depending on the presence of private dwellings or commercial premises and their accesses extending onto the road. To take account of this irregularity, two "target" parameters were defined in the design of the cross-section: one "horizontal" and another "vertical". This makes it possible, when creating the corridor in Civil 3D, to select feature lines as targets for the extrusion extension. The horizontal target determines the greater or lesser width of the section, while the vertical target allows agreement with the elevation trend.

The section can be further parameterized by defining various parameters, either string-type for entering textual information, double-type for numerical information (parameters that directly modify the geometry) and grade-type for influencing the cross slope.

Once the cross-section has been properly designed, it is imported into Civil 3D and linked with the feature lines previously obtained. So, the corridor is created by extruding the cross-section through the main axis and using the other two as target feature lines.

At this point, the model is almost complete. External surfaces were added taking care to resolve some minor extrusion errors manually. Next, the solids corresponding to the corridor were created and extracted as independent objects. The model obtained at the end of the whole procedure is a solid parametric object viewable in its topographic context. The maps are made available in Civil 3D through the Bing search engine. Fig. 9.a shows the effect of overlaying the solid parametric model (when selected, it is underlined in blue colour) with the Bing map and the geometric model of the point cloud (in the Figure it overlaps the surrounding premises).

The last operation in Civil 3D involved manually creating Property Sets to associate with the parametric objects created, i.e., containers of properties, which are initially empty, but then take the form of more or less long and elaborate lists of information. Property sets are a tool that enables the information model to be explored, i.e., by clicking the parametric object, its properties can be explored, just as they were previously customized. The output of this process is illustrated in Fig. 10: the property sets contain the results obtained from the tests described above and summarize the considerations made, which is why they were divided according to the locations where the tests were carried out.

In the following step, the potential of Dynamo, an extension of Civil 3D, was explored. It allows the user to create scripts in VPLE (Visual Programming Language Environment). VPLE coding consists of the representation of the code in graphical form. The graph is composed of nodes and arcs. The nodes may constitute simple single instructions, or multiple instructions to the point of becoming actual functions. Arcs connect nodes in cause-effect, input–output relationships. Dynamo is an interface between the script and the main BIM-tool, Civil 3D. It allows

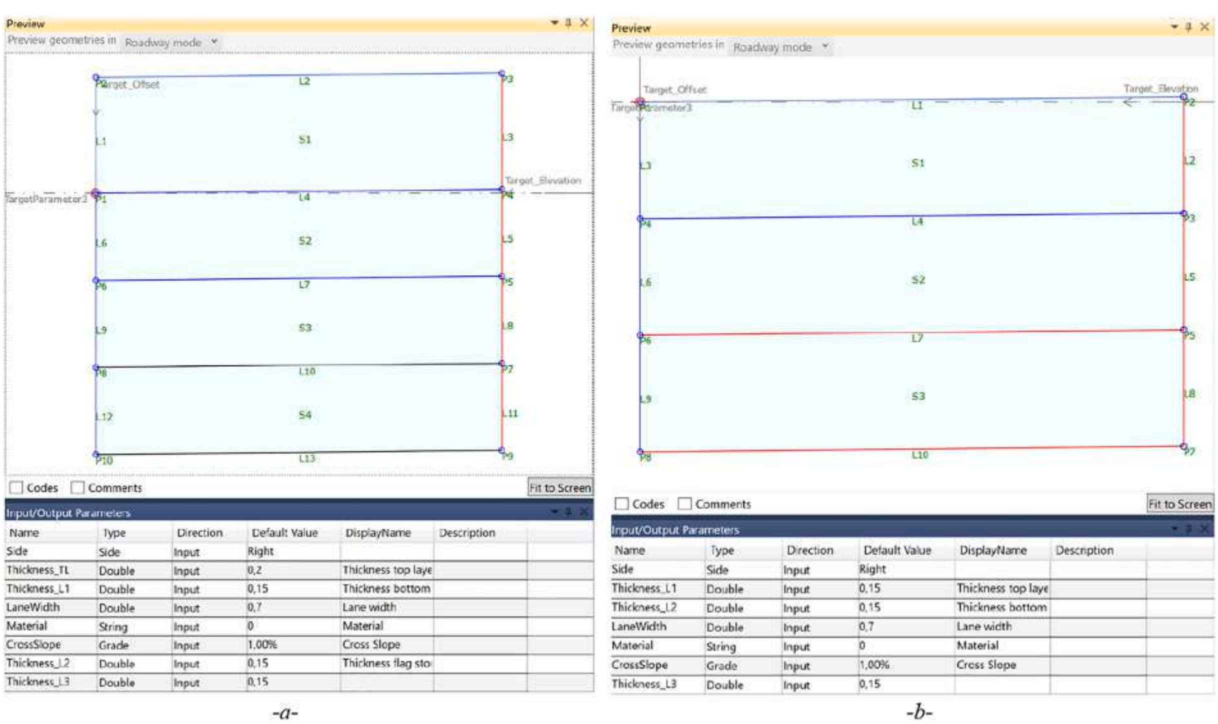


Fig. 8. Assemblies overview in Subassembly composer with some parameters: (a) Paved stretch cross-section; (b) Unpaved stretch cross section.

Fig. 9. Model view: selection of the parametric object is edged in blue colour; the southern part of the alley is represented by the point cloud; the topographic background is made available from BING maps.

both to build parametric geometries from scratch, and to automate operations that could be performed in Civil 3D manually but with greater expenditure of time.

In Dynamo a script has been developed to identify the section of the corridor in which the cross-section changes, that is the section in which it passes from non-paved road to paved road, and to characterize the corridor itself. Indeed, through a customized Python script, the corridor is characterized with two different colour (Fig. 11.a). The correct functioning of the python script is subordinated to the correct writing of the properties inside the property sets associated with the parametric model. Indeed, the script in Dynamo extracts the various associated property sets from the parametric object, that is the previously extracted solid from the corridor in Civil 3D: from the total list of all the properties, the script gives the instruction to extract the property named "Paved" contained in the property set named "Paved_YorN". This property can assume only two values: "yes" or "no". Clearly, it is to the discretion of the user to give the value "yes" to the property in question when it is contained in the property set associated with the paved part of the road, and the value "no" when unpaved.

The Python script, shown in Fig. 11.b, receives the input "yes" or "no" relative to the property mentioned previously; defines three variables, R, G, B; correlates different values to them according to the input; finally, it exports these results in a list. The variables R, G, B are the Red-Green-Blue components used to define a color in Civil 3D. Once this color has been defined, it is associated with the object selected at the beginning of the script. This is an example of a highly intuitive application of a mixed system of visual and textual programming, which makes Dynamo quite a competitive tool. This script is applied identically to all parametric objects in the model and the graphical result is shown in Fig. 12.

Discussion

A BIM model of a stretch of stone paved road located in the Archaeological Site of Pompeii in Italy was created. The first phase of the work was to carry out both the survey of the visible geometry, using a Terrestrial Laser Scanner, and to re-envision the geometry of the non-visible structure, i.e., the structure of the road, in an indirect way. Indeed, the load-bearing capacity was used to derive the extent of the materials used for the layers of the road structure and to derive the layer's thickness. Thus, the focus on these parameters was crucial for the reconstruction of the geometric scheme of the road cross-section, which is fundamental information to enable the subsequent modeling in the BIM environment. The model was created once all the necessary geometric information had been obtained and was subsequently enriched with information on the surface characteristics. On the other hand, an algorithm was also developed to identify the road section where the road changes from paved into unpaved.

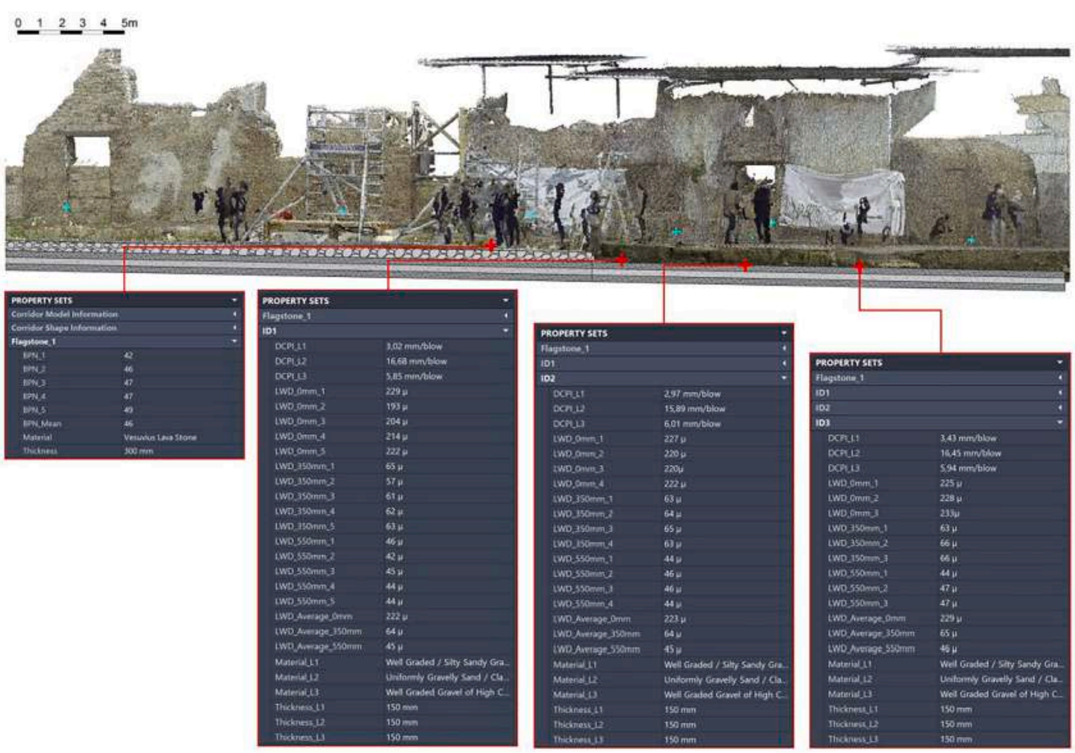
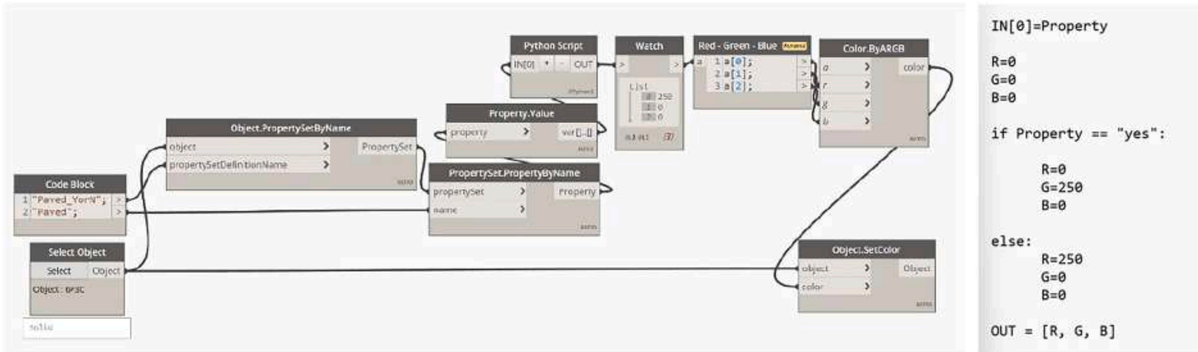
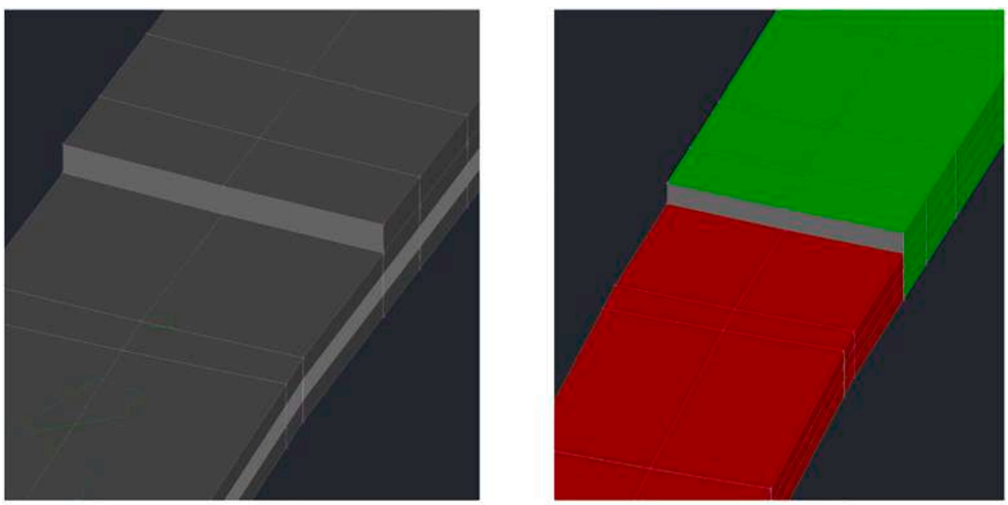


Fig. 10. Juxtaposition of point cloud profile section, parametric model schematic profile section, and Property sets.



-a- -b-

Fig. 11. Dynamo Script for setting different colors to different sections of the corridor: (a) Graph; (b) Python script.



-a- -b-

Fig. 12. Model update in Civil 3D after the Dynamo Script run: transition from paved to unpaved road parts is underlined.

The application of the described methodology to the case study presented above led to the informative digital model of an archaeological road, and therefore an Archaeo-BIM, which can be used as a tool that facilitates the management of the modelled artefact. Indeed, the model is designed to support maintenance and management operations since it contains crucial information, from geometric to semantic definitions. Moreover, VPLE methodology has also been exploited for the conceptual characterization of the 3D model, depending on the database content, so that data have a visual meaning as well.

Further considerations can be made:

(i) The aesthetic aspect of the model was not considered of primary importance for this research. On the contrary, the focus was on the extent and quality of the information content. The model, in this way, is to be considered as a browsable archive.

(ii) It is important to emphasize that data from experimental surveys and tests - usually carried out for modern road pavements - have been applied to an archaeological context probably for the first time. These data are a valuable contribution to the knowledge we have regarding this asset.

(iii) Existing and well-proven informatics tools have been exploited for an original application. Although, as discussed in the introduction of the present paper, there are many application cases of models made on buildings of an archaeological nature, hardly any of them focuses on the study of roads. The cause of this is also to be found in the constitutive characteristic of the archaeological artifacts themselves. In fact, it is not possible to carry out invasive engineering investigations, and it is not possible to alter in any way the appearance or the internal structure of any artifact. Thus, if on the one hand, the study of the artifact to be modelled it is essential for the definition of the information apparatus that the model is consistent with the very idea of reverse engineering, on the other hand, it is limited by the very nature of the archaeological site.

(iv) The methodology described has certain limitations. Firstly, the lack of suitable working tools: a latest generation TLS, a computer with excellent performance, and the authoring software package from Autodesk and Leica. In addition, the selected software has not been programmed for the creation of Archaeo-BIM models, and therefore lack a certain essential tool for a good aesthetic rendering.

Conclusion

Although the results of this paper are promising, more must be done in the field to improve an overall generally valid methodology.

The digitization of works in the AEC field is a process which is currently in full development, and BIM affects all stages of a work's life while digitization can intervene at any time with its effects. For example, the model can be built for a new design or for maintenance operations. When an as-built digital model of a work is available, it is much easier to plan the maintenance. In the case of archaeological works, conservation is the key word. Therefore, digital models of information should be created with the aim of conservation and protection of original artifacts, considered unique, and maybe for online communication.

The work presented set out to explore the theme of road BIM applied to archaeology and increase the possibilities of future applications with the proposal of a methodology of general validity. This aim has been pursued and partially achieved. The actual use of this kind of model should be further examined by the body managing the archaeological site since there are many applications imaginable, related to the management and conservation of archaeological heritage.

A further research direction that should be carefully explored to give archaeological sites managers a better developed tool, is to enlarge the scale of the application, trying also to stress the use of algorithms development to management purposes.

CRediT authorship contribution statement

S.A. Biancardo: Conceptualization, Methodology, Validation, Writing – review & editing, Supervision. **M. Intignano:** Software, Visualization, Writing – original draft. **R. Veropalumbo:** Formal analysis, Visualization. **R. Martinelli:** Data curation, Resources. **V. Calvanese:** Project administration, Resources. **F. Autelitano:** Formal analysis, Investigation. **E. Garilli:** Formal analysis, Investigation. **F. Giuliani:** Conceptualization, Validation, Funding acquisition. **G. Dell'Acqua:** Methodology, Validation, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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