Visualizing cityscapes of Classical antiquity : from early modern reconstruction drawings to digital 3D models

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Title: Visualizing cityscapes of Classical antiquity: from early modern reconstruction drawings to digital 3D models
Date: 2018-05-16

3. Three-dimensional visualizations in archaeology: An additional tool in the archaeologist's toolbox

'Fundamentally a model is understood from the first [i.e. theory] as a simplification for purposes of making sense of complex data-sets, to be set against alternative models for the goodness of it. This is also a procedure to be constantly renewed as new data and new models appear within the discipline.' (Bintliff 2015, 33, emphasis of the author)

3.1 Introduction

As shown in the previous chapter, drawings of archaeological remains have been used since the 15th century; it is therefore undeniable that these kinds of visual representations are deeply connected with archaeological studies. Outlines of archaeological layers and pottery, plans and sections of buildings were sketched down in order to keep a memory of these remains, to allow comparison and the creation of typologies. Illustrations displaying hypothetical reconstructions of archaeological structures that were created out of a fascination for their distant past have also been employed to facilitate the understanding of the context that is being studied and to get a more vivid impression of what a site or structure might have looked like. These representation modes continue to be used nowadays both to keep a record of all information and hypotheses that arose in the field, and in the post processing phase, and also to communicate the results to the public in a way that is comprehensible also for non-specialists.

The obvious problem with this traditional way of documentation is the lack of the possibility to record the 'z' value, the depth of the recorded entity, being it an artefact, a stratigraphic unit or a building. In order to create a complete documentation, several 2D drawings are therefore needed, representing the archaeological record from different perspectives. Although archaeologists have become familiar with this way of representing archaeological evidence using sections and prospects to account for the three dimensionality of the recorded object, it is undeniable that this process is not ideal. The result is in fact a segmentation of a continuous reality into separate entities, which not only requires a cognitive and interpretative effort to reconciliate the different parts, but also limits the amount of recorded information, and constraints the possibilities of further manipulation, exploration and analysis.

It is therefore not surprising that archaeologists have soon become interested in 3D digital recording and modelling techniques. A 3D model can be defined as a mathematical representation of a concrete or abstract entity in which its features are displayed according to the geometry of their real volume. This means that the modelled entity is fully described from any point of view and can be seen from different perspectives with the same level of detail. To create 3D models, dedicated programs are needed that allow the representation of an object as a set of points that are connected to each other by geometric shapes (triangles or polygons). Once the 3D model is created, it can still be rendered as a 2D image, which allows a final photorealistic result, or used in a computer simulation for a real time interaction.

Besides the creation of a complete documentation encompassing all the three dimensions, other advantages of 3D digital models can be highlighted. First of all, many different types of information can be summarised within a single model with a multi-scale approach. A 3D model, in fact, allows us to recreate the complete picture of a landscape from a single unit to the entire territory. Secondly, a 3D model permits further manipulation of data that are not static as notes, sketches drawn on paper or plaster models, but that can be more easily updated and transformed. Thirdly, their digital nature allows an easier circulation within the scientific community, thereby stimulating a more dynamic debate on interpretations and methodologies. 3D models are also important tools of interpretation because the addition of volumetric characteristics allows a deeper understanding of the recorded entity. Moreover, 3D representations are an effective means of communication, since they are appreciated by the public of non-specialists as comprehensible and immediate visions from an ancient past.

During the 1980s, examples of publications concerning archaeological 3D models were appearing, still sporadically, especially in technical journals. One of the first articles concerning a 3D archaeological reconstruction was written by Smith in 1985 and presented the 3D model of a Roman bath.[229] The first researchers that tried to develop complex 3D models of archaeological remains were however faced with many technical limitations. A telling example is the paper presented at the Computer Applications and Quantitative Methods in Archaeology (CAA) conference in 1991 that illustrated a guided-tour through the Sanctuary of Demeter at Eleusis.[230] Since each of the four processors that were used for the project had only between 8 and 32 MB of memory, the authors decided to model only what was visible to the viewer and represented the model with 'as few objects as possible'.[231] This solution is comparable to Gismondi's decision to add details only to the parts of his plaster model of Rome that could be seen by visitors. To save time and costs, only 15% of the Gismondi's model was in fact characterised with doors, windows and other architectural features, while the rest was simply white plastered.[232]

Not only technical problems burdened early archaeological applications of 3D visualizations. A more challenging and long lasting problem was related to the dominant role of technology to the detriment of the actual archaeological content. As Ryan wrote in 1996, many early virtual reality projects were in fact undertaken as 'vehicles for demonstrating advanced graphics techniques with any archaeological considerations playing a less important role'.[233] A telling example is the reconstruction of virtual Pompeii, made by the Simlab of Carnegie Mellon University (Pittsburgh) and shown at De Young Museum in San Francisco in 1995. As Frischer *et al.* wrote, 'Despite the project's financial support by the Archaeological Institute of America, no professional Pompeianists are known to have been consulted when the project was in its inception, nor to have had any major input on the final product (...) [They] were not expected to do anything but admire the results'.[234] As will be discussed later, this is a recurrent problem in 3D archaeology and Ryan's call for archaeologists to 'communicate archaeological and historical information to their colleagues and to the public, not to demonstrate their skills in the latest computer graphics techniques'[235] can be considered still applicable nowadays.

Another problematic aspect of 3D digital visualisations in archaeology was the fact that they were perceived as more truthful than traditional reconstruction drawings, although both are used to suggest reconstruction hypotheses and both imply a process of interpretation by the draftsman/3D modeller.[236] A change in the communication medium alone (from paper to computer-aided

229 Smith 1985, 7-9.
230 Cornforth *et. al.* 1992.
231 Cornforth *et. al.* 1992, 220.
232 This realization hampered Frischer's initial plan to run a miniature robotic camera through Gismondi's model to create a virtual tour, see B. Frischer, 'Beyond Illustration: New Dimensions of 3D Modeling of Cultural Heritage Sites and Monuments', Keynote address to CNI Plenary, 15 Dec., 2009, available at https://www.cni.org/wp-content/uploads/2011/06/cni_beyond_frischer.pdf (last accessed Sept. 2016).
233 Ryan 1996, 107.
234 Frischer *et al.* 2002, 7-18.
235 Frischer *et al.* 2002, 7-18.
236 Daniels-Dwyer 2004, 261.

drawing) created a shift in the perceived truthfulness of the representation, which was increased by the degree of immersion and realism that 3D visualisations allow the user to experience. As Favro pointed out, 'the use of computers imparts an imprimatur of scientific validity that must be constantly challenged as any reconstruction is only as good as the data and methods used'.[237] Niccolucci *et al.* paralleled this situation to the introduction of Database Management Systems in archaeology, when it seemed that 'after they have been recorded into a database, archaeological records lose any element of uncertainty and subjectivity and become as trustworthy as the computer itself'.[238]

This problem is typical of any kind of data stored in, and processed by a computer, and lies in the difficulty of dealing with data that are fragmentary, uncertain and subjected to the individual's interpretation. However, it becomes even more visible in the case of reconstructions of archaeological evidence. When documenting finds and architectural pieces, archaeologists usually use dashed lines or a lower level of detail to integrate the missing parts when necessary (see Figure 3.1). For digital 3D reconstructions, researchers have not agreed on a standardized way to visualize the reconstructed parts, although several different methods have been suggested to deal with this aspect.[239] Moreover, early 3D reconstructions were not supplied with additional information on the sources that were used as comparison, which makes it difficult to distinguish the archaeologically documented from the integrated elements. The 3D model appears therefore as a 'closed box', or a monolithic block that leaves the viewer little possibility both to assess the reliability of the reconstruction, and also to re-use the work for different purposes.

Since the mid-1990s, scholars expressed concerns about the misuse and deceptive power of 3D reconstructions. Taking on board these concerns, a fruitful discussion has started from the early 2000s aiming at developing standard methods for the creation and presentation of 3D visualizations of archaeological evidence. As will be discussed in detail later on in this chapter, this debate has converged in issuing guidelines such as the London Charter for the computer-based visualisation of cultural heritage,[240] and the Seville principles for computer-based visualisations in archaeology.[241] These efforts have the merit to have raised the awareness of problems that have afflicted 3D reconstructions in archaeology since its beginning. The sign that this problem is far from exhausted, however, is that a practical implementation of the general guidelines offered by the above mentioned documents is still missing. No standard workflow has been developed about how to deal with and how to present the sources that have been used for the reconstruction and how to account for the modelling choices employed in the process, so that practitioners in this field have come up with *ad hoc* solutions tailored to the needs of their current projects.

When London-charter compliant 3D visualizations are created, it is still rare that the results of these efforts are made publicly available as an interactive experience that could engage the public and foster discussion among the scientific community on the proposed reconstruction hypotheses. The 3D visualizations that are created for museum settings are often not available anymore when the exhibition closes, and those that are made for research purposes remain locked in the creator's computer and are usually published as 2D renderings. This means that all the human and financial resources that have been invested in the project have little impact (or at least not as much as they could have) on society and on the actual progression of hypothesis-generating archaeological inquiry.

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237 Favro 2013.
238 Niccolucci *et al.* 2001, 109.
239 See below, § 3.4.1.
240 http://www.londoncharter.org/ (last accessed Sept. 2016).
241 The Seville principles is available at http://smartheritage.com/seville-principles/seville-principles (last accessed Sept. 2016).

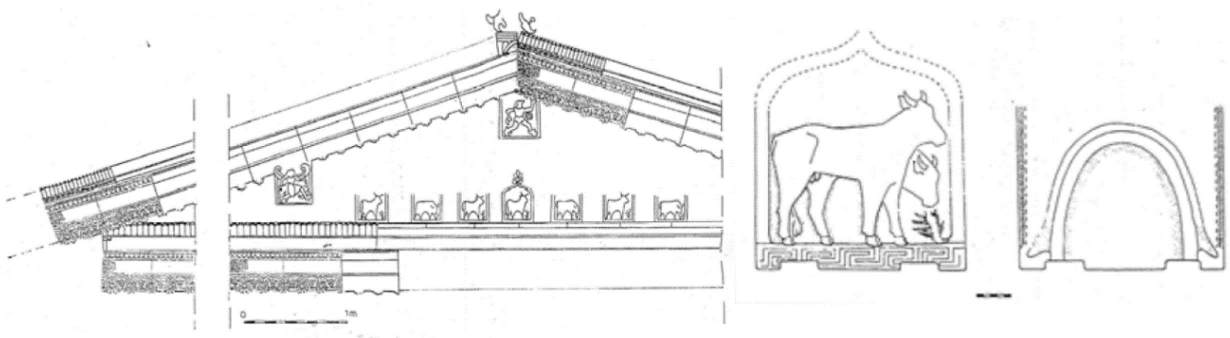

Figure 3.1 Example of reconstructive drawings of elements of the Mater Matuta's temple (Satricum) by P. Lulof (after Ratto 2009).

Technical constraints are usually at the basis of a reluctance of sharing the 3D environment. As for any tool that is made publicly available, one has to ensure the full functionality of every aspect of the navigation in the virtual environment (especially when a free navigation of the user is desired),[242] the compatibility with any computer system, and the development or availability of the right platform to share it. This requires extra expertise, time and costs that are often not within the research team or the available budget.[243] The journal *Digital Applications in Archaeology and Cultural Heritage* was launched in 2014 to promote the online publication and peer-reviewing of 3D models.[244] The high open access fees (3,000 USD) and the technical limitations for the publication of interactive digital models, however, represented a substantial obstacle for researchers in this field. For these reasons, the founding editor of the journal, Bernard Frischer, has recently left the editorial board and launched *Studies in Digital Heritage*, an open access journal with no article processing charge, which uses WebGL technology to publish 3D models online.[245]

In a field that has been since its beginning more practice-driven than theory-laden, the impression is that archaeologists have adopted these visualization techniques as fancier and more sophisticated replacements of traditional drawing tools, instead of exploring the new possibilities that they offer.[246] In recent years, however, a growing number of archaeologists with technical skills in this field is contributing to a methodological discussion on good practises, and are using 3D visualizations with a more mature view both on their limitations and on their analytical potential. In the next section I will present a brief overview of the main modelling techniques that are used to make 3D reconstructions of structures that are now (partially) lost. Next, I will deal with the topic of source documentation and the solutions that have been implemented for the creation of 3D visualizations as intellectually transparent knowledge providers. The following section focuses on the scientific value of 3D reconstructions, by exploring their still underestimated role as analytical instruments in their own right and not only as presentation aids and educational tools. Through a discussion of published case studies, I will argue that 3D reconstructions enable us to generate new insights and hypotheses on ancient construction techniques, and on the use and the social implications of architecturally defined spaces. The chapter closes with some considerations on the past, present and future of 3D visualizations in archaeology, suggesting some practical solutions for an effective use of 3D modelling techniques by archaeologists as both research and presentation tools.

[242] See e.g. Fleury *et al.* 2014.

[243] A successful example of such implementation is the online navigation through the 3D virtual environment of Montegrotto, Italy (by CNR-ITABC) available at http://www.aquaepatavinae.it/portale/?page_id=2174 (last accessed 30-11-2015, OSG4WEB plugin required); see also Fanini and Ferdani 2012, 107-15.

[244] http://www.journals.elsevier.com/digital-applications-in-archaeology-and-cultural-heritage (last accessed March 2017).

[245] https://scholarworks.iu.edu/journals/index.php/sdh/index (last accessed March 2017). A blog post at the bottom of the page presents the new journal and the context of its launching.

[246] Gillings 2005.

3.2 Creating computer-aided 3D models

Nowadays, there are several ways in which a computer-aided 3D model can be obtained. The main difference in approach lies between the techniques that are used to *record* archaeological finds (reality-based models) and those that are used to *reconstruct* a site that is now (partially) lost. A digital documentation of objects or still standing buildings can be obtained with so called 'remote sensing' techniques that are based on either image-based or range-based 3D data collection at distance. 3D reconstructions can be manually done with Computer-Aided Design software such as AutoCAD and computer graphics software such as the open source Blender or commercial packages such as 3D Studio Max, Maya or Cinema4D. Alternatively, as will be discussed below, procedural modelling offers a parametric approach to (semi-) automatically generate 3D geometry. These two ways of obtaining digital 3D models are not meant as being part of separate workflows but can be combined, depending on the available dataset and on the purpose of the project in order to achieve the best result. For example, 3D data of extant architectural remains that are acquired by remote sensing techniques, such as laser scanners, can be manipulated and integrated with reconstruction hypotheses by means of CAD or computer graphics software. On a more conceptual level, in both real and non-real approaches the process of obtaining the 3D digital model poses numerous challenges: during the recording of a still standing structure, uncertainties may arise related to e.g. correctly identifying *in situ* remains, or distinguishing contemporary phases from later additions, while creating a digital reconstruction implies the formulation of justified hypotheses about a reality that no longer exists. In this respect, the sources used to integrate the missing data and the thinking process that led to a specific reconstruction need to be documented, in order to offer to the viewer the possibility to assess the value of the archaeological visualization. This topic has been debated since the earliest applications of virtual reconstructions in archaeology and will be treated extensively later on in this chapter. I shall now present the main techniques used in recent years in archaeology, with a particular focus on their application to the built environment. Since the methodology that I will discuss in chapter 6 aims at the reconstruction of a lost site, and since the use of image-based and range based modelling techniques applied to heritage has been extensively treated in numerous publications,[247] in the following sections I will focus only on manual and procedural modelling approaches.

3.2.1 Manual 3D modelling

The software packages that allow the manual creation of a 3D environment can be divided into Computer-Aided Design (CAD) and Computer Graphics (CG) software. These two types of software are targeted to different purposes and users and their differences have to be considered when choosing the most appropriate software to fulfil the requirement of a project. While the roots of CAD software (e.g. Autodesk AutoCAD) lie in prototyping and drafting, CG software packages (e.g. the open source Blender and commercial suites such as 3D Studio Max, Maya and Cinema4D) have been developed with other users in mind, namely game developers and graphics artists. The main characteristics (and limitations) of these software packages reflect therefore their originally intended purposes.

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[247] Overviews on 3D recording techniques applied to cultural heritage include: Stylianidis and Remondino 2016, Remondino 2011, Remondino and Rizzi 2010. Image-based recording techniques such as photogrammetry and Structure from Motion are extensively used in archaeology. Recent applications for heritage purposes to create a 3D digital documentation of lost or endangered sites include: the digital reconstruction of the big Buddha statue in the valley of Bamiyan (Afghanistan), destroyed by the Taliban in 2001 during a raid of non-Islamic iconoclasm (see Remondino and El-Hakim 2006, 309-10; Grün *et al.* 2004, 177-99); the Project Mosul (http://projectmosul.org/) initiated by Matthew Vincent, Chance Coughenour, and Marinos Ioannides and partly funded by the 'Initial Training Network for Digital Cultural Heritage: Projecting our Past to the Future' (ITN-DCH); and the 'Million Image Database' project (http://www.millionimage.org.uk/), a collaboration between the Institute of Digital Archaeology at Oxford University and UNESCO, aiming at capturing images of endangered objects and heritage sites in order to create 3D replicas (both digital and physical through 3D printing). For the application of laser scanning techniques for the recording of archaeological artefacts and structures, see e.g. Thuswaldner *et al.* 2007, 1-27; Salonia *et al.* 2006, 347-52; Blersch *et al.* 2006, 389-94; Boochs *et al.* 2006, 395-400). For urban reconstruction techniques based on imagery and LiDAR data see Musialski *et al.* 2013, 146-77.

From the 1980s, CAD software started to become more and more used in those fields in which drafting and documentation processes could benefit from digital drawings. This software improved and speeded up two dimensional drawings by offering tools that made almost obsolete the usage of pencil, ruler and compass. Moreover, it also allowed for a 3D documentation of objects that can be manipulated and rotated with ease in the virtual environment. CAD software packages guarantee a high precision in data handling, hence they are very useful when it comes to creating 2D or 3D objects starting from exact measurements. For this reason, CAD software has been widely used also in archaeological documentation where accuracy of drawings is essential.[248]

CG software packages, on the other hand, are able to produce highly realistic scenes, allow an easier modelling of organic shapes, have elaborate settings to accurately recreate the properties of the materials, allow a high control on lighting parameters, and include complex shaders, namely scripts that are attached to the 3D object and govern its rendering effects.[249] These software suites allow moreover the animation of characters by creating a skeleton that controls the mesh (a procedure called *rigging*), which can then be imported into a game engine. While their functionalities are very extensive, traditionally the control on accurate measurements has a low priority given their target market.

Often the use of a single software limits the possibilities; for this reason, a familiarity with different software packages is recommendable when dealing with a complex project, in order to construct a workflow that best exploits the characteristics of each software. In this respect, the major obstacle is related to the limitations in exchanging files between different platforms, which was either impossible for the use of proprietary formats, or risky for the possible loss of information. To this end, the CG industry has agreed on a number of platform independent formats, most notably Wavefront OBJ and DAE Collada, which can be used to exchange files across different software.[250]

Regarding the most common techniques to obtain a 3D model in different software, the most common way is to convert 2D elements into 3D entities by *extrusion*, namely the extension of a 2D surface (that has to be a closed path) perpendicularly into the third dimension. In this way, a cylinder or a tube is obtained by extruding a circle, likewise a box is generated from a square or a rectangle. The process of extrusion can also be made along a curved path, so that a variety of more complex shaped solids can be created. Extrusion was one of the most frequently used techniques in the earliest applications of 3D modelling in archaeology. One of the first examples is the digital model made by J. Eisler *et al.* of the Mortuary Temple of Raneferel at the Unfinished Pyramid at Abusir.[251] The aim of this project was to create a 3D model both of the structure of the Temple and of the terrain behind it that summarised

[248] A software that has become quite popular in recent years is Google SketchUp, originally developed by Google to allow an easy creation of 3D assets to be imported in Google Earth. SketchUp allowed in fact the addition of a geolocation to the scene and the export of the created model in kmz format to be used in Google Earth. The availability of a free version, its user friendly interface, the intuitive modelling process and the numerous plug-ins have increased the number of its users over the years. This software has however some limitations, for example in the available options for texture and material mapping, and in the allowed import and export formats in the free version, e.g. the standard CAD formats dwg and dxf among the import options; among the export options only two formats (DAE Collada and kmz) are available, while other formats such as fbx (recommended for the import into a game engine such as Unity3D) is supported only in the Pro version.

[249] An overview is given in Wittur 2013, 219-47.

[250] Both OBJ and Collada are text based formats, the main difference being that while OBJ stores only the geometry information (with an additional file with *.mtl extension needed for materials), Collada is XML based and can store also information on lighting and animation. The downside of using these formats is that being text-based they create potentially very large files. Other formats, such as the Autodesk proprietary fbx, are also supported by many software for its wide use and capabilities. Ideally, the 3D modeller should be able to know the strengths and downsides of each software in order to create a hybrid workflow that is best targeted to the project's needs. For example Blender can be used as an intermediate step to import the DAE Collada created in the free version of SketchUp in order to export fbx. Also, the plan and eventually the building shell which is drafted in AutoCAD can be exported as dxf and then imported to a CG software to create a detailed 3D model.

[251] Eisler *et al.* 1988, 109-32.

the results of the excavations that had been obtained until the end of 1984. While the 3D model of the structure was created mainly by extrusion, the creation of the terrain was based on original methods of digital terrain-modelling developed in Prague in the late 1970s and early 1980s.[252] A slightly later example of the application of extruding techniques is the 3D model of the Hoffman Limekiln at Langliffe, UK created by G. Chapman in the early 1990s.[253] The base of the kiln was formed by two polygons, one that followed the shape of the cross-section of the base and the other one that described the path taken by the outside edge of the kiln viewed in plan. The basic 3D shape was then obtained following the extrusion procedure by 'sweeping' the cross section around the path. The extrusion technique remains a fast and effective way to elaborate the 3D visualisation of an entity, and it is particularly suited to add the elevation to 2D plans of buildings. Additional 3D modelling techniques include the creation of a so-called 'shell' that describes only the surfaces and not the entire geometry of an object. These techniques, which range from the creation of polygonal meshes to Non-uniform rational Basis spline (NURBS) surfaces, are especially useful to create curves and complex geometries.

An additional step in the workflow for the creation of a 3D model is the mapping of textures and materials, which adds both colour information and details without increasing the polygon count, i.e. the complexity of the scene from a geometrical point of view. Textures can be created in a variety of ways. 2D images that are mapped on the 3D object can be created anew in a photo editor programme or by using existing pictures. An alternative approach relies on procedural textures, i.e. computer generated images that allow the creation of randomized patterns replicating realistic characteristics of materials (e.g. wood and stone veining and cracks) or the addition of noise to create more visually interesting results (e.g. stains on surfaces). Materials, instead, simulate properties and behaviours in relation to lighting conditions, such as opacity, reflectivity, and roughness. A useful technique to add detail to the model, while at the same time avoiding distortions and saving rendering time, is *texture baking*. With this technique, the properties and the behaviour of the materials, including the interaction with light sources which are assigned to the 3D model, are pre-calculated and the results are saved into a texture, which is in turn mapped onto the 3D model, thus avoiding the repetition of these calculations in real time during rendering. Techniques such as *bump* and *displacement mapping* allow the user to respectively simulate and create irregularities on the object's surface. Bump maps, in fact, do not affect the geometry of the object, but only how its surface interacts with the lighting conditions, which is useful to add realism to a texture. On the contrary, displacement maps actually modify the object's surface, which makes this technique useful for a variety of purposes such as creating realistic landscapes and waves.

3.2.2 Procedural modelling

In the case of recursive geometry that would be too tedious to be manually modelled, a procedural modelling strategy is the best suited solution. Procedural modelling allows a formal, parametric and hierarchically encoded description of the 3D geometry that is obtained by writing rule files that follow a specific syntax. Such a strategy is particularly useful for the efficient modelling of large scenes and repetitive elements that can be populated from a concise set of rules. Parametric values are used to define the characteristics of the 3D entities. These parameters can be easily modified when needed and the 3D model will update accordingly, thus making this modelling method interesting for archaeological reconstructions to display different hypotheses. In this way the user is able to speed up the modelling process, since it is easy to update the 3D visualisation simply by changing some parameters in the script. The main drawback of a procedural modelling approach is the steep learning curve, since one first needs to learn the shape grammar of the software, which makes the modelling process less intuitive than in computer graphics where one starts the modelling by directly interacting with shapes.

[252] Eisler *et al.* 1988, 110.
[253] Chapman 1992, 213-18.

Procedural modelling is particularly suited for the creation of cityscapes, where several domestic neighbourhoods need to be populated by buildings with similar characteristics and yet different from each other for a realistic result.[254] Being quite challenging from a technical point of view, the 3D modelling of cities has triggered the interest of computer scientists to create solutions that simplified and automated this process.[255] Several domains are touched by this demanding task. The game and the movie industries are especially interested in tools that allow the creation of realistic virtual cities from scratch in a reasonable amount of time. Urban planners and geo-designers, on the other hand, are concerned with the creation of a 3D GIS of modern cities where multi-scale information can be stored efficiently in a semantically meaningful, three-dimensional environment and different development scenarios can be visualized in real time to improve the decision making process and to facilitate the involvement of local communities. A general move towards the representation of spatial data in 3D is perceivable in recent years, one of the main signs being the creation of user-generated 3D buildings to insert in Google Earth. This need has inspired the development of tools that allow a (semi-)automatic extraction of information from aerial images and 3D point clouds.[256]

Several tools have been developed over the years to create 3D cities with different target users in mind. For example, ProGen, a procedural tool (not yet available) that is being developed in a collaboration between academia and a computer games studio, is aimed at the game industry.[257] A plugin for Autodesk Maya has been created to enhance the capabilities of this CG software with the procedural generation of buildings' facades.[258] Focussing more on the semantic of 3D cities is CityGML, an XML based format for the storage and exchange of 3D city models, thus enabling their sustainable maintenance and reusability.[259] Among the currently available software packages that are targeted to the creation of 3D cities, we chose to use the procedural modelling tool CityEngine (CE). Since it constitutes one of the main components of our methodology that will be discussed in chapter 6, I will dedicate the next paragraphs to describe the characteristics of this software.

CE, originally developed by Pascal Müller during his PhD at ETH Computer Vision Lab in Zurich, was commercialized in 2008 by Müller's company Procedural. The acquisition of CE by Esri, the developer of ArcGIS, in 2011 has introduced the possibility to work with real world data, thus broadening its possible domains of application. CE handles in fact GIS data, aerial images, 2D building ground plans and a 2D street network that can be either automatically generated by the software or imported directly as a shapefile or in the drawing exchangeable format (dxf). Moreover, it can export the created 3D scene as a geodatabase containing textured multipatches, the Esri format for describing 3D geometry.[260] With the acquisition of CityEngine and the partnership with CyberCity3D, a 3D modelling tool that processes real world data (stereo imagery) to generate high resolution models of buildings,[261] Esri is currently the market leader in the development of a 3D GIS of the built environment.

The procedural generation of buildings in CityEngine follows the CGA (Computer Generated Architecture) shape grammar created by Pascal Müller and Peter Wonka.[262] CE's grammar is based on the so-called

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[254] In fact, similar problems were already recognized by the makers of physical 3D model, as discussed in chapter 2 (pp. 44-5).

[255] For an overview of modelling techniques, including procedural modelling, that are currently available for urban environments in several domains (e.g. entertainment industry, urban planning and emergency management), see Vanegas *et al.* 2010, 25-42.

[256] See an overview in Meyer *et al.* 2008, 217.

[257] http://www.doc.gold.ac.uk/progen/

[258] Zweig 2013.

[259] See http://www.citygml.org/ and http://www.opengeospatial.org/standards/citygml

[260] See 'The Multipatch Geometry Type. An Esri White Paper. December 2008' available at https://www.esri.com/library/whitepapers/pdfs/multipatch-geometry-type.pdf

[261] http://www.cybercity3d.com/

[262] See Müller *et al.*, 2006 for a description of its implementation and previous work.

'L-systems', developed by the Hungarian biologist Aristid Lindermayer in 1968 to describe the growth of plants in a formalised language.[263] Lindermayer observed that plants grow by recursively repeating parts that have a similar shape (see Figure 3.2), according to the principle of self-similarity. L-systems were then adapted to be used in computer graphics in the 1980s by the American engineer Alvy Ray Smith, co-founder of the animation studio Pixar.[264] Initially, L-systems were applied in particular to the generation of fractal-like shapes and the realistic representation of plants, but they were soon translated to describe architectural shapes since the latter also are often composed by repeating similar elements. The CGA grammar is based on a sequence of rules defining steps and parameters for shape creation, which can be further detailed with the insertion of 3D models in OBJ and Collada DAE formats. These imported models can be instantiated or modified according to the procedural rules (for example, it is possible to model a column in a CG software and replicate it several times in CE). An example of a CGA rule file is shown in Figure 3.3.

Apart from creating 3D geometries from scratch, rules can be also used to generate 3D geometries according to the attributes of the GIS data. If aerial pictures and building plans are stored into a geodatabase or a shapefile where the information on the buildings' heights is provided, a straightforward processing of the data is possible: by writing a rule file that contains the instructions to extrude the footprints according to the height that is stored in the attribute table it is possible to automatically create 3D buildings and apply the aerial images as textures for the roofs of the 3D models. This procedure can be handled either within CE, or by importing procedural rules written in CE directly in ArcGIS

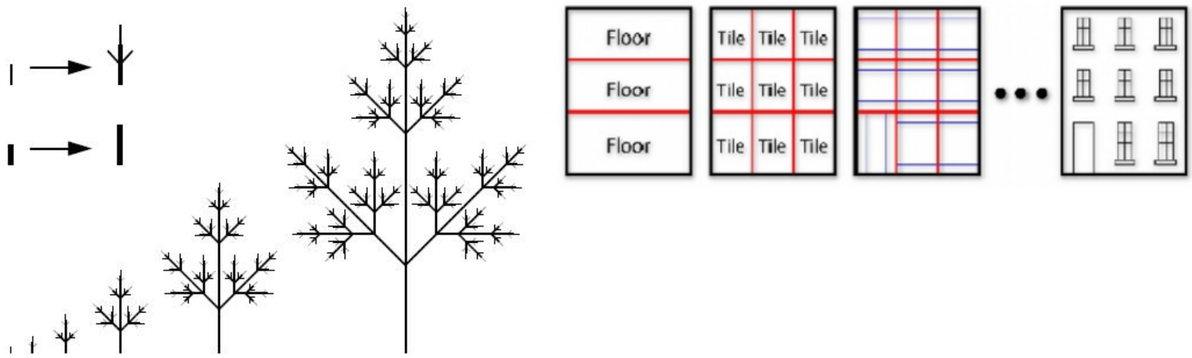

Figure 3.2 L-systems applied to plants and architecture. Left: picture from Prusinkiewicz et al.*, 2000, 397; Right: picture from CityEngine 2010.3 user manual.*

```
1. attr buildingHeight = rand (6, 8)
2. attr storeyHeight = 3
3. attr windowWidth = 2
4. Lot --> extrude (buildingHeight) building
5. building --> comp(f) {top : roof | front : facade | side: sideWalls}
6. facade --> split(y) {storeyHeight : groundFloor | ~1 : upperFloor}
7. upperFloor --> split(x) {~1 : wall | windowWidth : window}*
8. window --> i ("window_frame.obj")
9. groundFloor --> …
```

Figure 3.3 Example of a CGA rule for the creation of a building. Numerical values are stored as attributes at the beginning of the rule to control them more easily. In this case, buildings are assigned a random height between 6 and 8 meters (line 1). The 2D initial shape "Lot" is turned into a 3D building shell by extrusion (line 4). Next, a component split is used to separate the obtained 3D geometry in individual faces (line 5). A split rule along the y axis is used to divide horizontally the selected face corresponding to the building facade to create two floors (line 6). The first floor is then recursively split along the x axis to create a series of windows (line 7), which are substituted by an OBJ file containing a more detailed window frame (line 8).

263 Ochoa 1998.

264 Smith 1984, 1-10.

using the CityEngine toolbox that was introduced in the 10.1 release. In this way, a rule package (in rpk format) containing both rules and the textures can be applied to the (polygon) features to create the 3D environment. This recently improved interoperability with GIS, although being conceived to address the needs of urban planners and modellers of the modern city, makes CityEngine a valuable tool for archaeologists for the 3D modelling and analysis of past cityscapes starting from fieldwork data. In chapter 6, I will describe how I exploited the possibility of importing rule packages into ArcGIS to enhance the understanding of specific characteristics of the architecture survey data from Koroneia.[265]

From its initial implementation, CityEngine was used for the modelling of archaeologically attested cities and architecture. The procedurally modelled scene of Pompeii and the CGA rule for the Parthenon are part of the examples that are available as training material for CE users. The Parthenon rule offers an interesting example of how the mathematical principles that governed the proportions of Greek temple architecture are well suited to be implemented in a parametric modelling system. In chapter 6, I will describe in more detail the set of CGA rule files that I have developed for Greek architecture and applied to the creation of reconstruction hypotheses of 4th century BC Koroneia. Sets of rules for Roman housing architecture have been created for a variety of Roman cities,[266] including Rome itself,[267] Bononia (Bologna, Italy),[268] Portus[269] and Forum Lepidi (Reggio Emilia, Italy).[270] Other architectural typologies, such as pre-Columbian Maya architecture,[271] and historical cities, such as 19th century Nicosia in Cyprus,[272] have also been formalized in a rule-based approach. Rule based modelling is less suited for less standardized (or less well known) architectural traditions, such as prehistoric contexts and rural areas, although a rule file could be written to efficiently deal with the automatic placement of manually made 3D models on the target locations.[273]

Since the earlier applications of CityEngine to archaeological case studies, the developers have highlighted the usefulness of this approach for the visualization of alternative reconstructions and for the embedding of semantics into the procedurally created 3D models.[274] The parametric modelling approach on which CE is based allows in fact the possibility to change in real time the numerical values that have been declared in the rule files. This possibility is particularly useful to display and test alternative reconstruction hypotheses, e.g. the building's height, the number of windows, slope angle and appearance of the roof. However, the potential of creating procedurally modelled variations to clarify and explore uncertain aspects of the archaeological record has been so far not yet fully exploited in archaeological projects, with the exception of the pioneering work by Earl *et al.* on the Basilica Portuense.[275] The text-based nature of scripting allows moreover the insertion of comments within the lines of code, which increases the intellectual transparency of the modelling process.[276] As I will show more extensively in chapter 6, I made use of this opportunity to include in my rules references to published work that I used as comparative material and if necessary also on the modelling choices that I made.

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265 See chapter 6, § 6.2.1.

266 Müller *et al.* 2006, 287-97; Noghani *et al.* 2012, 41-4; on Roman and Hellenistic architecture: Saldaña 2015, 148-63.

267 Dylla *et al.* 2010; Saldaña and Johanson 2013.

268 Pescarin *et al.* 2010.

269 Harrison *et al.* 2013.

270 Forte and Danelon 2015.

271 For the creation of an individual building, see Müller *et al.* 2006, 139-46; for the procedurally modelled reconstruction of a cityscape in Honduras, see Richards-Rissetto and Plessing 2015, 85-8.

272 Charalambous *et al.* 2012.

273 This approach is similar to what I have adopted for the automatic distribution of 3D models of special architectural finds in Koroneia's 3D GIS, see chapter 6, § 6.2.1.

274 Haegler *et al.* 2009.

275 Earl *et al.* 2013.

276 Single line comments are preceded by a hash sign (#) or a double slash (//), while multi-line comments start with /* and end with */ (see JavaScript). The same notation can be used to prevent execution of lines of code.

Operation	Efficient use of CityEngine	Comments
Learning time	+	Good documentation, adapted to complete virtual cities
GUI	+	Complete GUI, complex for sample operations
Time for modelling setting-up	+	Allows integration of many different formats
DTM	++	Construction and integration from GIS data
Integration of basic outlines	++	Integration from GIS and CAD datasets
Modelling of basic outlines	++	Extrusion tools, including for complex forms
Modelling of facades / faces	++	To decomposition in horizontal and vertical subsections
Modelling from ortho-images	+	Works well in classical cases
Modelling of curved elements	-	To decompose into polygons
Integration of existing models	++	Use of other modelers for complex details
Export / Interoperability	+	Towards GIS or classical formats
Texture	++	Easy application
Rendering	++	Several renderings available
Efficiency of unique model	-	Writing of a rule for a single operation is not effective in this case
Writing of rules	+	Simple for simple rules, CGI scripts
Re-use of rules	++	Simple but requires a decomposed end structured writing of rules
Creation of rules library	++	Interesting for re-use in case of massive modelling.
Export and web visualization	++	Web service for remote consultation

Figure 3.4 Table from Koehl and Roussel 2015, 144 highlighting strengths and weaknesses of the CityEngine software.

Being conceived to address the need of a fast modelling tool for cityscape creation, the CGA CityEngine shape grammar does not allow one to model elaborate architectural elements in detail. Such components (e.g. column capitals, window/door frames etc.) need to be created in other software packages, such as CG or CAD software, and then imported into CE, either as static models or as assets that can be subjected to procedural rules.[277] For a broader assessment of the main strengths and weaknesses of the CityEngine software, I will refer to Figure 3.4 showing the list compiled by Koehl and Roussel. The main drawback of modelling using procedural rules relates to the modelling of curved shapes, for which no standard rule syntax is available yet and that has to be solved either by importing assets that are created in

[277] Koehl and Roussel present for example a workflow that integrates CityEngine, SketchUp and Blender for the modelling of historical monuments at Turckheim, Alsace, France (Koehl and Roussel 2015). As will be discussed in chapter 6, Blender and Sketcup were also used as additional modelling tool for the Koroneia case study.

Figure 3.5 Process of creating a CGA rule from existing architecture using an inverse procedural modelling approach. Left: A 3D point cloud is evaluated to extract plane surfaces; Centre: detection of architectural elements and assessment of their size; Right: The reconstruction of the temple of Poseidon, Paestum, obtained with the above mentioned procedure (after Weissenberg 2014, figs. 7.1, 7.4 and 7.5).

another software, or by 'decomposing' the required shape into sub-polygons that can be handled by CE. Moreover, as already noted for procedural modelling in general, CE is advantageous for the creation of large environments, or, as shown in the case of Portus, for the modelling of parametric variations on one building. For the modelling of one single detailed building, instead, a CG software offers the best performance. Finally, Koehl and Roussel assigned a positive grade on the learning time that is necessary to master the software, but this depends much on the technical expertise of the user. As an experiment in the classroom has shown, in fact, students find the CGA grammar difficult to comprehend and the ESRI documentation not suited for beginners' needs.[278]

The procedural modelling approach discussed above deals with the creation of a synthetic city and can be applied to the reconstruction of past cityscapes that are now lost. The automatic modelling of an existing city – an interesting topic for urban planners, architects and the game and movie industry – remains instead a challenge. A 'Facade Wizard' is included in CityEngine that allows a fast and manual creation of 3D building's facades starting with the image that represents the facade. This procedure, despite offering an intuitive and quick tool to create a CGA rule from an existing building, still implies a high degree of manual intervention. The formalization of the architectural language that would allow the automatic extraction of architectural features from facades and the inference of a set of rules that define their style is particularly complex. This set of tasks is performed using the so called *inverse procedural modelling*, a modelling strategy that allows the derivation of a style grammar of existing buildings. An approach based on the CGA grammar has been proposed by Weissenberg in his PhD dissertation.[279] Starting from a 3D point cloud of a structure, the system performs an estimation of the plane surfaces that compose the structure, detects the architectural elements and assesses their size. This method could have interesting applications also in archaeological cities, such as Pompeii and Ostia, where buildings are conserved to such an extent to justify the application of inverse procedural modelling, and for temple architecture that follows a regular pattern of shapes created according to mathematical proportions. Weissenberg has indeed successfully applied his workflow to the modelling of Doric temple architecture (Figure 3.5).

3.3 Interactive environment: virtual and augmented reality

The term Virtual Reality identifies the computer generated experiences characterized by immersion, interaction and real time navigation. A 'proper' virtual experience, indeed, happens when users feel completely part of the virtual world, and in which their actions are followed by a real time change in the environment. This experience can be mediated by the use of devices such as Head Mounted

[278] Chamberlain 2015, 359.

[279] See Weissenberg *et al.* 2013. A comprehensive overview of this method is given in Weissenberg 2014.

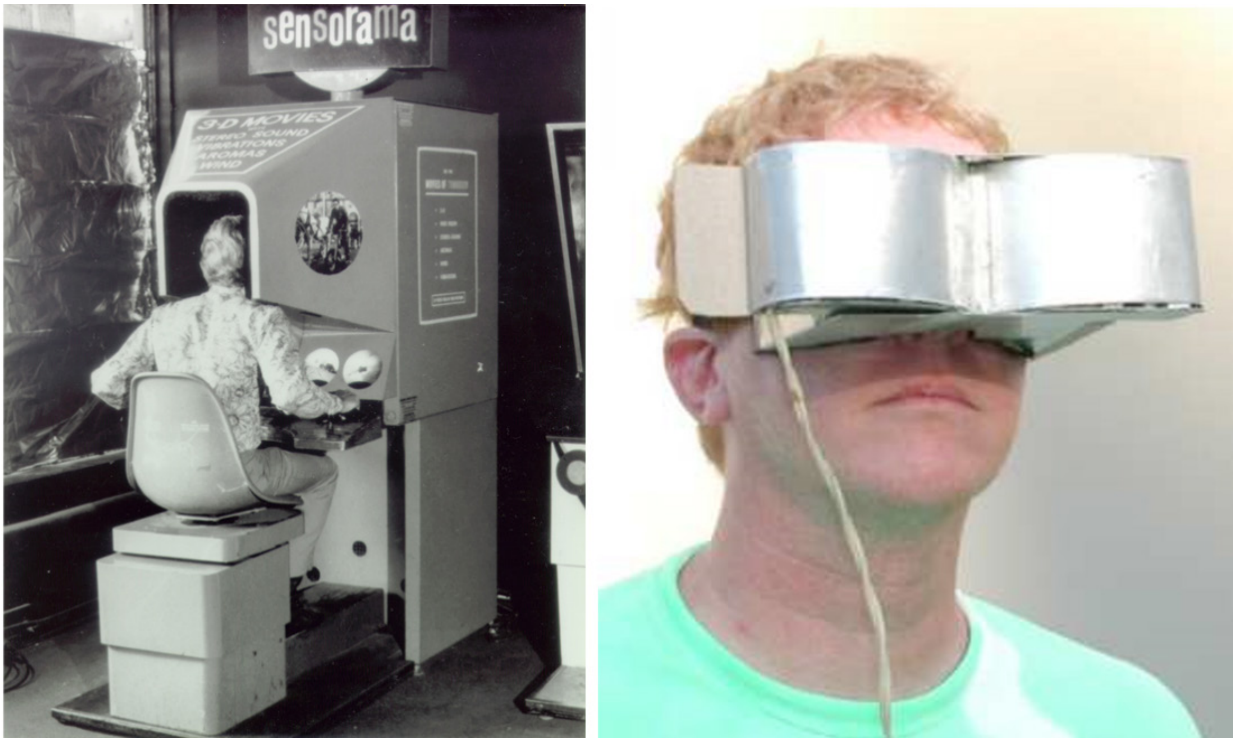

Figure 3.6 Two of Heilig's inventions: (left) the 'Sensorama Simulator' and (right) the 'Telesphere Mask' (source: http://www.mortonheilig.com/InventorVR.html).

Displays (HMDs) and interactive gloves that permit the manipulation of virtual objects, or can be guided by natural movement interaction. An expensive environment for experiencing VR is the CAVE (Cave Automatic Virtual Environment), a room where projectors display the virtual environment on its walls and floor.[280]

The term 'Virtual Reality' (VR) first appeared in the 1980s, popularised by the computer scientist Jaron Leiner who founded 'VPL Research', the first company that sold VR products. The group led by Leiner was a pioneer in this field by implementing 'multi-person virtual worlds', introducing a commercially available HMD, the 'EyePhone' system, and experimenting with the first avatars, virtual characters that represent players in a computer game.[281] Over the years, VR has been used, often inappropriately, to define a wide variety of applications. Two main streams can be recognised, namely Desktop VR and Immersive VR. Desktop VR defines all the 3D visualisations that can be experienced from a personal computer, while Immersive VR identifies all the ways to interact with 3D models, which give also the perception of being *present* in the virtual environment.

The idea of creating an immersive 3D world for entertainment purpose goes back to the mid 1950s when the visionary cinematographer Morton Heilig built a single user theatre called Sensorama Simulator (Figure 3.6), which was patented in 1962. This machine was the first to create a multi-sensory experience and the impression of a full immersion, by showing 3D movies and included stereo-sound, aromas, wind, vibrating seat and handlebars to simulate a motorcyclist's experience on a bumpy road.[282] The display of 3D movies was made possible by two other Heilig inventions, the Sensorama Motion Picture Projector

[280] For the use of CAVE's for heritage presentations see Tzortzaki 2001.
[281] A brief biography of Leiner can be found at http://www.jaronlanier.com/general.html (last accessed Sept. 2016).
[282] See http://www.mortonheilig.com/index.html for an impression of the Sensorama experience. An interview with Morton Heilig by Itsuo Sakane is available at https://www.youtube.com/watch?v=vSINEBZNCks (last accessed Sept. 2016).

and the Sensorama 3D Motion Picture Camera that was used to shoot the short movies that were seen by the users. Heilig patented also a multi-user version of the Sensorama machine, the 'Experience Theatre' and the 'Telesphere Mask', the first HMD with stereoscopic TV and stereo-sound. The complexity of the machine, which was ahead of its time for the concept and technological level, resulted in a lack of further investments to go beyond a prototype development.[283]

The conceptualization of Virtual Reality is attributed to the American computer scientist Ivan Sutherland, who published an influential paper in the mid-1960s titled 'The Ultimate Display'.[284] In the period where computers were only able to plot dots and draw lines, Sutherland sets the challenges for the developments in VR hardware and software for the following decades. His 'ultimate display' would be a kinaesthetic and multi-sensory experience, where the computer can track body and eye motion and change the presentation depending on where the user looks. A display connected to a computer, in Sutherland's words, should act as 'a looking-glass into the mathematical wonderland constructed in computer memory', which enables the user to gain familiarity with concepts and simulations that are not realizable in the physical world.[285]

Developing further his vision, Sutherland invented in 1968 the first Head-Mounted-Display, which was tethered to a computer and was able to display images in stereo, thus creating the impression of depth.[286] This system was a very heavy and complex machine that occupied an entire room and needed to be attached to a mechanical arm to be operational. Its imposing architecture overarching the user thus earned it the nickname 'Sword of Damocles'. Sutherland's HMD allowed the viewer to see simultaneously the real environment and virtual images by means of a system of mirrors, and therefore represents the first major step towards the implementation of Augmented (or Enhanced) Reality technology (AR).

Contrary to VR, in AR the virtual world does not *replace*, but it is *merged* into the physical world, which remains an important component of the visualisation.[287] It is possible to 'augment' the reality with a variety of objects (2D images, text or 3D objects) and there is an ever-growing variety of applications on the market that allows the creation of augmented reality experiences in this broader sense. Although AR technologies are quickly progressing, the development of a stable and precise AR application is far from simple. In order to align the superimposed object with the real world, two techniques exist: marker-based and markerless AR. Marker-based AR uses optical tracking of known images to determine the position and orientation of the device, whereas markerless AR uses general feature detection of camera images, often in conjunction with the device's sensory data (accelerometer, gyroscope, compass, GPS).[288] Until recently, marker-based AR has been the only reliable technique to obtain a relatively smooth AR experience. Due to advances in smartphone technology and dedicated software,[289] now, also markerless AR has become possible. Also for HMDs the creation of a smooth AR experience is still a challenge, given the numerous non trivial tasks (e.g. head, gaze and gestures tracking) that are

[283] Turi 2014 (online resource).
[284] Sutherland 1965a.
[285] Sutherland 1965a, 506.
[286] Sutherland 1965b.
[287] The idea of combining a reconstructed image of an object with its real entity is not new and was empirically realised for the first time by Brunelleschi in his famous experiments on perspective. The Renaissance architect designed a system that allowed him to superimpose his drawing of the Baptistery in Florence onto the actual building in order to check the correctness of its perspective lines. Brunelleschi depicted the Florentine Baptistery on a wooden panel in which he drilled a small hole that permitted him to see through. With a system of mirrors, he could superimpose the depicted image to the real Baptistery, in such a way that the perspective of his drawing perfectly matched the real building. See Kubovy 1986, 32-33.
[288] For a more detailed explanation of these concepts, see Butchart 2011, 2-4.
[289] Recent developments include the introduction of AR development kits by both Apple and Google (ARKit and ARCore respectively).

necessary to guarantee a reliable and comfortable experience.[290] In the heritage sector, the potential of AR has been early recognised. However, due to technological constraints, high equipment costs and high level of computer skills necessary for the creation of AR applications have, so far, been the main obstacles for its widespread adoption.[291]

Since the time of its conception, VR has been employed in several domains and numerous studies and experiments have been conducted on its applications, benefits and issues.[292] The first application was in military training, especially for flight and combat simulations, to prepare trainees for the real situation and improve their decision making response in stressful circumstances by virtually recreating the latter in a safe environment.[293] Training was the main focus of the development of VR in other fields, as it was employed for example to train medical students and to facilitate the learning of skills in individuals affected by disabilities.[294] In the field of clinical psychology and neuroscience, virtual environments were created for a variety of purposes, including the treatment of phobias and eating disorders, support during a rehabilitation process, and the training and enhancements of skills in children with disabilities.[295]

During the 1990s and early 2000s, VR was surrounded by excitement and high expectations. Futuristic VR applications featuring in movies and novels[296] generated a false impression about what real implementations of VR technology could achieve given the current state of the art of hardware and software. The expectations were therefore soon frustrated, as the promises and envisaged capabilities of VR systems were very different from the products that were made available on the market.[297]

Alongside the growing interest for the envisaged potential of VR across different domains, the concept of 'virtual archaeology' was introduced in 1990 by Paul Reilly, an archaeologist and IBM research scientist.[298] The idea that Reilly presented in his 1991 paper was quite different from the variety of applications that the label of virtual archaeology would encompass in the following decades.[299] His project aimed in fact at creating a simulated, but realistic computer-based 3D archaeological formation that would help novices to familiarize themselves with the concepts that lay at the basis of stratigraphic excavations (such as context, spit, phase, horizon etc). In Reilly's vision, archaeologists could moreover use this platform as a 'controlled dataset' to conceive different excavation scenarios and assess the validity of their excavation procedures. The solid models of the various layers that composed the simulated excavation could then be linked with additional resources that could be accessed by the user via hyperlinks.

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290 A recent survey of novel mobile AR interaction techniques is given in Härkänen *et al.* 2015.
291 Quattrini *et al.* 2016, 388.
292 A list of involved domains can be found in Bowen Loftin *et al.* 2005, 479-89.
293 See e.g. Dovey 1994.
294 Chestnut and Crumpton 1997.
295 See an overview of applications in Riva *et al.* 1998.
296 See e.g. the 'metaverse' coined in Neal Stephenson's science fiction novel *Snow Cash* (1992) and described as the successor of the internet where people would interact as avatars in a 3D virtual world.
297 A telling example is the video game console Nintendo Virtual Boy that was released in 1995 and advertised as the first affordable console to be able to provide a VR game experience. To keep the cost low, the developers had chosen a monochromatic display based on red shades, which strained the eyes and provoked headaches in the users. Moreover, the absence of a tracking system that could synchronize the user's movements and the display caused nausea. In the eyes of customers, the relatively high pricing of the console (180$) could not be justified in view of its shortcomings, which contributed to its rapid demise.
298 Reilly 1991, 133-9.
299 A reflection on virtual reality in archaeology and a comparison between its potential and its real uses are offered in Pujol 2008.

A few years after Reilly's article, the term virtual archaeology was echoed and popularized by the volume *Virtual Archaeology. Recreating Ancient Worlds,* edited by Maurizio Forte and Alberto Siliotti, which was published in 1997 with a foreword by Colin Renfrew.[300] This book was organized in richly illustrated chapters presenting numerous archaeological sites distributed in a wide geographical and chronological span. In the introduction to the volume, Forte describes the potential of computer-generated reconstructions in archaeology: besides having a strong impact on the public, they allow 'the presentation of complex information in a visual way that enables it to be used to test and refine the image or model that has been created'.[301] To emphasize the role of such computer-based visualizations as exploratory means and not as just 'graphic reproductions', Forte suggests to call them 'simulations' as they can be used for the 'objective verification' of possible interpretations of archaeological evidence.[302]

Unfortunately, this use of 3D reconstructions as expressed in the introduction does not shine through the following chapters of the book. The computer-aided reconstructions were used in fact only as illustrations of the text, and were not integral part of the interpretative process of the presented case studies. As Fletcher commented in his review of the volume, the illustrations were no more than 'electronic artworks', similar to 'regular artist's reconstructions'.[303] According to Fletcher, not only the useful outcomes of the use of computer-generated reconstructions that had been envisaged in the introduction of the book were not evident in the rest of the chapters, but their representations also failed to convey in most cases 'the sensual and emotive flavour of a graphic artist', which is instead present in many artistic reconstruction drawings.[304]

The fact that the 3D reconstructions included in the book as printed images were not exploited as interpretative tools by the archaeologists involved in the publication should not surprise. At that time, in fact, only few archaeologists possessed the competence and skills to be able not only to guide the creation of virtual archaeological worlds, but also to understand and take advantage of the potential of such computer-generated visualizations for archaeological interpretation. In fact, the creation of such visualizations was almost exclusively in the hands of computer-savvy programmers and graphics artists, who had also more easily access to the hardware and software needed for this purpose. Indeed, big companies such as Taisei Corporation in Japan, EDF in France, and ENEL in Italy invested in 3D modelling of archaeological sites in the 1990s, as archaeology was seen as an interesting field of application for demonstrating computational capabilities.[305]

As Forte pointed out, the 1990s were the 'wow era' of VR in archaeology.[306] Applications in this field were focused on the achievement of photorealistic results, with a strong prevalence of technology over archaeological content. There were moreover no clear boundaries between 'proper' VR applications as originally defined, and static renderings: all without distinction fell under the broad definition of virtual archaeology, since 'the label is so sexy that we would be foolish not to exploit it'.[307] The first enthusiastic and uncritical approaches to VR in archaeology as a tool to 'bring the past back to life' produced a sceptical reaction in academic settings regarding the contribution of virtual archaeology, which was seen as a field of application with a low interpretative value, in which many additions had to be made

[300] This volume was a translation of the original in Italian: Forte and Siliotti 1996.
[301] Forte 1997, 11.
[302] Forte 1997, 12-3.
[303] Fletcher 1998, 57.
[304] Fletcher 1998, 57.
[305] Forte 2015.
[306] Forte 2010.
[307] Fletcher 1998, 56.

to ensure the users' engagement with the reconstructed past, thus ending up creating 'acontextual, stimulating fiction'.[308]

In all fields, the expectations that surrounded the first wave of VR were not met. The long awaited and repeatedly announced revolution that virtual reality promised to bring about in how people lived, experienced the world, and interacted with each other was not realized for a variety of reasons. The costs for the hardware were tremendously high, thus limiting VR to an elitist technology. Moreover, the various types of HMDs that were developed caused nausea and made the VR experience very uncomfortable, while the 360° panorama that was displayed within the CAVE forced the user to unnatural constant movements of the head. VR therefore never became main stream, which resulted in relatively little content that was developed to be experienced with VR technology.

In the last couple of years some new developments have resurrected the idea that VR can eventually mature into a mainstream technology. The most interesting news relates to the commercialization of relatively low cost HMDs, such as the Oculus Rift[309] and the HTC Vive,[310] and of standalone headsets (e.g. Google cardboard and Samsung Gear VR) that transform the current top-end smartphones into VR viewers. The great investments made in the last years by the smartphone industry to improve video and hardware performances has created favourable conditions for VR, which is now more widely accessible, since the main needed components are already contained in the last generation smartphones: a good screen, enough processing power, and most importantly, an accelerometer and compass which are suitable for head tracking.[311] Facebook purchased the Oculus Rift in 2014 in order to develop further the possibilities of creating, sharing and experiencing immersive content.[312] The commitment of the largest social media platform and the integration into the major game engine suggest that important improvements will be made within the next few years that will contribute to a move towards the 'democratization' of VR. Moreover, investments in research and hardware by competing developers, to improve the components (such as eye tracking) that are needed for a comfortable experience will lead to the availability of a more stable and less bulky technology at a lower cost.

In the near future, technological advances will improve immersive VR and make the experience more comfortable and affordable. HMDs will become smaller and lighter than previous models and computer power will better handle the visuals with higher resolution images, while tracking software will be able to create a seamless navigation by synchronizing the user' movements in real life and the perceived movements in VR, one of the major causes of motion sickness. The issue remains however about the content development. For VR to be used beyond the game industry and become main stream, high quality content will have to be developed that exploits the possibilities of immersion and engagement that this technology offers to the fullest, and experiments with new storytelling modes instead of applying the old ways that are proper to traditional media.

In archaeology, the field of VR and AR applications has continued to exist and expand over the years.[313] During the 2000s, a great effort was invested in discussing guidelines for the creation of 'intellectually transparent' 3D reconstructions, a topic that I will treat in more detail in the next section of this chapter.

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[308] Earl *et al.* 2002.
[309] https://www.oculus.com/rift/ (last accessed March 2017).
[310] https://www.vive.com/ (last accessed March 2017).
[311] Pierce 2015 (online resource).
[312] Facebook has launched already 360° videos (https://www.facebook.com/Facebook360/) and aims at pushing the Oculus to provide an immersive experience.
[313] Recent projects using AR technologies for heritage purposes include for example the AR application developed for the gladiators school at Carnuntum, Austria (using the Wikitude platform, http://www.wikitude.com/showcase/wikitude-brings-roman-history-life-carnuntum/ last accessed Dec. 2016), and the applications for the *in situ* visualization of lost architecture discussed in Pierdicca *et al.* 2015 and Quattrini *et al.* 2016.

Advances in gaming technologies have been continuously adopted in the archaeological domains: Multi-user systems have been developed to promote (at distance) collaboration between different users,[314] interaction by human gesture has been introduced to make the navigation seem more natural.[315] In a process of 'gamification', elements and dynamics that are typical of game playing have been used to create engaging experiences in past environments.

The main target of these types of application has been public outreach and in fact museums have experimented with new ways to attract and engage visitors. The impression is however that we are still in a transitional phase where traditional ways of storytelling are used with new technologies, which instead should require a completely new approach in how a museum display is organized and how the objects are enriched with extra content. An example comes from the recent exhibition 'Museo Glass Beacon: Il Museo del Futuro' at the Museo dei Fori Imperiali nei Mercati di Traiano (Museum of Trajan's Market) in Rome, where Google glasses and Epson Moverio glasses have been used with the aim to provide extra content to visitors.[316] According to a review of the exhibition, the impression is that the additional information, although well presented, could have suited a traditional video guide, which would have been both less expensive and more effective.[317] Therefore, despite the praiseworthy efforts of musea to keep themselves up to date and experiment with technologies that could enrich the visits, we still witness the predominance of technology over content and a difficulty to put the former at the service of the latter in a way that goes beyond a catchy advertisement to attract more visitors. In this sense, not much progress has been made since the similar observations that were raised in relation to the exhibition Building Virtual Rome organized in 2005 at the same museum, where interviews to visitors showed that they 'were retaining more the application than the details of the contents and in general, could not tell if or how technology helped them to better understand the contents'.[318] The creation of professional digital content curators who both understand the technology and their potential, and have the required archaeological knowledge will bridge the gap between disciplinary compartments and offer a more informative and engaging experience to museum visitors.

In recent years, Forte suggested the new definition of 'Cyber-archaeology', to describe the last decade's 'post-virtual' approach in which the interaction with the virtual environment is at the core of the simulation process.[319] Contrary to the static and photorealistic virtual archaeology, in which the creation of 'the' model was the aim of the process and the data had to be transformed from analogue to digital with a possible loss of information, in Forte's view Cyber-archaeology deals with digitally born data and generates new 'affordances' through the interaction between the virtual environment and the user.[320] Using this Gibsonian term in the context of archaeological interpretation, Forte aimed to explain how a single artefact can have several uses that change through time and space. The meaning

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314 See e.g. Forte 2007 and Forte *et al.* 2010, 422 with related bibliography.

315 E.g., the 3D real time application 'Imago Bononiae' presented at the Digital Heritage Conference 2013 http://www.digitalheritage2013.org/imago-bononiae/ (last accessed Sept. 2016).

316 http://www.mercatiditraiano.it/mostre_ed_eventi/eventi/museo_glass_beacon_il_museo_del_futuro (last accessed Sept. 2016). The extra content was activated by beacon devices (broadcasting messages at specific point of interest using Bluetooth low energy network technology) and image recognition respectively.

317 See the review of the exhibition by N. Mandarano at https://nicolettemandarano.wordpress.com/2015/11/06/alla-prova-dei-google-glass-e-degli-epson-moverio-ai-mercati-di-traiano/ (last accessed Sept. 2016).

318 Forte, Pescarin and Pujol Tost 2006, 64-9.

319 Forte 2010; Forte 2015.

320 The term 'affordance' was coined by the American psychologist J.J. Gibson from the verb 'to afford', in order to indicate the opportunities and constraints that an environment offers to an animal (more specifically 'terrain, shelters, water, fire, objects, tools, other animals and human displays'), and the complementary relationship that is established between the animal and its environment (see Gibson 1986 (1979), 127). According to Gibson, the theory of affordances 'rescues us from the philosophical muddle of assuming fixed classes of objects, each defined by its common features and then given a name...But this does not mean you cannot learn how to use things and perceive their uses. You do not have to classify and label things in order to perceive what they afford' (Gibson 1986 (1979), 134).

and role of an object changes based on the interaction between the user and the environment. In Forte's view, therefore, the interaction in the simulated environment becomes the key process to disclose new interpretations.

3.4 The scientific value of 3D reconstructions

The benefits of a 3D digital documentation, by means of photogrammetric or laser scanning techniques, are appreciated by archaeologists as they provide a complete and accurate documentation of the geometrical and surface properties of archaeological finds, structures or sites. They are widely used during excavations and surveys and recent examples show that these techniques greatly enhance the comprehension of archaeological structures and are useful to contextualize the site under investigation in its three-dimensional environment, providing a documentation that accounts for the relationship between sloping ground and structures much better than a two-dimensional representation.[321] In contrast, 3D digital reconstructions, in which the missing pieces in our archaeological data are integrated with the most plausible reconstruction hypothesis, struggle to be seen as a valuable research tool. Several reasons, deeply rooted in how 3D reconstructions have been used since their first applications in archaeology, have contributed to this condition. In the next section (3.4.1) I will focus first on two aspects that have undermined the 'academic reputation' of 3D reconstructions, namely the lack of an explicit documentation for the research sources that are used, and the creation of only one reconstruction, which does not account for other equally plausible hypotheses that are possible given the available archaeological dataset. Secondly, in the following section (3.4.2) I will discuss another important aspect of 3D reconstructions that has been largely overlooked, namely their analytical potential to help in formulating hypotheses and observing otherwise oversight phenomena. Specifically, I will focus on the projects that have been successful in exploiting 3D reconstructions as research tools, with the aim to concretely show what kind of archaeological questions can be investigated by using 3D modelling techniques.

3.4.1 Rules for 'intellectually transparent' 3D visualisations in archaeology

Intellectually transparent data are crucial in all academic disciplines, as they are the prerequisite to allow quality control and peer reviewing. Traditional scholarship has developed a standardised way to publish results by including footnotes and references in scientific articles, which allow the reader to assess the scientific value of the results, to evaluate the supporting arguments, and to retrieve additional content for further research. 3D reconstructions that are not intellectually transparent can be paralleled to an article where only the conclusions are expressed, without discussing the sources and reasoning, which would represent an aberration in academic scholarship.[322] This problem was already identified in the 1990s,[323] and can be summarised by Forte's words highlighting that 'noticeable gaps are represented by the fact that the models are not 'transparent' in respect to the initial information (what were the initial data?), and by the use of peremptory single reconstruction without offering alternatives'.[324]

[321] See e.g. the analysis of the archaic temple of Hera at Olympia where the photogrammetric recording has allowed the researchers to reconsider the building in relation to the sloping ground which was not taken into account in previous documentation (Sapirstein 2015, 129-139).

[322] For the parallel between scientific articles and 3D reconstructions: H. Denard's lecture 'The London Charter' at the POCOS symposium 'Visualisations and Simulations', 16-17 June 2011, available at https://vimeo.com/26767611 (last accessed March 2017).

[323] E.g. Reilly 1991, 21; at this respect see Denard 2012, 57.

[324] Forte 2000.

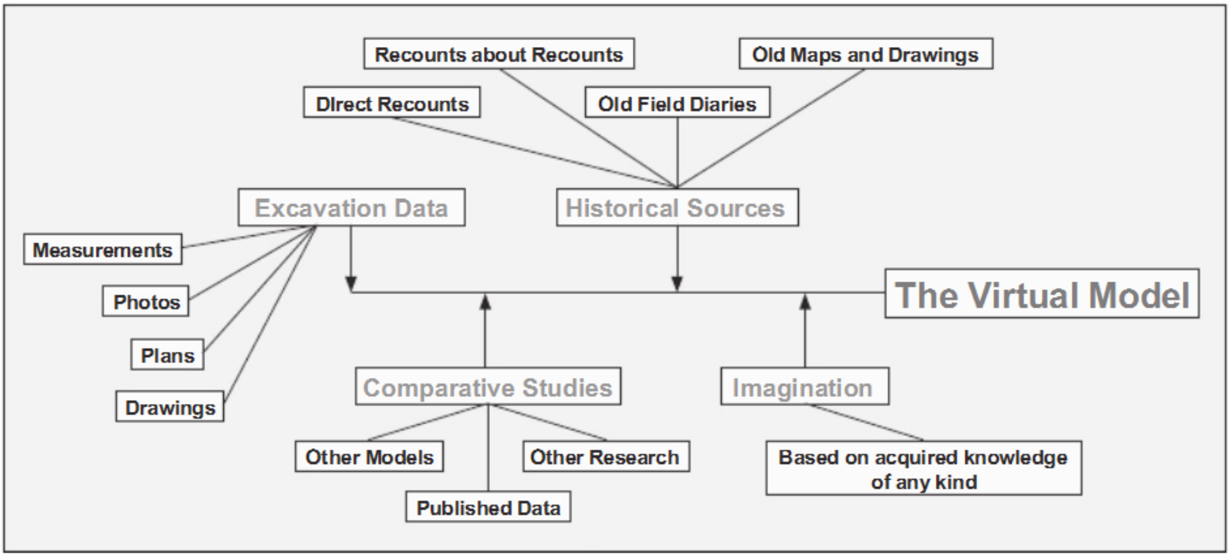

Figure 3.7 Schematic diagram of the sources that are generally used for a 3D model of archaeological evidence (after Hermon 2008).

The necessity of finding ways to provide 3D visualisations with an accurate documentation of the sources that were used, the thinking/interpretation process (the so called *paradata*) and the methodology that was followed has been recognized as a key element for increasing the impact of 3D models as knowledge providers. While this is important for reality-based 3D models, which need to be accompanied by a documentation explaining the methodology followed during the recording and data processing, it becomes even more crucial for 3D reconstructions (see a schematic diagram of the components that flow into the creation of a virtual model according to Hermon in Figure 3.7).[325] In a thoroughly researched 3D reconstruction, in fact, the time that is invested in evaluating and interpreting the sources in most cases exceeds the time that is employed for its actual creation.[326] Too often, however, 3D reconstructions are 'closed boxes' where the demarcation between original data and reconstruction hypotheses is too blurry, thus leaving the viewer puzzled about the reliability of the representation.

During the 1990s, a photorealistic result was sought after as if a realistic rendering was the warranty of the trustworthiness of the 3D reconstruction, thus giving a false perception of authenticity to what in fact was a modern sophisticated looking 'construction' of the past.[327] For this reason, the explicit presentation of the level of reliability of the 3D reconstruction has been deemed a necessary requirement for an intellectually transparent communication. To this end, in 2002 Frischer *et al.* suggested that 3D visualisations needed a 'new philology', making an analogy with how philologists prepare a corrupted text for publication by providing an *apparatus criticus* to explain their integrations.[328] By doing this for 3D reconstructions, other researchers are enabled to assess sources and thinking processes that led them to choose a certain hypothesis over others to be visualised in the virtual environment. It is indeed the complex relationship between the original data and the interpretation that is usually not apparent in 3D reconstructions, as they present an image of the past where all the elements are displayed with the same degree of certainty.[329] The 'different realities' that compose and need to be distinguished in a 3D reconstruction can be summarised in Zubrow's words: '(...) what part is based upon observation, what part is based upon 'connecting the material dots - interpolating', what part is based upon 'extending the

[325] Cf. Wittur 2013, 205-18.
[326] See in this respect Pletinckx 2012a, 205.
[327] On the 'authenticity' of VR representations, see Gillings 2002.
[328] Frischer *et al.* 2002.
[329] Early discussions on this topic can be found in Ogleby 1999 and Kensek *et al.* 2004.

material dots - extrapolating', what part is based upon ethnographic analogy, what part is based upon a theoretical stand, and what part is based upon informed speculation'.[330]

To fill the lack of a 'philological *apparatus*' for 3D visualisations, a group of experts in the field of virtual archaeology came together in 2006 to draft the 'London Charter' that aims to ensure a methodological rigour to computer-based visualisations of cultural heritage.[331] The later 'Seville principles' are more precisely focused on the needs and challenges of computer-based visualisations in archaeology.[332] The trigger for the compilation of these guidelines was the need to create a consensus on the best practice for such visualisations and to establish a series of rules to achieve intellectually transparent visualisations. Among the principles listed in the London Charter, some are particularly interesting. The second principle, for example, invites us to assess at first which are the project's aims in order to choose consequently the best approach to address them. 3D visualizations in fact should not be *a priori* considered the best method available, if other strategies can serve the same purpose. The third and fourth principles focus on the need to evaluate and document in a structured way the research sources of any kind that were used to create the visualisation, with the aim to make clear 'the relationship between research sources, implicit knowledge, explicit reasoning, and visualisation-based outcomes'. The last two principles deal with sustainability and access, stressing that it is important to plan a long term preservation of the 3D visualisation, along with the sources and the thinking process that led to its creation.[333]

The London Charter and the Seville principles represent a huge step forward in regulating the creation of 3D models of heritage and archaeological structures, and have set essential standards for their creation, which have been recalled and further specified in following projects and publications.[334] In order to encompass all the different applications of the vast field of 3D in archaeology, in fact, the principles listed in these guidelines are general and theoretical. For this reason, researchers have implemented various solutions to comply with the principles, some of which I will discuss in the next paragraphs. Despite these progresses, a recent survey taking into consideration papers presented at major conferences in 2012 has shown that still only a very small percentage of published papers dealing with 3D models in archaeology included methods to integrate this type of information within their workflow (1% of 686 papers).[335] This shows that this aspect is far from having become the norm, and a greater amount of simple and standardized solutions are needed to facilitate the documentation, analysis and comparison of sources used for 3D reconstructions and to ensure the long-term preservation of 3D visualisations in archaeology.

[330] Zubrow 2006, 24.

[331] http://www.londoncharter.org/ (last accessed Sept. 2016).

[332] The Seville Charter is available at http://smartheritage.com/seville-principles/seville-principles (last accessed Sept. 2016).

[333] The London Charter principles are available at http://www.londoncharter.org/principles.html (last accessed Sept. 2016).

[334] A recently closed European project, the Virtual Museum Transnational Network V-MUST (http://www.v-must.net/home) developed case studies where a practical workflow is suggested, tested and evaluated to be able 'to provide the heritage sector with the tools and support to develop virtual museums that are educational, enjoyable, long-lasting and easy to maintain'. Other European projects have been funded over the last years and have produced methodological results and practical tools available for the research community in the field of virtual heritage (see http://cordis.europa.eu/fp7/ict/creativity/digicult-heritage_en.html). Among others, we can note EPOCH (2004-2008) the EU FP6 Network of Excellence on the Applications of ICT to tangible cultural heritage (the webpage of the project, http://www.epoch-net.org/, is no longer supported. Documents related to the project can be found at http://public-repository.epoch-net.org/), 3D COFORM (2007-2013, http://www.3d-coform.eu/), CARARE (2010 -2013, http://carare.eu/eng), and 3D Icons (2012-2015, http://3dicons-project.eu/). The outcomes of 3D COFORM are the development of open source software such as MeshLab (http://meshlab.sourceforge.net/) created by a team of the Italian CNR-ISTI for the processing and editing of unstructured 3D triangular meshes typically produced by 3D scanning. CARARE was dedicated to finding the best option to publish 3D content online, especially to be included in Europeana, the European digital library. The more recently funded 3D Icons aims to take further the results of 3D COFORM and CARARE to bring 3D models of architecture and archaeological structures into Europeana (a European digital library of Cultural Heritage), by using digitisation and 3D scanning techniques (http://3dicons-project.eu/eng/Resources/VSMM-2012). See also the list of rules for the interpretation of sources and hypotheses in Pletinckx 2007, 6.

[335] Cerato and Pescarin 2013, 290.

The inclusion of additional information concerning research sources and thinking process is not only beneficial for assessing the academic standard of a 3D reconstruction, but also creates a more informative platform for the dissemination of cultural heritage to the public. To investigate the visitors' expectations, a survey was carried out during the multi-media exhibition 'Building Virtual Rome: Trajan's Markets in Rome' held in Rome in 2005, in which a virtual reconstruction of Trajan's Markets was presented. The interviews with the visitors showed that they would have liked to be able to access historical information about the meaning and the function of the virtually reconstructed building, and also wanted to be informed about the methodologies followed to create its 3D reconstruction.[336]

In the next paragraphs, I will discuss some of the methods for intellectual transparency that have been used over the years. Some differences in the chosen approaches are noticeable in relation to the final user (academic or general public) of the application, although the boundary can be very blurred and one user does not exclude the other. When 3D reconstructions are meant for museum settings, the choice generally falls either on leaving to the user the possibility to choose whether to access or not the extra content,[337] or on creating external resources (e.g. blogs) where the additional information is presented in a structured way. For the academic user, methods that would be less engaging for the general public, such as databases, XML schemas or simply textual explanations have been chosen for documenting the creation process of 3D reconstructions.

One of the first, pioneering solutions was developed by Kensek *et al.* in 2004 for the sanctuary of the Great Aten Temple at Amarna (Figure 3.8).[338] The 3D reconstruction of the temple was enriched with hyperlinks directing the viewer to additional information (such as the confidence level of the reconstruction or other possible reconstructions) that the user could access without leaving the virtual environment. Moreover, the system was devised in such a way that the user could change the columns, capitals and shafts types of the temple's facade to display equally plausible reconstruction alternatives. To this end, constraints had been added to prevent selection of stylistically incompatible elements. Conceptually, this system is still one of the most complete and elaborate solutions for the representation of the certainty level, the accessibility of research sources, and the possibility offered to the user to intervene in modifying the 3D reconstruction to convey the array of different interpretations.

More specifically developed for museum settings, was the virtual reality application of the Villa of Livia at Prima Porta, created by CNR-ITABC between 2006 and 2008 as part of the Virtual Museum of Ancient Flaminia for the National Roman Museum at the Baths of Diocletian in Rome.[339] Pioneering the possibilities offered by gaming dynamics, a multi-user VR system was developed, which allowed a third-person navigation around and within the Villa (with the possibility to choose between viewing the current state of the digitally documented site or its reconstruction). During the exploration, the user controlled an avatar that triggered icons granting access to extra content. For example, as shown in Figure 3.9, when the avatar walked through the icon 'references', a video started that gave an overview of the architectural comparisons that were used to integrate the parts of the Villa that are now lost. Time and technical expertise are needed to develop such a virtual navigation and the real time interaction, but it represents a successful attempt to make research sources available in a non-obtrusive way and only if the user desires to access them.[340]

[336] Forte, Pescarin and Pietroni 2006.
[337] Cerato and Pescarin 2013, 294.
[338] Kensek *et al.* 2004.
[339] Forte 2007.
[340] The assets that were developed for this project have been recently re-used in a VR application based on natural interaction for the Museo Nazionale Romano - Terme di Diocleziano (http://www.itabc.cnr.it/progetti/flaminia-re-loaded-museo-virtuale-della-villa-di-l-000. Last accessed Sept. 2016).

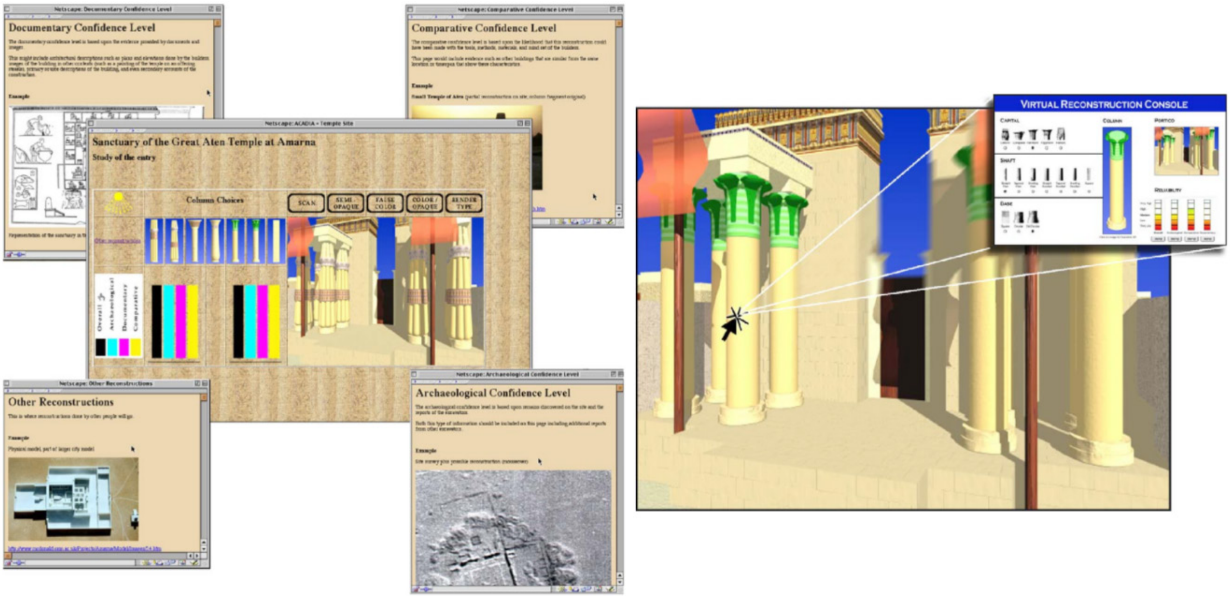

Figure 3.8 Screenshots from the virtual environment elaborated by Kensek et al. *Left: Hyperlinks point to additional information regarding the different confidence levels of the reconstruction and alternative hypotheses; Right: the interface that allows the user to choose different types of columns, capitals and shafts to be displayed (Kensek* et al. *2004, 181 and 182).*

Figure 3.9 Screenshots from the navigation through the virtual reality application of the Villa of Livia by CNR-ITABC, which used to be available at http://www.vhlab.itabc.cnr.it/flaminia/. The avatar that guides the user through the exploration of the Villa encounters icons that display extra content when triggered.

In other cases, the documentation of the creation process has been detached from the 3D visualisation, by exploiting blogs as instruments to present sources, methods and the reasoning behind the final product. This solution has been adopted recently by two visualisation projects, 'Etruscanning' and 'Abbey Theatre, 1904'. Etruscanning was carried out in the framework of the V-MUST by CNR ITABC and the company Visual Dimension with the aim of creating a virtual experience of the Regolini-Galassi Etruscan tomb (Cerveteri, Central Italy) for museum visitors (Figure 3.10). The tomb was discovered in the late 19th century and it is not accessible anymore, while the grave goods are kept in the Vatican museums. The virtual reconstruction was therefore the occasion to re-contextualise the objects and to provide an exploration of the nowadays closed tomb in a virtual environment. During the Etruscanning project, the structure was documented by laser scanning and the objects were photographed and turned

Figure 3.10 Left: Laser scanning session inside the Regolini-Galassi Tomb at the Sorbo necropolis, near Cerveteri (CNR-ITABC); Right: The installation of the virtual reconstruction at the archaeological museum in Leiden (RMO) (images from http://regolinigalassi.wordpress.com/)

into 3D models by applying photogrammetry techniques. All the process of recording the tomb and its content, and the different hypotheses and comparative material were published in a blog.[341]

The Abbey Theatre project aimed to digitally reconstruct this famous theatre in Dublin that was damaged by fire in 1951. Hugh Denard, a King's College historian and one of the initiators of the London Charter, set up a blog to document the phases of the reconstruction of the theatre as it was at the time of its opening in 1904.[342] The blog was chosen as the place to present the sources that were gathered, so that everyone could evaluate the choices made for the reconstruction, which is presented in video clips, one of which held information about the reliability of the reconstructed theatre.[343] One of the reasons for choosing blogs to document the process of creation of 3D visualisation is to stimulate and facilitate the exchange of opinions between researchers working on the same project. It seems, however, that the research community is not yet at ease with these tools, in particular if blogs are public. Observations on the use and reception of the Etruscanning blog proved, in fact, that 'experts are reluctant to contribute on a public blog as they see this as a kind of publication with final conclusions, while the contributions are ongoing research, of a volatile and progressive nature'.[344]

A different approach is based on the creation of standardised ontologies to describe heritage documentation in a formalised way. Such ontologies aim to improve the data integration and exchange among different sources of information and entities, such as libraries, museums and archives. The standardization of definitions and categories encompassing the variety of records is however a very challenging task. The Conceptual Reference Model has been developed with this purpose by the International Committee for Documentation of the International Council of Museums (CIDOC-CRM) and it has officially become ISO standard in 2006.[345] In recent years, progress has been made to integrate archaeological and architectural heritage in CIDOC-CRM to provide a common platform where also 3D models can be documented, exchanged and more easily found in the ever-growing amount of data available on the web.[346]

341 The blog, compiled by D. Pletinckx, can be accessed at http://regolinigalassi.wordpress.com/; see also Hupperetz *et al*. 2012.
342 http://blog.oldabbeytheatre.net/
343 http://blog.oldabbeytheatre.net/posts/visualisation
344 Pletinckx 2012b, 106.
345 http://www.cidoc-crm.org/index.html
346 See Niccolucci 2012, 35-6 and M. Doerr's presentation 'New Developments of CIDOC-CRM' given at the 'CIDOC-CRM seminar' (Istituto Centrale per il Catalogo Unico delle Biblioteche Italiane, Rome, 14 Sept. 2012) available at http://www.otebac.it/

Building on this and other existing standards for metadata mapping, the CARARE metadata schema was developed for this purpose within the framework of the 3D ICONS project.[347] Based on the CARARE schema was for example the process of documentation of the Hellenistic-Roman theatre of Paphos, Cyprus.[348] The data acquisition phase was carried out by aerial photogrammetry (aerostatic balloon) and terrestrial laser scanning and a virtual reconstruction was created of the architectural phases of the theatre. The theatre was hierarchically divided into architectural components (e.g. cavea, stage, orchestra etc.) that were then mapped into an XML structure equivalent to the various elements of the CARARE schema. The project dealt also with making explicit the reliability of the reconstruction, which was displayed by mapping RGB and saturation values onto the 3D model: red corresponded to high reliability, green to moderate and blue to low. For each of these colour channels, the saturation value further specified the reliability to create a more nuanced transition between the three categories.

Other approaches to make explicit the level of reliability of a 3D reconstruction have been suggested, ranging from a colour coding of each part of the visualisation, to the 'deconstruction' of the reconstruction process by using charts that show the relationships between the various components of the visualization,[349] to the application of a fuzzy logic approach that defines a scale between '0' (totally unreliable) and '1' (absolutely reliable) for each component of the 3D visualisation.[350] Alternatively, in projects such as in the case of the 'Villa of Livia' and 'Aquae Patavinae' (ITABC-CNR),[351] the online virtual environment makes it possible to switch between a 3D model of the extant remains and their 3D reconstruction. In the latter case, the user could choose among three levels: the *current state* of the archaeological evidence, its *interpretation* (in which the reconstructed buildings are rendered with see-through walls), and the actual *reconstruction*, in which the reconstructed buildings are rendered in their physical appearance. In this way, the user can see the current state of the archaeological evidence and is made aware of the existing relationship between the finds and the interpretation given by the archaeologists.

Besides the explicit presentation of documentation sources and the level of reliability, the second aspect that is rarely explored is the creation of multiple reconstruction hypotheses, which would better represent the range of equally plausible hypotheses that archaeologists formulate to explain archaeological evidence. Before 3D digital reconstructions, this problem was already apparent, even more dramatically, in some of the physical restorations of sites that were carried out in the early decades of the 20th century, the most notable example being the Palace of Knossos in Crete. As is clear from Evans' report, his work of consolidation and reconstitution of the excavated structures was a genuine effort to preserve the Palace and make it more understandable to the visitors.[352] Under the light of modern archaeological methodology, however, Evans' approach resulted in a misleading and heavily conjectural *anastylosis*. Not only the physical reconstruction was done in such a way that it is difficult to distinguish the original parts from the restored elements, but also the correctness of the restoration, including the use of modern materials, has been questioned. Moreover, the reconstitution took into account only one historical phase of the site, hiding the remains of other important periods

index.php?it/22/archivio-eventi/229/roma-seminario-cidoc-crm (last accessed Sept. 2016).

347 The current version of the CARARE metadata schema can be accessed here: http://pro.carare.eu/doku.php?id=support:metadata-schema (last accessed April 2017), where a list of schemas and best practises that the CARARE schema builds upon can also be found.

348 Georgiou and Hermon 2011.

349 Ogleby 2007. Demetrescu is developing a framework (Extended Matrix) for the integration of semantics in 3D virtual environments, aiming at documenting the scientific process behind the virtual reconstruction of a (partially) lost building (Demetrescu 2015, Demetrescu and Fanini 2017).

350 Hermon and Nikodem 2008; Niccolucci and Hermon 2010.

351 http://www.aquaepatavinae.lettere.unipd.it/portale/?page_id=2174 (last accessed Sept. 2016).

352 Evans 1927.

(namely the Neolithic, Greek and Roman settlement) both to visitors and experts.[353] As I already noted in the chapter on reconstructions before the digital age, once again the same issues that have been identified for 3D digital reconstructions were already evident in non-digital reconstructions. However, the reflections aroused from these early works, albeit in a different domain, have not been picked up by the early practitioners in the field of virtual archaeology and the possibilities that the digital *medium* offers to tackle this problem have not been fully exploited. For example, while the physical reconstruction obviously does not allow to present several hypotheses, this is actually possible in the digitally reconstructed environments, where alternatives can be created and displayed.

The problem of displaying a single reconstruction has been approached in various ways, since the early demonstration by Roberts and Ryan, who in 1997 suggested a system based on VRML.[354] One of the explanations for the lack of more numerous projects including different reconstruction hypotheses is that the creation of several 3D models is usually unfeasible as too costly and too time consuming. While in the last years a substantial drop in costs of hardware and software is noticeable, early projects had to sustain considerable expenditure for creating and setting up the infrastructure and the 3D environment, not to mention the limitations posed by the graphics hardware that were available.[355] Although this obstacle has been solved, the fact that creating several reconstruction takes up much time is still a problem nowadays, especially for 3D reconstructions created using a manual approach. As already mentioned, procedural modelling offers in this regard a very efficient solution, as the parametric approach allows the user to change in real time the appearance of the reconstruction.

As I will more extensively present in chapter 6, I chose a procedural modelling for Koroneia's case study as this seemed the best methodology not only for the characteristics of the site (an ancient town of which the archaeological investigation is still in process), but also to create an intellectually transparent 3D reconstruction. The text-based formal description of the created geometry allows in fact the introduction of documentation sources as comments; moreover, the parametric approach enables the creation of different reconstruction hypotheses in a time efficient and compact way. In the next section, I will deal with another aspect of 3D reconstructions, namely their underestimated value as research tools.

3.4.2 3D reconstructions as analytical tools

Over the last two decades, we have witnessed a dramatic increase in the number of papers dealing with 3D archaeology in a broad sense, which have been presented at archaeological conferences and have appeared in dedicated journals.[356] As Hermon noted, papers dealing with this subject can be divided in two major groups, namely those using 3D/VR for presenting heritage sites to the public, and those discussing technical advanced in the methods to create 3D/VR applications.[357] 3D models of archaeological artefacts or structures have been in fact traditionally exploited mostly for heritage purposes, with the aim to create convincing visual representations that allowed the preservation and the dissemination of (partially) lost or endangered artefacts or buildings. In some of these cases, however, one might question the actual usefulness and added value of such digital representations, as a creative use of traditional techniques may serve the same purpose in a cheaper and more sustainable way (see for example the solution adopted at Carnuntum in Austria in Figure 3.11). It is therefore reasonable to

[353] Papadopoulos 1997, 115-17.
[354] Roberts and Ryan 1997.
[355] See e.g. the reconstruction of the Temple Mount conducted by the Urban Simulation Team at UCLA and the Israel Antiquities Authority that was available on the internet and included pop-up windows with pictures and explanations of the extant remains (Kensek *et al.* 2004, 179-80).
[356] Olson *et al.* 2014, Hermon 2008, 35-6.
[357] Hermon, 2008, 35.

Figure 3.11 Archaeological site of Carnuntum, Austria. A perspex panel allows the viewer to see the Heidentor gate in its restored appearance (picture by Jan Madaras on panoramio).

expect that a digital 3D reconstruction should have a clear added value to justify the effort to create it, such as the possibility to access the reasoning process and sources that led to its creation, view alternative hypotheses, or to use them as tools to aid the archaeological interpretation.

Over the years, archaeologists working in the field of digital visualisations have in fact reflected on their use and on how to shift them from being simply 'pretty pictures' that can mislead the public by conveying a wrong image of the past, to become an instrument in the hand of the research community to answer archaeological questions and communicate archaeology responsibly. The need to ensure an academic standard to 3D visualizations has resulted in guidelines and solutions to present metadata and paradata that I have discussed in the previous section. These improvements, however, still mainly relate to 3D visualizations as presentations of already acquired knowledge, instead of as tools to work with for generating new questions and visualizing hypotheses. The analytical potential of 3D visualizations in archaeological interpretation has been not yet extensively explored. In the era of Cyber-Archaeology as defined by Forte, the interaction and embodiment in the virtual environment promises to generate new insights for the interpretation of archaeological evidence, a task that the dismissed 'Virtual Archaeology' has failed to persuasively fulfil. At present, however, this vision remains largely theoretical, as there is not yet any solid case study showing that the development of such interactive environments has yielded new interpretations that furthered a deeper understanding of our archaeological record.

The advantages related to the use of 3D recording over traditional documentation techniques are self-evident, and a shift from a collection management approach to a research driven agenda has resulted in the inclusion of digital recording techniques in the archaeologist's analytical 'toolbox'. These techniques allow in fact a quick creation of an accurate and complete documentation of extant archaeological remains, which represents an important source of information for monitoring a structure's condition and planning restoration interventions. The 3D models thus obtained become moreover measurable digital replicas that are stored locally or on the cloud, to allow researchers to inspect the recorded entity also when fieldwork is concluded. For artefacts and bone finds, the availability of digital models reproducing precisely their volumetric properties enables the creation of virtual reference collections in which information such as shape, size and texture can be easily retrieved and compared, encouraging the development of techniques for automatic feature extraction.[358]

The position of 3D reconstructions within the field of scientific research is instead more complex. The already recalled quest for realism and the uncritical claims about the potential of VR as a tool to bring the past back to life that have characterized many early applications[359] have distracted from the tangible added value of using them as research tools. Although the heuristic use of 3D modelling to enhance archaeological interpretations has often been highlighted,[360] the number of papers in which 3D reconstructions are used for this purpose are still few in comparison with those presenting methodological advances in 3D recording techniques or 3D reconstructions for heritage preservation. Not accidentally, amongst the papers submitted to the session 'The scientific value of 3D archaeology', organized by Hans Kamermans, Roberto Scopigno and the author at the XVII UISPP World Congress at Burgos, only one focussed on the use of a 3D reconstruction for research purposes, while the majority of the others were dedicated to 3D recording methodologies.[361] In the next paragraphs, I will discuss some examples of analytical visualizations and a set of related case studies that have successfully unlocked the potential of 3D models. In line with the topic of this work, my attention will be especially directed to research aiming at the formulation of hypotheses on past built environments and their social implications. I shall argue that these types of application set the direction for the inclusion of 3D visualizations within the 'toolbox' that archaeologists should be equipped with, to investigate specific archaeological questions.

Gordin has divided visualizations into 'interpretative' and 'expressive':[362] the former encompassing all visualizations that help to clarify complex evidence or abstract concepts, while the latter allows the communication of knowledge in an easier and more intuitive way. Depending on their use and the purpose of their creation, 3D reconstructions and simulations can belong to both groups. They allow for example the contextualization of landmarks into their urban surroundings, show more clearly the relationship between above and under surface archaeological elements, and help a non-expert viewer to comprehend fragmentary remains by offering a summary of the available data and interpretations.[363] A good example of interpretative visualization is the Oplontis project.[364] The 3D model of the Villa A at Oplontis acts as a spatial index for all the data that have been collected during the archaeological campaigns. In doing so, all the pieces of information (both raw data and reconstruction hypotheses) are organized in a structured way following the spatial arrangement of the Villa. Apart from collating all the available data and reconstruction hypotheses, the 3D model allows the reposition of the Villa into the ancient landscape, showing for example that while nowadays the villa is located about half a

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[358] For artefact analysis, see e.g. Karasik 2008; for palaeosteology, see e.g. the recently funded project VZAP by the Centre for Virtualization and Applied Spatial Technology of the University of Florida led by Professor Herbert Maschner, aiming at creating a virtual 3D osteological reference collection from the Arctic which exploits the functions of 3D PDF to view, rotate and measure the 3D objects (see Betts *et al.* 2011, available at http://vzap.iri.isu.edu/)

[359] See e.g. Gillings 2002, 232-3.

[360] See e.g. Frischer and Dakouri-Hild 2008 and Wittur (2013, 30-6), who discusses some analytical applications of 3D reconstructions with a series of case studies.

[361] See Kamermans *et al.* 2016.

[362] Gordin *et al.* 1996.

[363] See Hermon 2008, 40.

[364] http://oplontisproject.org/ (last accessed Sept. 2016). The project aims to develop 3D models of the Villas A and B at Oplontis that are linked to an online database.

kilometre inland, recent studies have proved that it was originally built on a cliff 13 meters above the sea.[365]

A third category, that we could call *analytical visualizations*, should be added to the two main groups mentioned above. This kind of visualizations consists of 3D models that are created both to turn heterogeneous data into knowledge and to act as proper analytical tools in their own right. The most obvious type of 3D analytical visualization is the creation of a 3D GIS environment. The enhancing of GIS with the 3rd dimension has the advantage of enabling the possibility to store information and conduct analysis in a georeferenced and fully 3D environment. The development of a 3D GIS for modern cities has attracted ever growing attention since the 1990s,[366] but the possibility to work in a 'full' 3D GIS is a recent development as common GIS platforms were either 2D or 2.5D in the past. In the latter case, the z value could in fact be stored as a single attribute of the x and y coordinates (e.g. TINs) and not as a separate entity or as multiple values, thus limiting the analytical capabilities of the system, especially for the built environment. In fact, while the capabilities of 2.5D are sufficient in landscape studies (e.g. for *viewshed* calculation), visibility analysis for buildings was confined only to establishing whether a building could or could not be seen in its entirety. A recent development exploits procedural rules for the quick creation of a uniformly separated grid of points on the buildings' facades, that can be exploited as target or observer points to achieve a more detailed visibility analysis on portions of buildings in ArcGIS.[367] In chapter 6, I will discuss in more detail how I included this possibility in Koroneia's workflow.

A 3D GIS is particularly interesting for municipalities that need to have tools for improving their ability to plan, manage, design and analyse infrastructures, public transportation, alternative development scenarios etc. The creation of 'smart' cities that could exploit digital technologies to achieve a more efficient urban planning and a more effective communication with citizens and stakeholders, has led companies to create targeted software packages that allow an integrated approach for data handling and provide analytical tools for a variety of analyses.[368] A 3D GIS for the modern city allows in fact municipalities to store and interrogate their data in a 3D cadaster, thus solving problematic situations that were common with 2D mapping (e.g. how to represent a bridge that crossed a street in a 2D environment). Besides improving the mapping capacities, a 3D GIS increases also the analytical possibilities, which include visibility analysis, shadow impact, sun exposure and flood modelling.[369]

Visibility analysis in a 3D GIS

In recent years, archaeologists working on past cityscapes have increasingly become familiar with the new capabilities of a 3D GIS environment and have started to use it for both research and dissemination purposes. The 3D reconstruction hypothesis embedded into a georeferenced environment can shed light on topographical choices that were made in antiquity. Moreover, types of documentation that are not usually included in a GIS environment, such as old perspective drawings and landscape views depicting archaeological features that are now lost, can enrich the georeferenced data set with additional data. A 3D GIS was for example created for the Roman city of Tarrago, which was used to compute several views of the Roman city from various perspectives and supported the theory that Tarrago's topography was laid out to be best appreciated by the visitors coming from the sea.[370] The location of a lost stretch of the

365 Clarke 2012.
366 See e.g. Gruber 1999; Stoter *et al.* 2011; Stoter *et al.* 2013.
367 Van Maren 2014.
368 See e.g. the suite of software packages for 3D cities by Bentley https://www.bentley.com/en/solutions/3d-cities.
369 On 3D urban mapping, see 3D Urban Mapping: From Pretty Pictures to 3D GIS. Esri Whitepaper. December 2014 available at https://www.esri.com/library/whitepapers/pdfs/3d-urban-mapping.pdf (last accessed Sept. 2016).
370 Orengo and Fiz 2008.

Roman walls was moreover estimated by deriving their location from a 16th century drawing depicting a view of Tarragona from a church's tower.

Focussing on the analytical capabilities of 3D GIS is the recently started project aiming at analysing Insula V 1 in Pompeii, within the framework of the Swedish Pompeii Project carried out by the Swedish Institute in Rome. For their case study, the researchers chose to focus on the house of Caecilius Iucundus that was documented with a laser scanner device. The 3D model obtained was used in a 3D GIS that aimed both at acting as a platform for integrating old and new data and as an analytical tool.[371] The possibility of editing in 3D, which is enabled by the 3D Analyst extension of ArcGIS, allowed the annotation of observations and interpretations that were made in the field directly on the 3D replica of the building. A virtual reconstruction of the house was made in 3D Studio Max by using as reference the 3D model obtained by the laser scanner recording of the extant remains. This 3D interpretation of the structure was then imported into the 3D GIS and used to perform a visibility analysis within the domestic space. As a starting point for further research, two inscriptions of different dimensions and located in different rooms were used as a case study to formulate hypotheses on the symbolic use of space in the Roman house.[372]

In the last few years, several projects have been initiated aiming to develop web-based (2D and 3D) GIS platforms, as the online availability of these tools facilitates data sharing and encourages collaboration between different research groups.[373] Recently, a web-based 3D GIS has been developed for the ancient Maya city of Copan in Honduras as part of the MayaArch3D project. A pilot initiated in 2009 has grown into an international interdisciplinary project that integrates LiDAR data and low resolution 3D reconstructions of buildings made with SketchUp in a WebGIS platform, thus allowing the user to perform spatial analysis (e.g. line of sight) on the 3D landscape and architectural remains.[374] A forerunner of this system is the ARCHAVE, a virtual reality CAVE-based visualization that was created to allow archaeologists to view and query the finds collected from the Great Temple of Petra within their architectural context.[375] The project was initiated in 1999 and represents a successful synergy between computer scientists and archaeologists, in finding a solution for visualizing and better understanding clusters of finds and their relationships in a 3D environment when 3D GIS solutions were not yet available. The finds were spatially distributed and contextualized in the excavated trenches where they came from, thus allowing the archaeologists to perform spatial analysis and to observe patterns in the data that had been not previously identified.[376]

Analysis of visibility and the use of space using computer graphics methods

Alternative methods have been developed to perform visibility analysis on 3D past built environments.[377] A methodology for the visibility analysis in 3D spaces that exploits CG techniques is the approach developed by the Archaeological Computing Research Group at the University of Southampton and presented at the CAA conference in Tomar in 2005.[378] This method is based on the principle that a single light source that casts light in all direction will illuminate or keep in the dark the parts that

371 Dell'Unto *et al.* 2016; Landeschi *et al.* 2015.

372 Landeschi *et al.* 2015, 356-8.

373 See e.g. the web GIS created within the Mappa project (University of Pisa), which aims to create an open digital archive of the archaeological data that are produced by Italian municipalities (http://www.mappaproject.org/?lang=en) and the 3D Spatial Data Infrastructure developed for the *Mapping the Via Appia* project (De Kleijn *et al.* 2016).

374 Von Schwerin *et al.* 2016, 99; Auer *et al.* 2014; Von Schwerin *et al.* 2013.

375 Vote *et al.* 2000; Acevedo *et al.* 2001.

376 Acevedo *et al.* 2001, 496.

377 For a recent discussion on the approaches for visibility analysis in 3D spaces see Paliou 2013.

378 The paper has been published in the conference proceedings in 2007 (Paliou and Wheatley 2007); on the same technique see also Earl 2005.

are respectively visible or not visible of the structure under investigation. In practise, the 3D model of a building created using a CG software is first illuminated by the light source and then its textures, which conserve the information on the amount of light received, and are extracted using the so called *texture baking* technique. This technique is usually used to speed up the rendering process and to reduce the polygon count of a 3D model. By doing so, all the geometry's characteristics, which derive by the combination of mesh, texture and environment settings, are pre-calculated and saved ('baked') into an image (texture). The approach developed in Southampton exploits this CG technique to quantitatively calculate how many times a part of the 3D model has been seen, by summarizing the information of the extracted textures.[379]

This method has been used for the quantitative assessment of the visibility of wall paintings in a digitally reconstructed building (Xeste 3) in Late Bronze Age Akrotiri, to advance hypotheses on the reception and function of mural decoration in Theran society.[380] The building was interpreted as a ritual centre for the community, where ceremonies took place both on the ground and the first floor.[381] On the walls of rooms 3a and 3b, in particular, famous scenes were depicted such as the 'Adorants', the 'male scene' and the 'Crocus gatherers'. The visibility analysis identified the most seen portions of these paintings from the adjoining spaces, which corresponded to the figures that were visually emphasized also by iconographic attributes such as their position in the scene, their posture, their hairstyle and dress.[382] In another application of this approach the researchers investigated the social implications of the distribution of believers in the Church of San Vitale in Ravenna, showing that the place in which women were allowed to stay were the least visually integrated part of the church, both on the ground floor and in the *matroneum* on the second floor.[383] This approach expanded the analytical limitations of space syntax which is confined to the assessment of degrees of visual integration or seclusion based on a single horizontal or vertical portion of space.[384] Besides providing an analysis based on visual perception, they integrated also acoustic data within their mapping, thus implementing a multi-sensory analysis of the space.[385]

Focussing on the social implications of the visibility of roof architectural terracottas was the project on the virtual reconstruction of a 6th century BC temple dedicated to Mater Matuta at Satricum initiated at the University of Amsterdam in 2003.[386] The 3D visualization created in the CG software Maya was aimed at investigating specific theories about the role that the temple decorations assumed as propaganda means for pre-Roman elites. Details of the temple architecture could be reconstructed, such as the original colour of the decorations, which was derived by the pigments that were still present on the terracotta fragments, and the heavy and low roof, sloping at 17°.[387] With the help of a CAVE, the 3D reconstruction of the temple was inspected in an immersive navigation, which showed that the decorations could not be seen from a distance as previously hypothesised, and thus could not carry a political message for the public.[388]

Interestingly, although being a rare example of a thoroughly researched 3D reconstruction that was used in combination with CAVE technology, with the specific purpose of helping in the archaeological interpretation, this project was met with scepticism by both terracotta specialists and computer

379 Paliou and Knight 2013, 232.
380 Paliou *et al*. 2011; Paliou 2014.
381 See e.g. Vlachopoulos 2008.
382 Paliou *et al*. 2011.
383 Paliou and Knight 2013, 233-5.
384 Paliou and Knight 2013, 231.
385 Paliou and Knight 2013, 233-5.
386 Lulof 2011, 16.
387 Lulof 2011, 18.
388 Lulof 2011, 20.

scientists.[389] The specialists were in fact not convinced by the use of these tools to assess the visibility of the decorative motifs, while computer scientists judged the technology as too old and the visualization as not visually appealing enough. When submitted for the Virtual Reality, Archaeology, and Cultural Heritage conference (VAST 2005), the project was in fact rejected by the reviewers' panel.[390] Ratto identified the contrasting epistemic commitments of the two research groups as one of the causes of the not particularly favourable reception of this project.[391]

Besides the analysis of a single structure, 3D modelling and simulations are useful tools to investigate the relationships between buildings, allowing the testing of theories on the 'grammar of space' underlying choices in urban planning. A reconstruction of the Roman Forum that can be explored in a first-person visit and was developed with the game engine Unity 3D has allowed researchers to simulate the location and the evolution of the space for performance within the Forum during the Republican period.[392] The creation of a multi-period simulation that follows the building phases of the Basilicas in the Roman Forum suggests that the space hosting the games was confined at the beginning to a restricted area and occupied later on a much larger area corresponding to the plaza itself.[393]

Another aspect that can be investigated using 3D models is the dialogue that ancient architects wanted to establish between inner spaces and natural landscape. This was one of the aims of the 3D reconstruction of the 3rd century AD House of the Drinking Contest at Antioch.[394] The house was lavishly decorated with mosaics, which are however dispersed across several museums in the United States and in Turkey. The digital model allowed researchers to restore the mosaics in their original location and to create different reconstruction hypotheses with different possible ceiling and column heights. The presence of large windows in the triclinium and in the courtyard wall was hypothesised based on comparative evidence (e.g. Pompeii, Zeugma), where such windows allowed views to inner courtyards or landscape features. Sight lines were tested using computer modelling which showed that there was an unobstructed view to Mount Casius to the south of the house. Besides visibility analysis, a script in Maya was used to simulate the position of natural sunlight. This simulation showed that low light rays would enter the *triclinium* in the late afternoon, thus illuminating the mosaics of the drinking contest. Moreover, the computer model showed that the portico protected the rooms of the northern side (possibly bedrooms) from direct sunlight, which greatly improved living conditions during the hot summer months.

Simulation of lighting conditions

The simulation of light behaviour in past built environments has been the focus of several 3D modelling projects. Natural or artificially created light sources were crucial elements in defining how space was used, experienced and perceived in antiquity, thus making lighting conditions an important interpretative key to shed light on the type of activities that were carried out in a specific space.[395] The simulation of a physically correct light is not a straightforward task. The light source properties need to be simulated correctly, and at present only a few studies have formally investigated the characteristics of different fuels.[396] Moreover, environmental factors that influence how light is distributed in space (such as dust, smog, and humidity) need to be included as well in the 3D modelling process to ensure a reliable

389 Ratto 2009.
390 Ratto 2009.
391 Ratto 2009. Cf. Favro 2006, 329 on how different groups of viewers use opposite criteria to evaluate Virtual Reality models of historical cities.
392 Saldaña and Johanson 2013, 208-9.
393 Saldaña and Johanson 2013, 208-9.
394 Gruber and Dobbins 2013.
395 Papadopoulos and Earl 2014, 135-65, esp. 135-7.
396 See e.g. the work by Roussos (2003) and by Devlin *et al.* 2001, 2002 (below).

result.[397] Also, the computation of lighting conditions usually requires long rendering times as both light parameters and their interaction with the environment (i.e. how the geometry and the materials that are assigned to objects in the scene absorb, reflect and refract light) have to be calculated. For this reason, high performance workstations are currently needed to handle such complex calculations.[398]

The simulation of sunlight for investigating the Augustan planning of the Campus Martius in Rome was the aim of the 'Digital Meridian of Augustus Project', commissioned to the IDIA Lab, Ball University by the Virtual World Heritage Laboratory at Indiana University, directed by Bernard Frischer.[399] For the simulation of the correct position and size of the sun, the researchers developed a plug-in for Unity that used the NASA Horizon's system database.[400] The simulation aimed at shedding light on the relationship between the Montecitorio obelisk and the Ara Pacis, two monuments that were both constructed in the previously unbuilt northern part of the Campus Martius under Augustus. The obelisk, with a sphere added to its top, worked as a *gnomon* (indicator) for the nearby meridian and it is therefore known as the *Horologium Augusti*. The simulation was used to test different theories about the role of the obelisk and suggested a different interpretative key for the relationship between the monuments: the most important elements would not have been the obelisk's shadow, nor the date of Augustus' birthday, as originally thought, but the position of the sun which was centred over the obelisk in the late afternoon of 9th October, the annual festival to Apollo, whom Augustus had appropriated as his patron god.[401]

As far as indoor spaces are concerned, pioneering the application of 3D models for the simulation of lighting conditions in such environments was Simon Ellis, whose case study was the *triclinium* of the upper class Late Antique residence, the so called 'Huilerie' in Salamis, Cyprus.[402] The aim of his study was to investigate how Romans controlled and manipulated light sources to reach the required dining 'ambience' and how darkness and shadows were also acceptable in part of the house. Although Ellis' computer reconstruction was not physically accurate (sunlight was approximately located and windows were absent), it confirmed the hypothesis that the apse of the *triclinium*, where the dinner took place, functioned also as a 'light trap' for natural light. Even when artificial light was used by means of pottery, bronze or glass lamps, the apse was the best lit part of the room, while the rest was deliberately left darker.

One of the first projects dealing with a physically correct lighting simulation within an architecturally defined space was carried out in the early 2000s and aimed at producing a computer model of the frescoes of the House of Vetii in Pompeii as lit by olive oil lamps.[403] The researchers recreated a replica of an olive oil lamp flame and gathered its spectral data using a spectroradiometer. These values were then transformed into RGB and simulated using the software *Radiance*,[404] a suite of programs developed at the Lawrence Berkeley National Laboratory in Berkeley and released as an open source platform in 2002. The results show how the red and yellow pigments that were used as main shades in the frescos are considerably warmed-up by the organic fuel, which accentuates also the *trompe l'oeil* that characterised the composition. A similar workflow was used by Sundstedt *et al.* to simulate the interior and exterior lighting conditions at the Egyptian temple of Kalabsha, which was moved from its original location in the early 1960s. The team created a 3D reconstruction of the temple and recorded various

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[397] See in this regard Gutierrez *et al.* 2008. An early example can be found in Chalmers *et al.* 1995.

[398] The Iridis3 that is used at Southampton has up to 8000 cores (for comparison: a good laptop currently has up to 8 cores).

[399] See http://idialab.org/virtual-meridian-of-augustus-presentation-at-the-vaticans-pontifical-academy-of-archeology/ (accessed Dec. 2015).

[400] http://solarsystem.nasa.gov/

[401] From B. Frischer's opening speech '3D Simulations as Tools of Discovery' at the 2014 CAA conference in Paris.

[402] Ellis 1994.

[403] Devlin and Chalmers 2001; additional case studies are presented in Devlin *et al.* 2002.

[404] Ward Larson and Shakespeare 1998.

organic flame spectra with a spectroradiometer, which were then rendered in *Radiance* to simulate how sunlight entered the building and how the hieroglyphics would have appeared if lit by olive or sesame oil lamps.[405]

A recent paper by Papadopoulos and Earl presents an overview of projects that included physically correct lighting simulation aiming to suggest how illumination may have affected building design and the reception of mosaics or polychromy decorations.[406] In addition, they enriched the number of case studies with their own research on the role of lighting in Minoan architecture, focussing on the burials of the cemetery at Phourni, one house at the harbour of Kommos, and a room that was identified as a pottery workshop at Zominthos. Several reconstruction hypotheses were created for the burials, accounting for different possible roofing arrangements as this was not established with certainty. The reconstruction of the investigated house confirms how light penetration within the building responded to the functions of the rooms: areas that were used for everyday activities were well lit through doors and windows, while the storage unit received little illumination, as the position and small size of the windows allowed air circulation, but not direct contact of the sunlight on the kept food.[407] The most interesting result regards the interpretation of a small room in which the presence of elements such as tools and a potter's wheel had led to its identification as a ceramic workshop. The 3D reconstruction and light simulation showed that this room was poorly lit, in contrast with the typical light conditions that were observed in ethnographic comparisons of pottery workshops.[408] This simulation triggered a reconsideration of the archaeological evidence found in this room, which pointed towards its use as a space to dry and store vessels produced elsewhere in the building.

Analysis of construction techniques and structural behaviour

Furthering their approach on the use of 3D modelling as a research tool, the Amsterdam team focussed on the Temple of Caprifico di Torrecchia, which was chosen because it was well studied and had been also represented in several illustrations.[409] They approached the reconstruction of the temple as a stone by stone process,[410] mimicking its physical building, thus aiming at shedding light on the construction techniques employed for its erection. Interestingly, the 3D modelling process highlighted aspects that had not been seen before, had not been fully investigated or had been ignored in textual descriptions and traditional illustrations, notwithstanding the wealth of publications that had been produced on this structure. New insights into the temple construction could be identified, such as the presence of an interlocking system to allow each *ranking sima* (the pan tiles around the edge of the pediment) to overlap with the following one in order to avoid water percolation on the lower part of the structure. Moreover, a trussed roof appeared to be a better option than the post-and-lintel system (common in Greek temple architecture) as the former guaranteed a better stability to the wooden temple construction.

As illustrated by the example of the Temple of Caprifico, a stone by stone virtual rebuilding can help in shedding light on ancient construction techniques, reaching a deeper understanding of the structure under investigation, but also on the economics behind its construction (e.g. how much material was needed, how many persons, how much did it cost). The use of 3D modelling for such purposes was already evidenced in the 1990s,[411] but was criticised by Gillings, who sustained that the insights that

[405] Sundstaet *et al.* 2004.
[406] Papadopoulos and Earl 2014, 135-165. These projects include: Happa *et al.* 2009; Dobbins and Gruber 2013; Callet and Dumazet 2010; Frischer and Fillwalk 2012; Earl *et al.* 2012.
[407] Papadopoulos and Earl 2014, 146.
[408] Papadopoulos and Earl 2014, 148.
[409] Lulof *et al.* 2013.
[410] The models of the architectural components were mostly created using commercial CG software such as Cinema4D, Autodesk 3D Studio Max and Google SketchUp, but obtained also by structural light scanning of original pieces (Lulof *et al.* 2013, 336).
[411] Daniel 1997.

were reached in this way could not be justified by the effort that was put into the creation of the 3D reconstruction.[412] This critique has nowadays lost its value not only for the improved software and hardware availability and capabilities over the last years, but also for the use of 3D reconstructions for a holistic analysis of ancient buildings. Simulation tools such as the ANSYS structural software can for example be used to assess the stability and the design of a structure.[413] A recent project has performed a structural analysis of the Early Bronze Age so called ‘corridor house’ in Helike (Achaea, Peloponnese). This study has suggested that the house could sustain a second floor and shed light on the type of roof that would allow the structure to stand both in dry and wet weather conditions.[414]

Simulation of acoustics

In the case studies that I discussed so far, sight acted as the central sensory receptor to perceive and simulate space, and indeed a preference towards a visual approach to the past environment has been already recognised and criticised as limiting the broader sensorial experience of people in the past.[415] Among the few projects that have included other senses into their simulations is the ERATO project (2003-2006), which aimed at investigating acoustics in ancient Greek and Roman theatres. The researchers have created virtual reconstructions of both open air and closed theatres (*odeia*), and avatars representing Greek and Roman actors and public to simulate ancient performances.[416] The software that was used for the acoustic simulation was the ODEON Room Acoustics developed at the Technical University of Denmark, which is used by design engineers to predict indoor noise propagation.[417] The software allows the import of the building’s 3D model to set the type of audience, the noise receivers and the characteristics of the building materials, to simulate the correct absorption and refraction of sound waves. The analysis confirmed the different uses of the theatres, showing that the acoustic characteristics of open air theatres made them particularly suited for plays and speeches, while *odeia* were more appropriate for musical performances with instruments such as the lyre and cithara.[418]

Simulation of human behaviour

Virtual crowds of avatars have been used in other projects to populate reconstructed archaeological sites. The aim has been not only to integrate the human component into the architectural space, which otherwise would appear as a void shell, but also to simulate human behaviour in closed and open spaces. One project aimed to test the long held assumption that the Colosseum was efficiently planned to guide people’s movements via eighty large staircases (*vomitoria*), which could empty the audience in just a few minutes.[419] The researchers used a multi-agent Artificial Intelligence system to study the behaviour of avatars that were instructed with a set of AI algorithms commanding their reactions and movements through the *cavea* of the amphitheatre.[420] The simulation showed some bottlenecks in the structure, which slowed people’s movements at critical points, such as at entrances and at the convergence of several paths.[421] Although more tests with different parameters (e.g. higher numbers of avatars, instructed in different ways and with different timings to enter the building) should be made to reach firmer conclusions, this application shows the potential of crowd’s simulation for formulating and evaluating hypotheses on how the past built environment was used in a quantitative and controlled way.

412 Gillings 2002, 228.
413 http://www.ansys.com/
414 Kormann *et al.* 2016.
415 Frieman and Gillings 2007.
416 De Heras Ciechomski *et al.* 2004.
417 http://www.odeon.dk/
418 Rindel 2011; Farnetani 2006.
419 Gutierrez *et al.* 2006. See also Gutierrez, Frischer, Cerezo, Gomez and Sobreviela 2005; Gutierrez, Frischer and Seron 2005.
420 For a more detailed overview about the components of the system see Gutierrez, Frischer and Seron 2005, 56-7.
421 Gutierrez *et al.* 2006.

The simulation of social behaviour by means of virtual crowds has been exploited also in modern urban planning to evaluate different development scenarios, in order to envisage the most practical solutions for traffic and pedestrian flows.[422] Besides the technical challenges related to handle a complex environment made both by architectural and human components (especially when it comes to real time navigation), the most difficult part regards the modelling of human behaviour, which is complex and not easy to formalize into a set of rules. This problem, which has already been observed for the simulation of virtual crowds in modern urban settings, [423] is intensified when past behaviour has to be simulated, as different social rules, emotional responses to space and memories have surely influenced the way people moved individually and as a crowd.[424]

This observation is part of a broader set of considerations related to the use of 3D digital reconstructions for analysis and simulations, that I will like to add to conclude this section. Such visualizations have to be used as an aid to formulate and test hypotheses on past built environments and use of space, but the fact that these analyses are calculated by a computer and in a 'quantitative' way should obviously not be taken as a guarantee of their reliability. In archaeology, a high degree of 'educated guesses' that have to be introduced in the reconstruction is inevitable from the very nature of archaeological data, which are by definition fragmentary. However, such hypothetical integrations, as well as the quality of the original data, have a great impact on the reliability of the results. For analyses such as lighting simulations and visibility, for example, the position and size of windows, the presence of lost and movable elements such as curtains, folding wooden screens (the Roman *valvae*) or plants, played a great role in preventing or allowing the view and exposition to direct lighting in parts of a house. It must be noted, however, that these problematic aspects do not belong only to 3D reconstructions, but are intrinsically rooted in archaeological practise and emerge also when other analytical techniques, such as GIS or Space Syntax, are applied. These techniques have been originally developed in domains (geography/military and modern urban planning respectively) that deal with complete datasets, and have therefore to be used with care in archaeological contexts. While on the one hand, dealing with a fragmentary dataset is one of the most challenging aspects of 3D reconstructions, on the other hand the employment of such techniques represents also a great advantage. By creating 3D reconstructions that are intellectually transparent, missing information that would remain implicit are made explicit in the visualization. Moreover, different hypotheses can be created and tested, thus making visible the array of possibilities that matches the available dataset.

3.5 DISCUSSION

The overview that I presented in this chapter gives us the opportunity to elaborate on the role that 3D modelling has had so far and will have in the future of archaeological research. The developments in the field of 3D recording techniques, their increased ease of use and their decreased costs have made them a valuable tool in the hand of archaeologists for the digital documentation and analysis of archaeological evidence. 3D reconstructions, on the other hand, have been traditionally used as the digital counterpart of manual drawing to create computer-based illustrations, especially for heritage purposes. Their use has proved to be successful in communicating the past to a large audience in documentaries, museum applications and archaeological sites, but an unbalance is clearly visible between 3D reconstructions used for heritage purposes and those used to explore possible answers to questions in the archaeological domain. The examples that I discussed in the previous section show however that 3D reconstructions can play an important role in research, acting as 'laboratories' where hypotheses are visually and quantitatively formulated, tested and opened for discussion. In this sense, they can provide the ideal

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[422] E.g. Aschwanden *et al*. 2009.

[423] Aschwanden 2014, 4.

[424] See at this respect Merlo 2004.

platform to bridge data interpretation and public outreach. They can be in fact used initially as research tools to analyse the available datasets, explore and compare possible models, and then employed as a visual and approachable means to communicate the results of this process to a larger public.

As was shown in this chapter, the critiques related to the authenticity of 3D reconstructions and the lack of instruments to assess their reliability are being dealt with by developing ways to make explicit the initial data and the interpretations. Their impact as research tools has been instead not much explored. With computers having conquered in various degrees even the more conservative archaeologist, the reason why 3D reconstructions of (partially) lost architecture still struggle to be seen as tools that can be used for analytical purposes, besides their value for heritage presentation, cannot be ascribed anymore only to the 'luddism of old-style archaeologists'.[425] In investigating the reasons why the interpretative and analytical value of 3D reconstructions has been so far exploited only in a few projects, I would like to draw the attention to two interrelated aspects that play a crucial role, namely the role of archaeologists in the creation process and the perceived correspondence between realistic renderings and accuracy.

When 3D reconstructions are created for heritage communication, there are few requirements that are usually sought after to meet the public's high expectations, such as a high visual impact and a smooth interactive experience. To reach these goals, the development of these applications is usually assigned to professionals that are called in when the archaeological research and the interpretation of the archaeological evidence are already completed. At this stage, the computer graphics studio entrusted with the creation of the 3D reconstruction (however knowledgeable about archaeology) is rarely in the position to engage deeper with the archaeological evidence, also from the constraints posed by deadlines and production costs. For this reason, questions that arise during the 3D reconstruction process (such as: What was the original colour? Which height should be estimated for the building giving the width of the preserved walls? What are the roofing configurations that are possible for this building? Is this reconstruction feasible? What are possible alternatives?) are therefore often overlooked.

The traditional identification with 3D reconstructions as heritage visualization tools and their creation entrusted to dedicated team of graphics designers have prevented a larger experimentation and exploration of these techniques for research purposes and as heuristic research tools in academia. With few exceptions, little attention has been dedicated to include 3D modelling techniques as topics within university curricula (and in fact many archaeologists-3D modellers are still nowadays self-taught, despite early calls for the creation of a new field of practitioners).[426] Dedicated summer schools and extra-curricular courses include overviews of the main techniques for 3D modelling applied to archaeology, but rarely the analytical possibilities of these tools are explored, as the time available is limited and the focus is usually on heritage valorisation. This combination of factors risks however to perpetrate the situation that was already noted during the 1990s, namely that computer-based visualizations of archaeological sites have been traditionally used as show-cases for technological advances, all too often with little archaeological value.[427] Archaeologists have therefore to play a key role within the team of experts to guarantee the scientific quality of the result.[428] To do so, however, they should be equipped with an adequate general knowledge in the field of digital technologies to guide the creation process and interact in a fruitful way with IT specialists.

As the overview of case studies, that successfully employed 3D reconstructions in formulating archaeologically meaningful hypotheses, shows, 3D modelling cannot be narrowed down to a simple 'press-button' approach. Such applications require in fact both a deep understanding of the possibilities

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[425] See Ratto 2009, citing Niccolucci 2002, 46.

[426] Frischer *et al.* 2002.

[427] Miller and Richards 1995.

[428] Wittur discusses the often problematic collaboration between archaeologists and technicians (Wittur 2013, 36-7).

and limitations of the currently available software packages (looking also at domains other than strictly archaeology), and the capability to develop new solutions from scratch if necessary in order to develop the most appropriate workflow for the specific project requirements. Moreover, the fast evolving field of digital technologies and the complexity related to the creation of some virtual reconstructions require the inclusion of skilled modellers, programmers and technicians that are specialized in developing *ad hoc* solutions. This is especially true if such virtual experiences are meant for the public and heritage valorisation, as visitors' expectations are high in terms of the quality of visuals and the easiness of interaction.[429]

Only when archaeologists develop competencies in 3D modelling tools, will they be able to assess more profoundly the role that the creation of a 3D model, whether a digital replica, a 3D reconstruction or a 3D GIS, can play within their research and will be able to see beyond their use as a visualization aid, but transform them into effective research tools. In the future, when archaeologists will be more aware of the potential of these techniques, 3D scientific visualizations will find their place as platforms for discussion within archaeology as they do already in other domains. The view by Gordin, that 'Images are useful in that they address the common problem whereby people often 'talk past one another', that is, they disagree but do not have any easy way to resolve their differences because they have no common basis around which to make meaning'[430] can be extended also to 3D reconstructions. To this end, however, archaeologists still need to develop visual literacy and train their spatial thinking, which will allow them to use and effectively interpret 3D models.[431]

In this panorama of fast changing technologies, academia should be the place in which these digital tools are taught and experimented with. This requires certainly an interdisciplinary collaboration with experts in complementary fields to provide an up to date knowledge of techniques and software packages to students. An interesting parallel can be established with the use of GIS, which in 1995, Goodchild lamented was used 'as little more than a mapping system',[432] echoed some years later by Stoter and Zlatanova in relation to the path that 3D GIS was undertaking.[433] Since Goodchild's remark, researchers have become more familiar with the analytical possibilities of GIS, which resulted in an increased use of this environment not only for overlaying different data sources, but also for analysis. Likewise, 3D visualizations will start to be increasingly used not just for visualization purposes, but also as analytical tools.

In this chapter, I hope to have demonstrated that 3D modelling techniques have earned a place as research tools within the archaeologists' toolbox. The future developments of 3D reconstructions in archaeology are however in the hand of researchers. Only through a larger experimentation, can new methodologies be developed or existing methods adapted to help archaeological interpretation. 3D models can become the equivalent of today's databases: an index that organizes in a spatial way the data and related hypotheses on the site, which will be considered as the embodiment of multidisciplinary research and a laboratory where to formulate hypotheses and make explicit one's assumption on the past. More work is to be done however towards content curation and the development of transparent, unobtrusive technologies in order for the content to be fully appreciated.

In this process, a more mature approach to 3D archaeological visualizations will emerge. Researchers will be able to choose the most appropriate tools and the visualization types (e.g. a more realistic look

[429] See recent user experience studies on VR museum installations, such as Ray and van der Vaart 2013.
[430] Gordin 1997, 36.
[431] These observations are common in other domains, such as in biochemistry where visual models are used as teaching material (see e.g. Schönborn and Anderson 2009; K.J. Schönborn and Anderson 2010).
[432] Goodchild 1995, 46.
[433] Stoter and Zlatanova 2003.

or a more conceptual rendering) calibrated to the aims of their project. While one may argue that a realistic looking rendering is still to be preferred if the final aim is to present the 3D reconstruction to the public, other, more schematic and simple to achieve visualization types can be more appropriate for analytical purposes. As demonstrated in the project ARCHAVE, for example, the textured model of the surviving architectural ruins was considered to be distracting for the purpose of analysing the finds, and therefore the architecture was instead rendered with grey colour.[434] In this way, the demand for realism, often lamented as being taken as a sign of an accurate and trustworthy 3D reconstruction, will become less cogent.

[434] Acevedo *et al.* 2001.