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Original article

3D reconstruction and validation of historical background for immersive VR applications and games: The case study of the Forum of Augustus in Rome

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ABSTRACT

In the last decades, thanks to the success of the video games industry, the sector of technologies applied to cultural heritage has begun to envisage, in this domain, new possibilities for the dissemination of heritage and the study of the past through edutainment models. More recently, experimentation in the field of virtual archaeology has led to the development of virtual museums and interactive applications. Among these, the "serious game" segment – the application of interactive technologies to the cultural heritage domain – is rapidly growing, also including immersive VR technologies. Applied VR games and applications are characterized by a thorough historical background and a validated 3D reconstruction. Indeed, producing such products requires a tailored workflow and large effort in terms of time and professionals involved to guarantee such faithfulness. Drawing on our previous work in the field of virtual archaeology and referring to recent experiences related to the deployment of applied VR games on PlayStation VR ©, we describe and assess a workflow for the production of historically accurate 3D assets, targeting interactive, immersive VR products. The workflow is supported by the case study of the Forum of Augustus and different output applications, highlighting peculiarities and issues emerging from a multi and interdisciplinary approach.

1. Introduction

The use of virtual reality (VR) within the cultural heritage domain dates back to the end of the 80s and Paul Reilly was the first researcher to coinage the term "Virtual Archaeology" (VA) in 1990 to describe the use of computer-based simulations of archaeological excavations:

> *What does the term virtual archaeology mean here? The key concept is virtual, an illusion to a model, a replica, the notion that something can act as a surrogate or replacement for an original. In other words, it refers to a description of an archaeological formation or to simulated archaeological formation*" [55].

From the first experiments, an onward interest has arisen towards a thoroughly combination between humanities and hard science in order to achieve reliable reconstructions of the past. Since the 90s, method, theory and application of three-dimensional simulation and visualization in cultural heritage have been annually debated in several conferences (e.g. CAA, Eurographics, Digital Heritage) and internationally recognised principles have been established by the scientific community such as "London Charter"[1] or "Sevilla Principles".[2] According to the most recent studies we could define the VA as a process that allows to reconstruct and simulate the past (artifacts, architecture or landscapes) through a theoretical and multidisciplinary approach and the use of digital technologies [2,51].

Continuous experimentation and cross fertilization between the disciplines, led the community to new horizons of research. On the one hand they opened new perspectives and possibilities

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[1] www.londoncharter.org.
[2] www.sevilleprinciples.com.

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1296-2074/

of analysing, interpreting and simulating the past, on the other hand they contributed to develop specific technologies or adapt paradigms and tools, originally created for other fields of applications (computer graphics, VR, image-based modeling, etc.), to this domain. More recently, researchers paid close attention to those technologies, media and communication paradigms aimed at heritage fruition through 3D real-time applications such as virtual reality, augmented reality, serious game, etc. They could allow users to experience history and archaeology both visually and narratively, to observe and interact with artifacts, architecture and characters belonging to a specific period in history. Historical content, in fact, conveyed by means of this media with a scientific approach, could help institution in dissemination and understanding of the past [3,52,4,11].

The start was slow and hesitant due to the absence of adequate technological solutions and theoretical guidelines. Furthermore the information science still had to formulate appropriate communicative languages and paradigms for this emerging domain. Given that, the first experiments were too complex, lacking of interest for users or deficient of historical accuracy and validity. Nowadays, thanks to the evolution of effective theories, methods and tools, virtual archaeology and 3D application for heritage are increasingly growing inside museums and sites. This success depends also on the use of dramatization and storytelling which take advantage of emotional processes to engage users and disseminate knowledge [54,47].

One of the most innovative ways for understanding culture and history is the "serious game" or rather the adaptation of an interactive technology, well-known in the entertainment industries, to the cultural heritage domain [5].

1.1. Games and culture: state of the art

The success of entertainment game industries has given birth to new types of outputs in the field of cultural heritage, including serious games and some virtual museum applications (based on mixed reality, virtual reality, virtual worlds, etc.) that share the same infrastructure and core games technologies and use virtual reconstruction and engagement mechanism for edutainment and educational purposes [1]. Ancient Pompeii [46], the Virtual Museum of the Ancient Via Flaminia [32], the Virtual reality reconstruction of Otranto [16] or Roma Nova [64] – virtual experiences which allow the exploration of ancient contexts – are just some of the first examples of interactive applications for the cultural heritage with game-like navigation mechanism.

More recently, serious games, thanks to its intrinsic balance between learning, narration and fun experience, are becoming very popular. A virtuous connection between games and culture is constantly growing and its impact on the society is testified by some recent virtuous case studies which uses storytelling and modern video games logic [12,62,47].

In 2011 the Foundation of the Hellenic World produced *Battle of Thermopylae*, a game that mixes storytelling techniques and game to disseminate historical knowledge about the battle and the associated legends [15].

In 2012 the Department of Art History and Visual Studies of the Duke University performed the *Fort Ross Virtual Warehouse* project, a 3D real-time multiplatform serious game aimed at discovering an outpost located on a bluff along the Northern California Cost and its landscape with the purpose of disseminating and teaching cultural information related to the site in an innovative way [42].

In 2015 *Defend the Wall* was created by Evoca srl. It is serious game that deals with the technology and tactics of siege of the 4th Century BC, the war machines and the strategies of attack and defense, the architectural characteristics of the towers and the city walls of Paestum. The issue is developed through a short movie followed by a game using gesture-based interaction, suitable for a diverse audience, particularly young people [31].

In 2017 the MANN, Archaeological National Museum of Naples, produced *Father and Son*,[3] a narrative 2D game rated 4.7/5 on Google Play and downloaded by more than 33,000 players. It is a story of a son who travels across time and space, from the ancient Rome and Egypt to the modern Naples, to discover the life of his father, an archaeologist he never knew.

In 2018 was released *Mi Rasna – Io sono l'Etrusco*, a strategy game for mobile based on the Etruscan civilization where the user discover the ancient society and earn extra-bonus when geo-located on Etruscan archaeological sites or museum.[4]

During the last years VR games are emerging in the cultural panorama. In 2018 the start-up "Beyond the gate" produced the on-site VR game called *Beyond the Castle*. The game is located in the ancient Torre Falconiera of the Sforzesco Castle (Italy), where visitors, wearing HDM and taking up a special crossbow, have to defend the castle under siege.[5] The current Horizon 2020 financed project *i-MARECULTURE*[6] investigates immersive technologies – virtual visits, serious games with immersive technologies and underwater augmented reality – to increase exploration time in an underwater archaeological site as in the case of the VR visualization of the Mazotos shipwreck [43].

An interesting application is *Arkaevision Arkeo*. It is an immersive VR application aimed at discovering the temple of Hera in Paestum Posidonia. During the experience, the user finds himself interacting with a digital actor, the priestess Ariadne, who accompany him on an interactive journey through the rituals, myths and architectural and artistic artifacts of the Magnogreek city in the 5th Century BC [9]. This application was developed within Arkaevision, an integrated digital platform which uses immersive virtual reality and mixed reality as main technologies and experiential modes for disseminating cultural heritage.[7] It is the result of a research and development project funded by MISE within "Horizon 2020 Call for Proposals" and was carried out by Digitalcomoedia in collaboration with CNR ITABC and Beyond.

All the mention games have been designed and developed by specialist in collaboration with institution (museum or archaeological sites) and under the scientific assistance of expert in different cultural domain. Peculiar examples are the Discovery Tour of *Origins* and *Odyssey*, the last two chapters of the Assassin's Creed saga, produced by the famous Ubisoft Entertainment game industry.[8] Discovery tour is a purely educational game mode that allow users to explore and interact with reconstructed historical sites through guided tours divided into thematic areas and according to recent studies, performed by the V-Must consortium on digital heritage sectors, this spin-off application can be properly considered as a virtual museum.[9] The great novelty of this two last chapters is the innovative approach and attention the creators paid to historical reconstructions. Indeed Ubisoft entrusted a team of historians and archaeologists with the role of consultant for supporting the team and validating virtual reconstructions.

In this kind of games, which take place in a given and well known historical period, three-dimensional assets and virtual reconstructions take on a fundamental role. They are the setting for the game and the success depends not only by the screenplay but also by the accuracy and the faithfulness of the represented histori-

[3] www.fatherandsongame.com.
[4] www.egameapps.com/mi-rasna.
[5] www.beyondthegate.io/en/homepage.
[6] www.imareculture.eu.
[7] www.arkaevision.com.
[8] www.ubisoft.com.
[9] www.v-must.net/virtual-museums/what-virtual-museum.

cal environment. Both historic and imaginary world are perfectly integrated. Maxim Durman, historian of the Ubisoft team for Origins, during an interview said that even if playing the game cannot substitutes historical studies, however it plays an important role in edutainment, supporting didactic activities and disseminating information through amusing experiences. For this reason any presented asset in the historical reconstruction must be accurate as much as possible[10] .

Projects oriented at integrating heritage and video games are consistently increasing also in the field of applied science. Creative Europe and Horizon 2020 are focusing on this topic and the recent announcements are even more oriented at edutainment, fostering creative industries, researchers and museums at developing this media in museum in order to improve visitor engagement, interaction and learning mechanism. Interesting results on advantages of applied immersive VR games compared to traditional approaches, were already obtained for instance in [9,59,49] and [40].

2. Research aim

Historical accuracy and validation are the keywords that portray the virtual backgrounds made for applied VR games and applications mentioned in the previous sections, however in order to guarantee such faithfulness their production requires a complex and well-founded workflow. Indeed, creating such interactive VR applications targeting cultural heritage requires extra effort in terms of time and professionals involved which rigorous collaboration is crucial to achieve robust results. The aim of this work is to provide a complete reproducible reconstruction workflow – purposely designed for real time VR products, highlighting peculiarities of this multi and interdisciplinary work and challenges arisen, with practical application to the case study of the Forum of Augustus.

3. Material and methods

3.1. The case study

The case study we are going to deal with in order to better illustrate the workflow is the 3D reconstruction of the Forum of Augustus at the beginning of the 1st Century AD for VR cultural applications and games. In Section 4 this aspect will be dealt with in detail.

The Forum of Augustus is a magnificent architectural complex built by the Emperor Augustus between the end of the first century B.C. and the beginning of the first century A.D. and it is the second of the Imperial Forums of Rome, after the first forum built by Caesar (fig. 3). It was a monumental complex which hosted the majestic temple of Mars *Ultor* (the Avenger): Augustus made the vow to build that temple before the battle of Philippi (42 B.C.), taking revenge on the murderers of Julius Caesar, Brutus and Cassius. Two porticos supported by corinthian colonnade enclosed the square, and behind this columnade there were four semi-circular exedrae (two for each side of the forum). The two major exedrae could have served as courts while the two minor were probably used as archives and for educational activities (Gymnasium). The back wall of the porticoes and of the exedrae were articulated with columns framing a series of rectangular niches adorned with a rich variety of different statues. At the end of the northern portico, there was the Hall of the Colossus, a decorated chamber which hosted the colossal statue, approximately 11 m tall, representing the Genius Augusti (the protective deity of Augustus).

Nowadays, the remains of the Forum are still visible and well preserved in the archaeological area of the Imperial Fora (see Fig. 1), and all the findings discovered during the excavation performed during the last century (statues, architectural elements and decoration) are shown in the nearby museum of the Trajan's Markets – Imperial Fora Museum. Even if the Forum of Augustus is one of the most known and studied buildings from Roman times and several reconstructive hypotheses were drawn over the years, archaeological discoveries have revealed new elements and new reasoning, and hypothetical reconstructions have been proposed and adopted in this work [60,61,41].

Our laboratory has already designed a full 3D reconstructions of the Forum for "Admotum" [27], a gesture-based application created for the exhibition "Keys to Rome"[11] which was held between 2014 and 2015 at the Museo dei Fori Imperiali and organised by V-Must, the virtual museum Transnational Network.[12] This reconstruction, however, represented the Forum in the Trajan's period (98-117 A.D.) when its shape had been significatively changed as a result of construction work carried out for the edification of the Forums of the emperors Nerva and Trajan. In addition, some internal areas of the forum had not been modelled in detail as they were not accessible in the previous application. Given that, it was decided to restart from this baseline by remodelling the Forum from scratch according to an approach more oriented to the world of games but reusing, when possible, the 3D assets and historical study.

3.2. Preliminary remark

3D models created in the reconstruction of the game scenarios are commonly defined as "figurative", which means they represent reality in a plausible way. Although their complex topology is optimized to respond to operational needs, they do satisfy some important characteristics such as the recognizability of the basic geometry that composes the object and the characterization of the surfaces with chromatic information derived from photographs or procedural images (textures) [7]. The virtual reconstruction of the Forum of Augustus was created on the basis of direct surveys – characterized by great precision and reliability – study and interpretation activities based on scientific approaches and principles of virtual archaeology [14,44]. This operation has guaranteed the historical reliability of the model but required an articulated and multidisciplinary workflow that we have divided into three main segments and can be reused for future project (NB: The workflow described below refers only to the creation of cultural assets and is not exhaustive of all the development phases of a video game for which we ask the readers to rely on specific literature):

- *Pre-production* (Section 3.3): preliminary studies including 3D survey and digitisation activities and historical sources collection.
- *Production* (Section 3.4): it has mainly concerned the aspect of archaeological interpretation, reconstruction through 3D modelling of game assets, validation of historical background, performance analyses and optimization of the assets.
- *Level creation and authoring* (Section 3.5): it was mainly connected to the graphic layout and environmental simulation through the composition of the scene within the graphics engine and the addition of details that confer realism, such as lights, particle effects, sounds, etc.

[10] Interview on http://www.rollingstone.it/cultura/gaming/page/2/ (accessed 13.02.19)

[11] www.keys2rome.eu/eng/.

[12] www.v-must.net/.

Fig. 1. Right: the archaeological site of the Forum of Augustus nowadays. Left: Hypothetical reconstructive layout of the Forum in the Augustan era overlaying the archaeological remains (grey area). (A) Temple of Mars *Ultor*; (B) Hall of *Colossus*; (C) Guardpost; (D) Major *exedrae* used as tribunal; (E) Minor *exedrae* used as archives; (F) Porticos; (G) Central open area.

3.3. Pre-production workflow

This phase, which is preparatory to the creation of the game assets, is aimed at collecting all the documentation useful for the historical reconstruction of the game context. The documentation can be dived in two categories:

- geometric acquisition of cultural site and museum objects using image-based or range- based sensors with the aim of obtaining digital replicas.
- collection of all the existing historical and archaeological sources and testimonies regarding the sites and all the connected artifacts and testimonies.

3.3.1. 3D survey and digitisation

Technologies and tools for digitization are numerous: from three-dimensional surveying (laser scanner and digital photogrammetry) to topographic surveying, each with different characteristics such as accuracy, precision, portability, cost and automation [56]. The models, built on real data, ensure a high degree of realism in terms of formal coherence and aesthetic rendering [38].

During the 3D survey of the Forum of Augustus we used Image-Based-Modelling (IBM) method which combines computer vision and photogrammetric algorithms to obtain three-dimensional models from a dataset of two-dimensional images taken around the artifacts. In this particular case we used a full-frame camera equipped with a 35 mm lens to capture photos and a laser total station to measure the topographic network of control points (which are fundamental to achieve models featuring high geometrical precision and georeferencing accuracy). Using this method we scanned both the architectural remains of the Forum, in Via dei Fori Imperiali, and the remains of the marble decoration of the porticoes and the Temple of Mars Ultor preserved in the Museum of the Imperial Forums.

The data gathered on the field were processed using Agisoft Photoscan[13] software. The software was able to estimate camera positions and then calculate depth information for each camera to be combined into dense point clouds. Subsequently the point clouds were triangulated to obtain meshes. Last step for creating the virtual replica of the scanned objects was the automatic parametrization of the meshes and the generation of textures. The final result of the digitisation process can be seen in Fig. 2.

3.3.2. Sources collection

It concerns the collection of all available historical documentation and archaeological evidences that can support the virtual reconstruction. The reliability of the reconstruction is determined by the meticulousness of the work of collecting and managing these data [34,33]. The sources used for the interpretation and 3D reconstruction can be uncountable. It depends on the context we are dealing with. In our case we have used the following:

- Extant structures: archaeological evidence still visible in situ.
- Archaeological evidence removed from the site whose original position is known.
- "special finds", archaeological evidence still existing but non in situ (i.e. found outside their original context) such as architectural fragments of lintels, columns or roof tiles collapsed to the ground (their existence, appearance and size is certain, while their original position is uncertain).
- Testimonies from the past, such as descriptions of buildings and their function contained in historical documentation; literary sources; ancient iconography; old photos, drawings, paintings, watercolours illustrating previous state of conservation; technical drawings from the 20th century.
- Scientific studies as archaeological reports and articles; structural, architectural, material degradation analyses.
- Theoretical building rules, orders and modules of the architecture of antiquity described by Vitruvius in *De architectura libri decem*.

3.4. Production workflow

This segment involved a team composed of different professionals including computer scientists, graphic designers, surveyors, modelers, archaeologists, architects and historians. The aim was to study the ancient artifact with a multidisciplinary approach and obtain its reconstruction through a range of proven activities [17,20]. The production was divided in 2 steps, interpretation and 3D modelling, both performed almost simultaneously.

[13] www.agisoft.com/.

Fig. 2. Digitization of the archaeological site of the Forum of Augustus and fragments of the marble decoration performed with IBM method.

3.4.1. Interpretation

All the sources acquired and organised in the previous phase were, at this stage, analyzed and discussed together with the scientific consultants, expert in the various disciplines (archaeology, history, architecture, structures, etc.), in order to sketch a plausible reconstructive hypothesis.

As a support tool for discussion we used the 3D models obtained from the surveys in order to carry out graphic simulations and extract accurate metric data. In this way it was possible to virtually restore the marble fragments and hypothesize the original location of the fragments through anastylosis processes. As in the case of the porticoes or the *attic* of the Forum (the architectural element above the colonnade embellished with decorative Caryatids alternating with heads of Juppiter), they were partially digitally recomposed by juxtaposing the scanned fragments of the decoration. The missing parts were then deduced from rhythm and proportions of the pieces, their size and Vitruvius' architectural rules. It was necessary to combine a large number of sources in order to formulate the reconstructive hypothesis. Furthermore, for each architectural element, part of the building, we had to reconstruct different physical properties: shape, volume, size, materials, decorative apparatus or architectural style.

Once the reconstructive hypothesis was formulated, the modelers then have sketched the first draft reconstruction of the assets. This first draft was then used for further investigation and verification before modeling the final assets (see Section 3.4.2). The continuous involvement and exchange between the different professionals ensured the quality of the virtual reconstruction. Each new version of the virtual reconstruction was verified until the approval of the final version discarding those that, during the work, resulted less probable.

Fig. 3 illustrates part of the sources used to elaborate the interpretative hypothesis of the temple and their relation with the virtual reconstruction: D01-06: images documenting the main architectural elements still present; D.07-09: architectural fragments preserved within the Museum of the Imperial Forums; D.09: Relevant fragment from the Ara Pietatis depicting the facade of the temple of Mars Ultor in the Forum of Augustus; D.10: Table by the architect G. B. Piranesi, depicting the Forum of Augustus at the end of the 17th century; D.11-12: scientific studies from journals and books. In order to set-up a reliable and "transparent" hypothesis, it is necessary to track the whole process of the virtual reconstruction. This means that not only the sources, but also the logical and deductive processes of analysis and synthesis, that led us to elaborate the virtual reconstruction from the interpretation of the sources, must be mapped and recorded in a formal language.

Reliability of the reconstruction and transparency of the data are primary requirements according to the principles of the London Charter [21] and can be managed with different approaches as long as the result is adequate. In our case we have adopted the Extended Matrix,[14] a visual node-based formal language that, being based on a stratigraphic approach in use in archaeology, allowed the archaeological documentation and the virtual reconstruction to be connected [18,19]. In this way, for each property of each object, it was possible to record the interpretative process used according to the available sources (deduction on the basis of comparisons, parallelisms, testimonies, etc.) and the reliability of the sources (see Fig. 3).

3.4.2. 3D modelling

This activity consisted in the modelling of the 3D reconstructive asset through the use of computer graphics and takes place almost simultaneously with the interpretation and validation activity. The final output of the work will inevitably influence the modelling approach (depending on target platform used to deploy the interactive game or application). It usually affects the overall workflow carried out on geometries, texturing, etc. when targeting specific real-time output, also including aesthetic aspects. In fact, virtual 3D environments created for standard or non-stereoscopic visualization, generally require vast re-adaption for immersive VR experiences targeting Digital Heritage field. Designing and crafting immersive virtual environments for such experiences may present bottlenecks and huge efforts in terms of 3D modelling and/or optimization tasks. Depending on locomotion models employed and spatial constraints, specific elements of the 3D scene may capture users' attention or require higher complexity. The amount of detail required to guarantee a consistent experience through Head Mounted Display (HMD) can be overwhelming for large 3D reconstructed environments, especially when small teams are involved in the workflow. For this reason, before starting the actual 3D modelling, a spatial prioritization map is produced in order to optimize and drive the overall 3D assets workflow. In order to employ such step, a preliminary 3D draft model of the 3D

[14] http://www.osiris.itabc.cnr.it/extendedmatrix/osiris.itabc.cnr.it/extendedmatrix/.

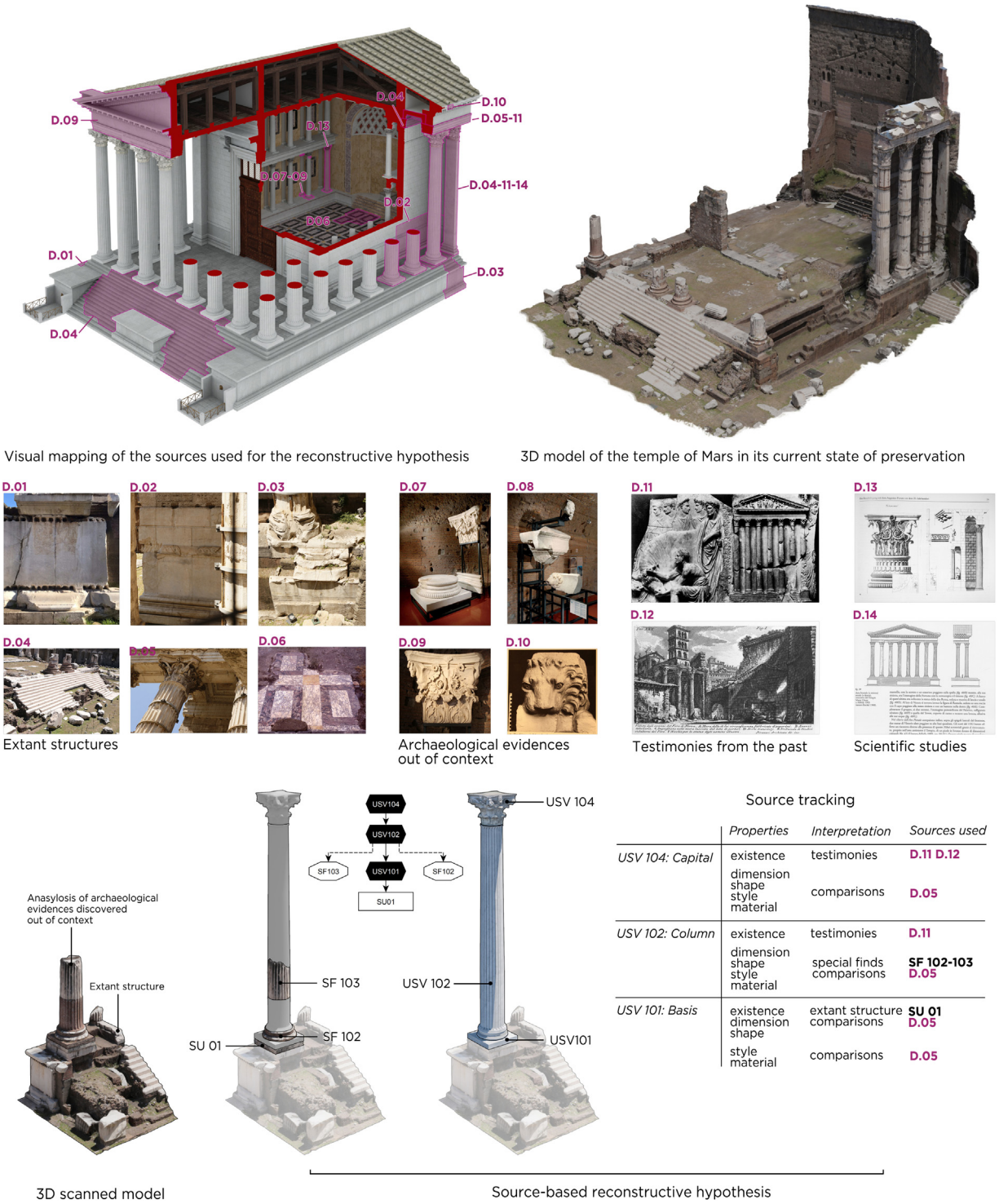

Fig. 3. Top row: visual mapping of the sources that allows to keep track of the reconstructive process making it transparent and scientifically accurate. At the top right: 3D model of the temple of Mars *Ultor* in its current state of preservation. Medium row: some of the sources used for the reconstruction. (credits: images D.07-09: Mercati di Traiano – Museo dei Fori Imperiali; images D.06 and D.10: Archive of the Sovrintendenza Capitolina). Bottom row: source-based reconstructive hypothesis of a column of the temple and tracking of the sources using the extended matrix approach. For simplicity we have used, in this example, a synthetic version of the EM. node system.

environment is required. In our case we exploited the Forum of Augustus – already reconstructed in the Trajan age [15] (see Section 3.1). Even if there are significant differences between the two models, the main architectural spaces and volumes were pretty similar and the quality of model sufficient for our purposes.

3.4.2.1. Spatial prioritization. Previous research on stereoscopic visualization and depth perception in HMDs [36,10] combined with the adopted locomotion model for the interactive VR experience – can be exploited to perform a preliminary step to *rank* the vir-

[15] http://keys2rome.eu/.

tual environment in terms of detail requirements. The main goal is to minimize 3D modelling effort targeting immersive VR by prioritizing the workflow for selected elements/areas of 3D scene, depending on planned user locomotion. In order to produce a spatial prioritization map, we took into account two target locomotion models for immersive VR exploration: (a) teleport and (b) node-based locomotion [8,6].

Fig. 4 shows the overall prioritization map resulting from the considered locomotion models, to support and guide 3D modelling workflow. We defined three different priority levels depending on users' potential proximity (d) during exploration: d <15 m (red); d <30 m (green); d over 30 m (white). Regarding the Augustus Forum 3D reconstruction for instance, this guided modelers to focus their effort on floor details (A) instead of roofs (B – e.g. porticoes). Thanks to the spatial ranking, some elements like the columns of the main entrance of Temple of Mars (2) resulted in light requirements in terms of geometric detail, especially regarding capitals (see Fig. 4).

Same considerations apply to Victory statues (1 – top of the temple), requiring minimal detail on both geometry and texturing level, being very far from all possible user locations. Such an approach resulted in a time-saving solution for 3D modelers, offering a small team a valid support to prioritize the effort during the creation of static elements of the 3D virtual environment.

Additional data can be employed to support or fine-tune the overall prioritization map: when available for instance, real users propensities and spatial behaviors can be exploited. An immersive VR application ("ovrWalker"[16]) was previously deployed during public exhibits to explore a set of scenes – including the 3D reconstruction of the Forum in the Trajan age (see Section 3.1). The interactive application was enriched with a special software component to anonymously capture casual user sessions.

During the public event TourismA 2018[17] for instance, the component was able to collect large amounts of locomotion data, with 0.1 s temporal granularity. Since the adopted locomotion model in ovrWalker offered visitors a completely free exploration within the forum, the dataset was analysed and encoded to understand users' spatial behaviors [24,26,25] providing 3D modelers additional information to refine the modelling workflow and priorities.

3.4.2.2. Asset creation. Reconstructive 3D assets were modelled and completed after the final validation and the availability of the digital replica of the site and artifacts (Section 3.3.1) facilitated the process and ensured greater accuracy. The digital replica of the site was fundamental in the design of the volumes according to the correct ratios and measurements and in the positioning of the architectural elements characterized by roman rhythms and proportions (columns, architraves, steps, etc.).

The juxtaposition of the two models allowed to reconstruct the geometries with great precision avoiding the typical problems that can be generally found using two-dimensional drawings: inconsistency between sections or plans, lack of information in the parts not that are not represented, etc. (see Fig. 5).

In computer graphics, the denser the polygonal resolution of the mesh, the greater the detail is. However, the topology and the amount of geometry of the model strongly affects the performance of the Graphics Processing Unit (GPU) and therefore it is necessary to overcome the problem by using some optimization techniques in order to minimise the workload and increase the efficiency of real-time rendering. These optimizations must not affect the aesthetic aspect but must always allow the recognition of the represented artifact and its details, thus ensuring fidelity and realism of the model. Therefore, in order to achieve a compromise between smooth performance and realistic visuals, the optimization can be performed borrowing different well-known techniques from computer game design. In the reconstruction of the Forum two main techniques were used to maintain a consistent detail: (1) LODs[18] for several elements and (2) normal mapping or parallax occlusion mapping (POM) techniques to simulate additional detail on surfaces (relief patterns, etc.).

In the first case, different versions of the model are created with a progressively lower polygonal resolution, which will then be dynamically managed by the game's graphic engine depending on camera range [45]. In our case, the polygonal detail has been also evaluated considering the spatial priority described in the previous paragraph. In other words, depending on the rank, the various elements of the virtual environment were modeled accordingly. For example, ceilings, roofs or decorations on the top (11 m far from the user's point of view), have very simplified geometries. Normal mapping and POM techniques are both used to simulate additional 3D detail through textures without increasing the geometrical complexity and maintaining simplified and low-poly meshes.

Normal mapping is the best compromise between visual quality and real-time performance. Normal map is a RGB texture which simulates the complexity of the relief of the surfaces without having to describe them topologically (e.g. bas-relief, mouldings, etc.). Each texel in fact encodes normal information that can be exploited by lighting model to simulate relief.

Parallax Occlusion Mapping or POM, is a similar but more advanced technique which relies on a gray scale texture representing a displacement map (or height map). It is an enhancement of parallax mapping, used to procedurally create a 3D definition for textured surfaces consistent with current eye position. This technique is more computationally expensive on the GPU compared to normal mapping, but offers a more consistent perception of relief and surface micro-variations due to the parallax effect, when performed on each eye of the HMD. We employed this technique only on low-poly assets presenting complex mirco-variations very close to user in terms of locomotion, like column shafts and the marble slabs of the Forum floor.

In our case study all the normal and height maps produced internally have been created through baking processes between models with different LODs. In the case of the temple of Mars *Ultor*, the high-resolution reconstructive model has a high geometric detail. On the outer wall of the *Cella*, the ashlar decoration and the continuous band with meander waves are modelled respecting the original measurements recorded in the acquisition phase. The optimized model used in the game instead has a more simplified geometry where the details of the above elements is purely visual and determined by normal map. The aesthetic perception is almost identical and the formal coherence to the historical artifact is guaranteed (see Fig. 6A).

Whenever possible, 3D models of very peculiar and complex architectural elements such as the Caryatids of the *atticus* or the Corinthian capitals of the *Cella* decorated with Pegasus protomes, were produced from 3D survey. The resulting high-resolution models have been simplified through polygonal decimation and then optimized through semi automatic re-topology operations. This approach allowed to obtain simplified meshes, consisting of quadrangular faces offering better manipulation in CG software than original triangulated high-poly models [39]. Furthermore during this operation it is possible to decide the target number of polygons that the model should have. Once regular and low-poly meshes were obtained, several baking operations were performed to trans-

[16] http://osiris.itabc.cnr.it/scenebaker/index.php/projects/osglab/ovrwalker/.
[17] http://www.tourisma.it/home-2/.
[18] Level of detail.

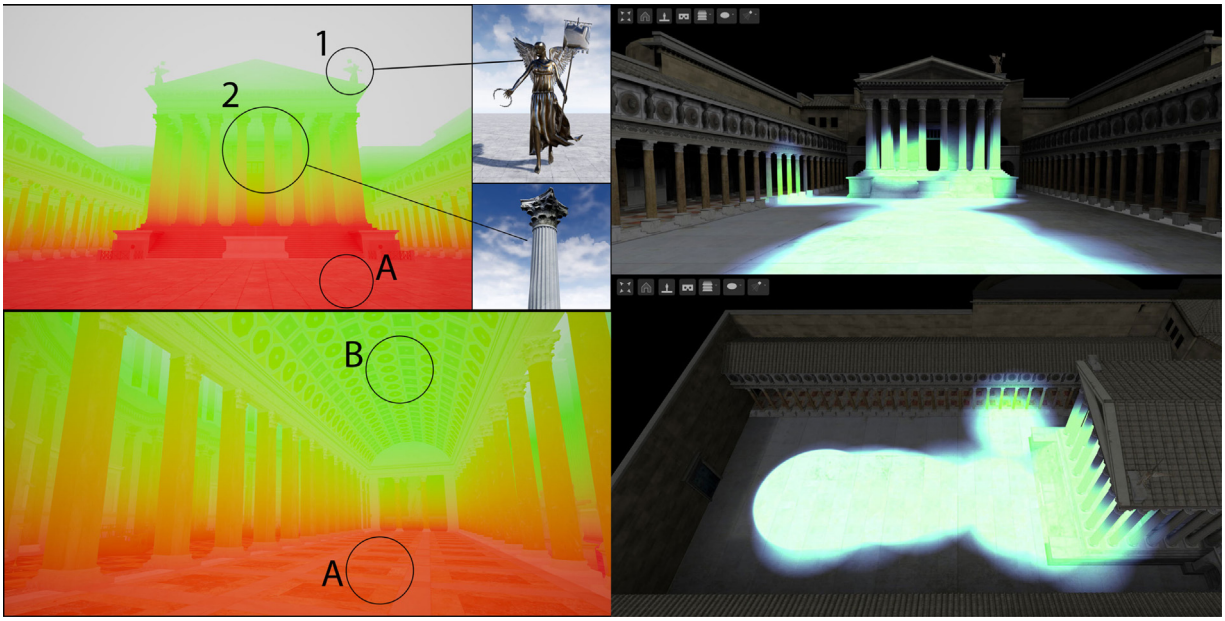

Fig. 4. Workflow prioritization map (left). Most visited locations of the previous 3D reconstruction of Forum of Augustus, resulting from locomotion data recorded during public exhibits (right).

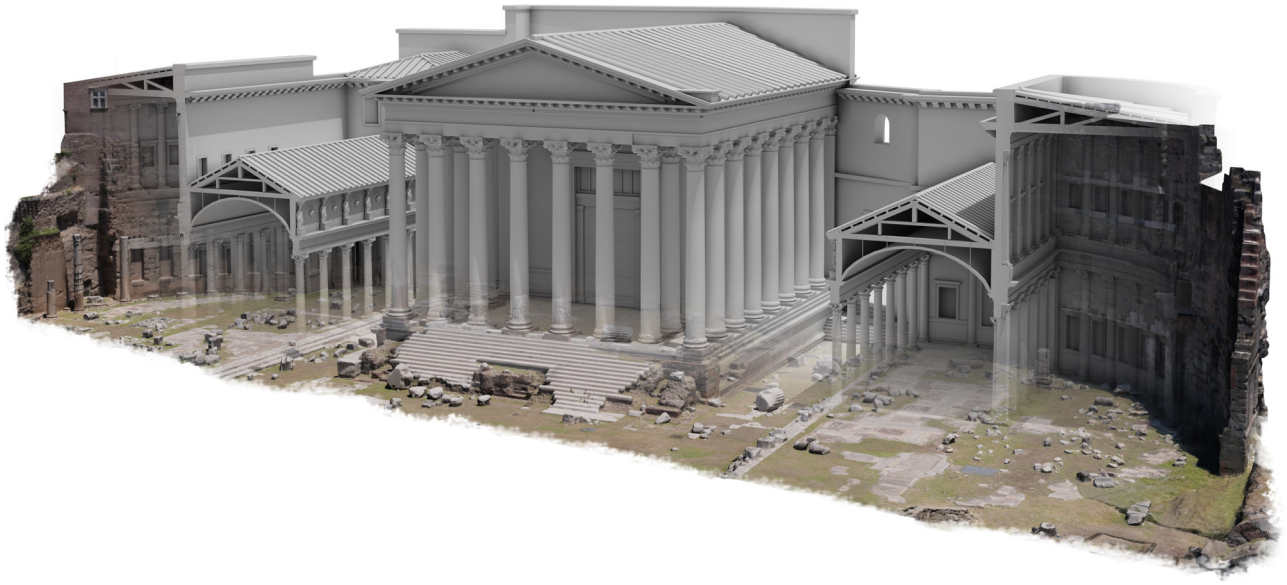

Fig. 5. 3D modelling of the Forum of Augustus. The creation of the reconstructive geometries is made directly on the reality-based model obtained with IBM techniques.

fer normal maps and to achieve the same visual result as the original models (see Fig. 6B).

Sometimes additional manual modelling work was necessary in order to virtually restore some missing parts or close small holes in the mesh caused by under-sampling in the 3D survey. Such a result, of high quality and great detail, allowed modelling team us to save a lot of time. Indeed, modelling such complex geometry and textures would have required laborious sculpting operations if carried out manually.

3.4.3. *Texturing*

Recent game engines like Unreal Engine, Unity 3D, etc. take advantage of a combination of textures to reproduce the physical behaviour of surfaces in relation to the flow of light. This texture are called PBR or physically-based rendering. Among the most used properties, we employed a metalness workflow (albedo, roughness, metalness and emission) along with normal-maps, whose use is by now part of modern game engines, in order to improve the appearance and photorealism of interactive virtual 3D scenes. In order to obtain photorealistic 3D models, different PBR textures type have been created:

- Albedo represents the base chromatic information and it is created either from photographs or through drawings made by graphics (especially for lost decorations). The simulation of patterns and colors of specific elements, such as frescoes, stuccoes, marbles, etc. required comparison with the historical-archaeological documentation.
- Roughness determines the micro-relief that influences the behaviour of light on the surface according to the type of material represented (marble, bronze, travertine, etc.).

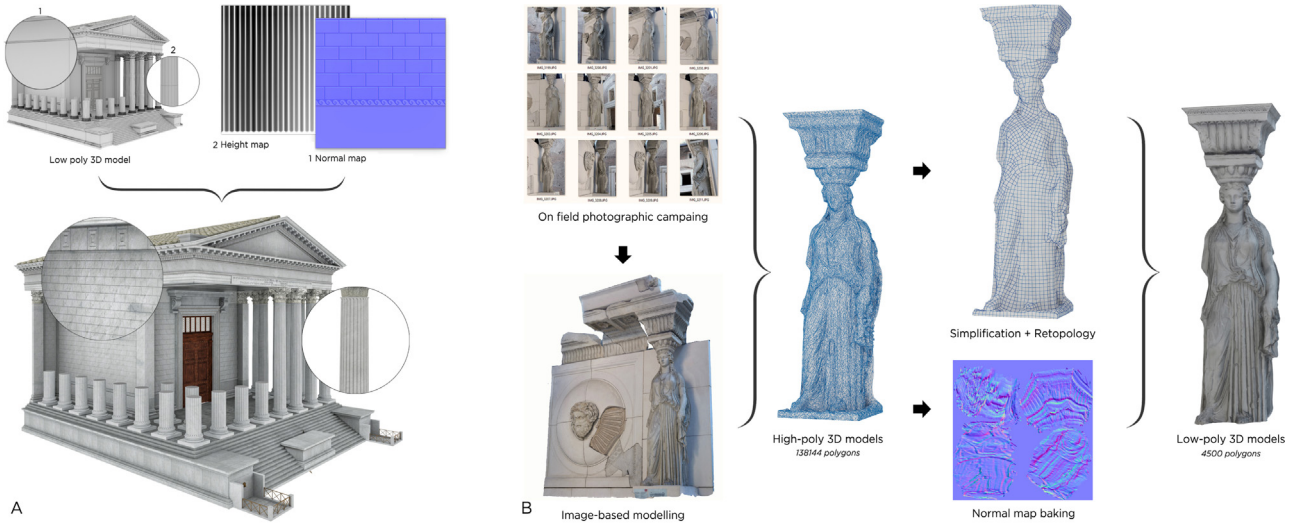

Fig. 6. Optimization workflow: (A) example of texture used on low-poly 3D model for simulating high-poly surface and resulting rendering. The ashlar decoration on the wall is created by normal maps while the vertical fluting on Corinthian order columns is generated by height maps; (B) example of the image-based models optimization workflow adopted to obtain realistic models from scanned museum objects.

- Metalness is used to set a material as metallic or non-metallic and is used in combination with the roughness map to control the amount of reflection according to specific material or surface degradation due to consumption (braziers, candelabra, fences, etc.).
- Emission is used to simulate a self-illumination of a model surface by increasing the pixel intensity. We applied this map to the glasses of the roman lantern in order to simulate the oil light and portions of the *Suburra*.

The combination of these properties (as textures) determines the surface behaviour of the model and how it will react to lighting. These are applied to the model by means of a UV mapping technique in which the polygons of the mesh are unwrapped and associated with the two-dimensional plane of the texture. For the creation of textures, some free online libraries were used to reproduce the most common materials such as metals or marbles, but in most cases it was necessary to create textures ad hoc through photographic campaigns or performing digital painting as in the case of the painted marble slabs.

In order to simulate some surfaces, such as the large wall in ashlar of *lapis Gabinum*, that separated the Forum from the *Suburra*, 3D survey was used. IBM techniques made it possible to obtain a high-resolution 3D model of a well-preserved portion of the wall. Then, in post production, it was possible to transfer the color and geometric detail from the model to the textures of albedo, normal and roughness using "backing procedures". Finally, further corrections in 2D editing software were necessary to make the resulting textures "tileable". This process was time consuming but allowed to build a highly accurate and realistic result during real-time rendering (see Fig. 7).

Creating textures for the whole Forum was laborious and complex. The amount of complex mouldings and architectural elements and the multitude of materials used, such as the different types of white and coloured marble (white *Carrara*, *pavonazzetto*, *giallo antico*, *africano* and *cipollino*) often combined in polycrome geometric decorations (floors, walls of the Cella and Hall of Colossus), required the production of several albedo textures arranged into approximately 50 atlas (see Fig. 7).

Table 1
Relation among material evidences and their reconstructions.

Material evidence	Reconstruction
Extant structure: archaeological evidence still present *in-situ*	Structural virtual reconstruction based on archaeological evidence *in-situ*
Fragmental virtual anastylosis: recomposition of collapsed architectural fragments which were found out of context and now preserved in museums	Fragmental virtual reconstruction. Completion of repositioned fragments
Lacking of physical evidence. Existence is deduced either by a various necessary conditions (roman styles, modules or architectural rules) or from testimonies (i.e. Ara Pietatis depicting the lost facade of the temple of Mars Ultor)	Non-structural virtual reconstruction based on comparisons of sources interpretation

3.4.4. Mapping the uncertainty

The 3D modelling is an integral part of the work of interpretation and allows archaeologists to refine the reconstructive hypotheses by verifying in the reconstruction – which is nothing more than a reverse engineering process (reconstruct the original project from remains) – the effectiveness of the reconstructive hypotheses. The work of interpretation, mapping of sources and their organization in a formal language can be represented on the 3D model through the use of proxies (see Fig. 8) that immediately show us the different levels of reliability of our reconstruction making its historical background transparent and allowing us to distinguish certain from the uncertain, the necessary condition from interpretations [53,20]). The levels of reliability were established as in Table 1 at page 12.

This uncertainty mapping is a working tool that allows the scientific community to evaluate and track the reconstruction work. However, appropriate graphic representations could be implemented into video games and could be interrogated by players in the "museum mode". This mode, being deprived of video games dynamics, allows the user to freely explore the spaces and get information about the history of the site. The integration of information related to the interpretative study and the historical reliability of the reconstruction (already developed for interactive applications but not for games [19]) could be an added dissemination strategy for future productions.

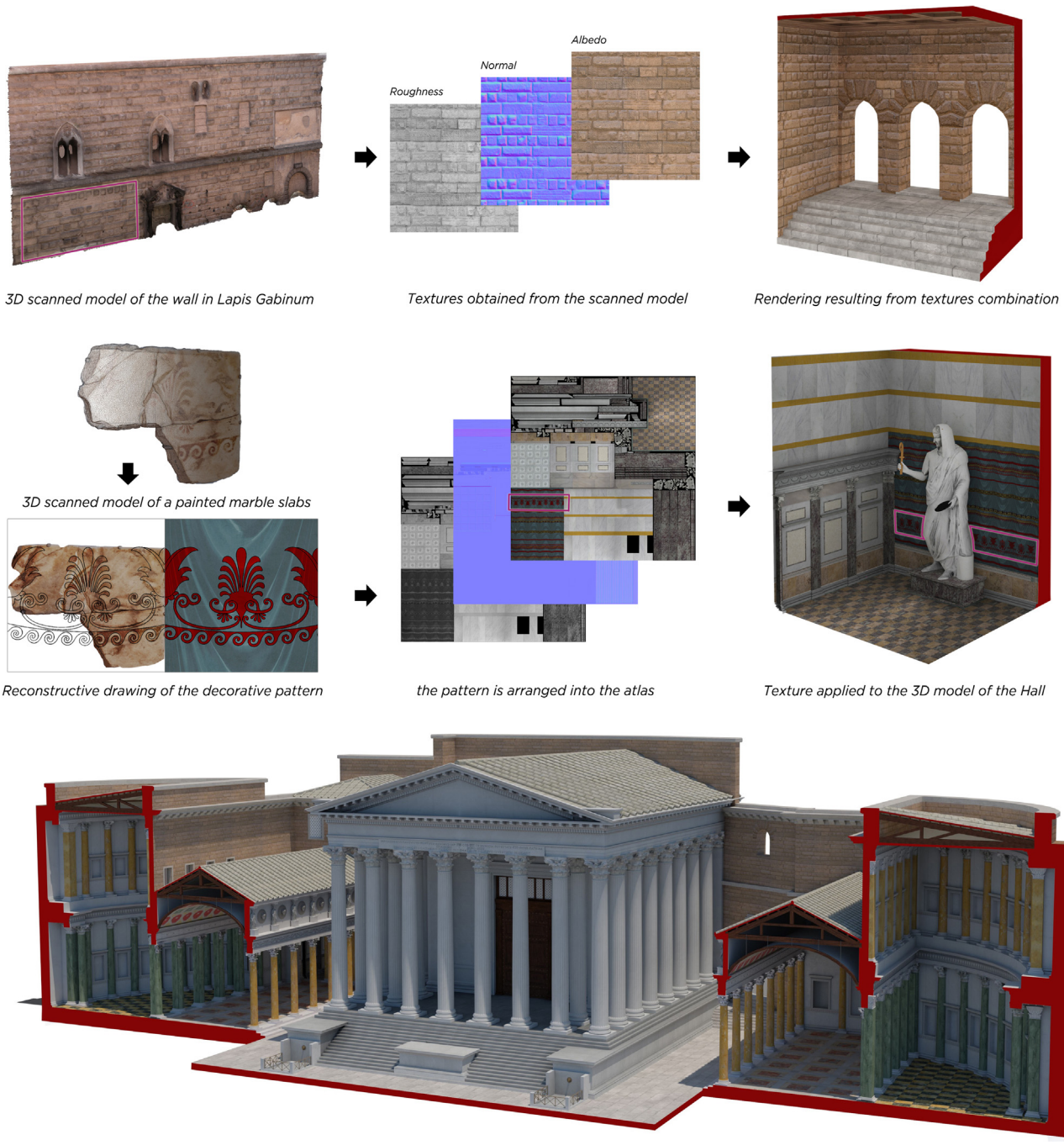

Fig. 7. Texturing. Top row: workflow adopted for creating textures from 3D scanned models. Bottom row: Textured model of the forum. The section shows the complexity of the architectural order and the polychrome marble decoration of the interiors and porticoes.

3.5. *Level creation and authoring*

These activities are carried out by the level designer inside the game engine with the support of 3D modellers, historical consultants, game designers and user experience experts. The level – or "game level" – represents an arrangement of static and dynamic 3D assets produced by the previous phases. This segment concerns the communicative and aesthetic aspect in which the work of virtual reconstruction is synthesized in a visual representation. In other words, the reconstructive model is imported into the game engine – software that allows to view real-time scenarios and game assets and perform programming operations that will define the behavior and dynamics of the game – to assemble the virtual reconstructive scenography.

After assembling the environment, further refinements are needed to set the graphic rendering that is based on the creative choices made during the design phase of the game: *scene dressing*, *real-time rendering* and soundscape set-up.

3.5.1. *Scene dressing*

In this step, props – dynamic object that can be moved and or interact with, are imported and instanced in the game scenario. In the case of the Forum of Augustus several props, fundamental to understand the function of architectural spaces and enrich them with realistic details, were added. The big exedrae were filled with roman furniture like wooden tribunals and curule seats while the small one with cabinets for papyruses and wax tablets, table

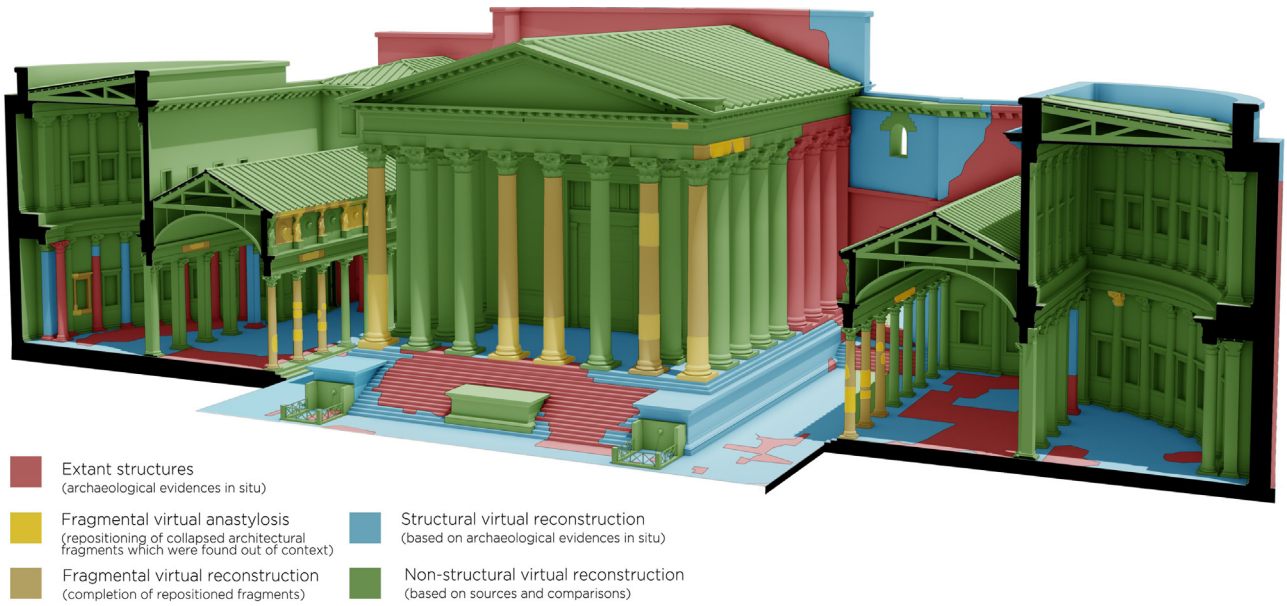

Fig. 8. Proxy model of the Forum of Augustus. The level of certainty are indicated by the colours which distinguish extant structures and repositioned fragments from their completion and reconstruction. The green colour instead, maps all those parts for which we have no structural or archaeological evidence but their reconstruction is entrusted to comparisons or interpreted sources.

and chairs. All the interiors were provided with braziers, oil lamps, torches and candelabra and statues. Furthermore, a building site area were deliberately inserted to show the south-west part of the Forum still under construction. Among the assets, in addition to those already mentioned, a roman crane, scaffolding, centering arches and other wooden infrastructures used by roman in the building site were modelled.

All these objects were made from scratch with the help of historical documentation (in the case of the crane we used different iconographic sources like the relief sculpted on the decoration of the tomb of the *Haterii* family which is preserved in the Vatican Museums). This expedient allowed us to address some issues related to the technologies and practices adopted by the Romans.

3.5.2. *Real-time rendering*

Another relevant aspect concerns the real-time rendering, highly dependent on the chosen game engine (e.g. Unreal Engine 4, Unity3D, etc.). In this phase the graphic style and realism of the experience is realized by setting up materials and lighting:

- Creation of materials associated with each 3D model (marble, stone, metal, glass, etc.) from PBR maps (see Section 3.4.3) to simulate or approximate its physical behavior (reflection, transparency or emission) inside the game engine.
- Lighting set-up by creating, positioning and tuning light sources in the level.

In order to ensure the historical consistency, these activities are often validated by specialists (e.g. historical consultants). Regarding the interiors of the Forum of Augustus for instance, it was important to choose which, among different types of light sources (braziers, torches, lanterns, oil lamps) were the most suitable for specific locations – see Fig. 9 – and their parameters to simulate the ancient light performance (temperature or light color) according to real data (see for instance [48]).

These tasks – including also previous scene dressing activities – must also ensure robust performances for the immersive VR application/game being created. In our case, we fine-tuned the process to maintain a range of 70–90 fps[19] on consumer-level HMDs (e.g. Oculus Rift) and hardware across the entire level of the Forum of Augustus.

3.5.3. *Soundscape*

These activities allow to create a collection of sounds arranged in specific locations of the level in order to enhance the sense of presence [57,13] for the immersive experience. Specifically, ambient sounds are background sounds with specific location and radius, used to create a sense of atmosphere [58] (wind blowing, barking, street noises, etc.). Sound sources – with given falloff distance – can be also attached to dynamic props inside the game engine to facilitate re-use in the level (e.g. braziers).

Once again, a validation process is required in order to maintain consistency of the overall soundscape. For instance, ambient sounds associated to the *Suburra* area (close to the guard-post) were designed with the support of historical consultants: specifically, during night time only sporadic sounds (e.g. barking) were probably heard due to the area being disreputable (lower-class area) and thus less crowded during that hours. In our case, the validation process was carried out on sound types only, without considering propagation properties of different materials (see for instance [63]).

4. Results and discussion

This section briefly describes multiple resulting immersive VR products, exploiting produced 3D assets, including applied VR games and explorative applications.

4.1. *A Night in the Forum*

A Night in the Forum is an Educational Environmental Narrative (EEN) Game for PlayStation® VR, set in the Rome of Augustan age, whose goal is to make the player understand the complexity of the administration of Imperial Rome. The game experience is based on the “environmental storytelling” and the “learning-by-doing”

[19] Frames-per-second.

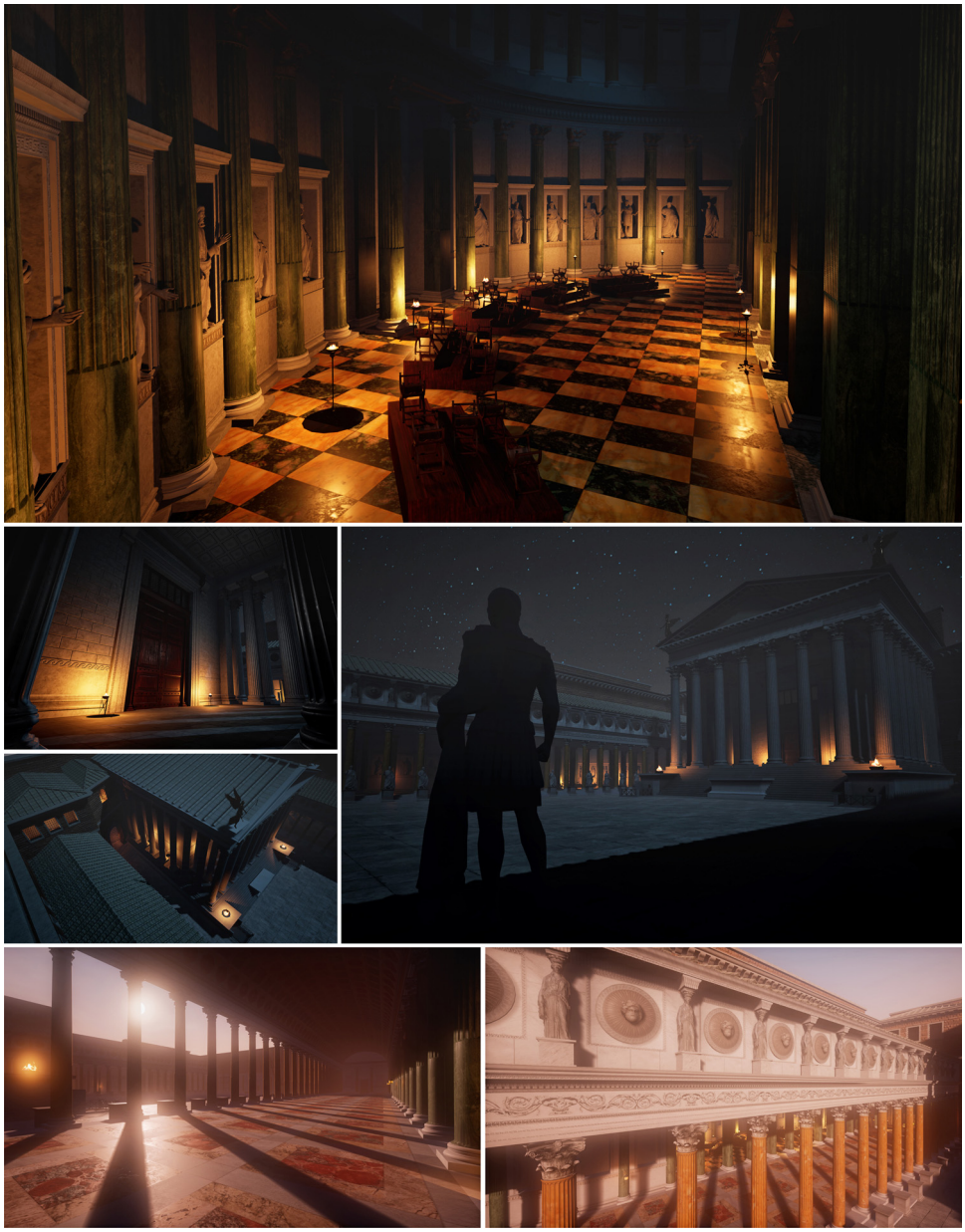

Fig. 9. Real-time rendering of the Forum of Augustus using different lighting conditions using Unreal Engine 4.

approaches [30,37]. The player is thrown into Forum of Augustus where he has to spend an entire night exploring the reconstructed ancient architectures and life spaces (see Fig. 10).

Furthermore he/she has to accomplish several tasks interacting with digital reproductions of real cultural artifacts and carrying out authentic assignments. The user plays the role of a guardian who has to watch both the public and sacred spaces of the Forum at night-time and arrange them for the next day's opening (e.g. sort out the tablets in the archives, light braziers in the Hall, etc.). During the journey the player discovers information and stories about the Forum and its elements (statues, decorations, ritual ceremonies, etc.).

The game was developed by VRTRON[20] and CNR ITABC (3D modelling of historical assets) with the collaboration of the Museo dei Fori Imperiali – Rome (historical consultant) within the European Project REVEAL.[21] and is available on the playstation store [22]

4.2. Forum of Augustus VR

This immersive VR application is purely explorative, developed using Unreal Engine 4.[23] The game engine allowed to fully exploit modern rendering capabilities, including high-fidelity PBR materials, spatialized soundscape and a few interactions with the environment through VR controllers (e.g.: opening doors). The locomotion model employed is point-and-teleport [8], providing a safe exploration for a wide range of users. Virtual hands (VR controllers) are included for teleport actions and provide basic interactions with the environment. Starting from produced 3D assets, multiple loco-

[20] vrtron.com.

[21] revealvr.eu.

[22] https://store.playstation.com.

[23] https://www.unrealengine.com.

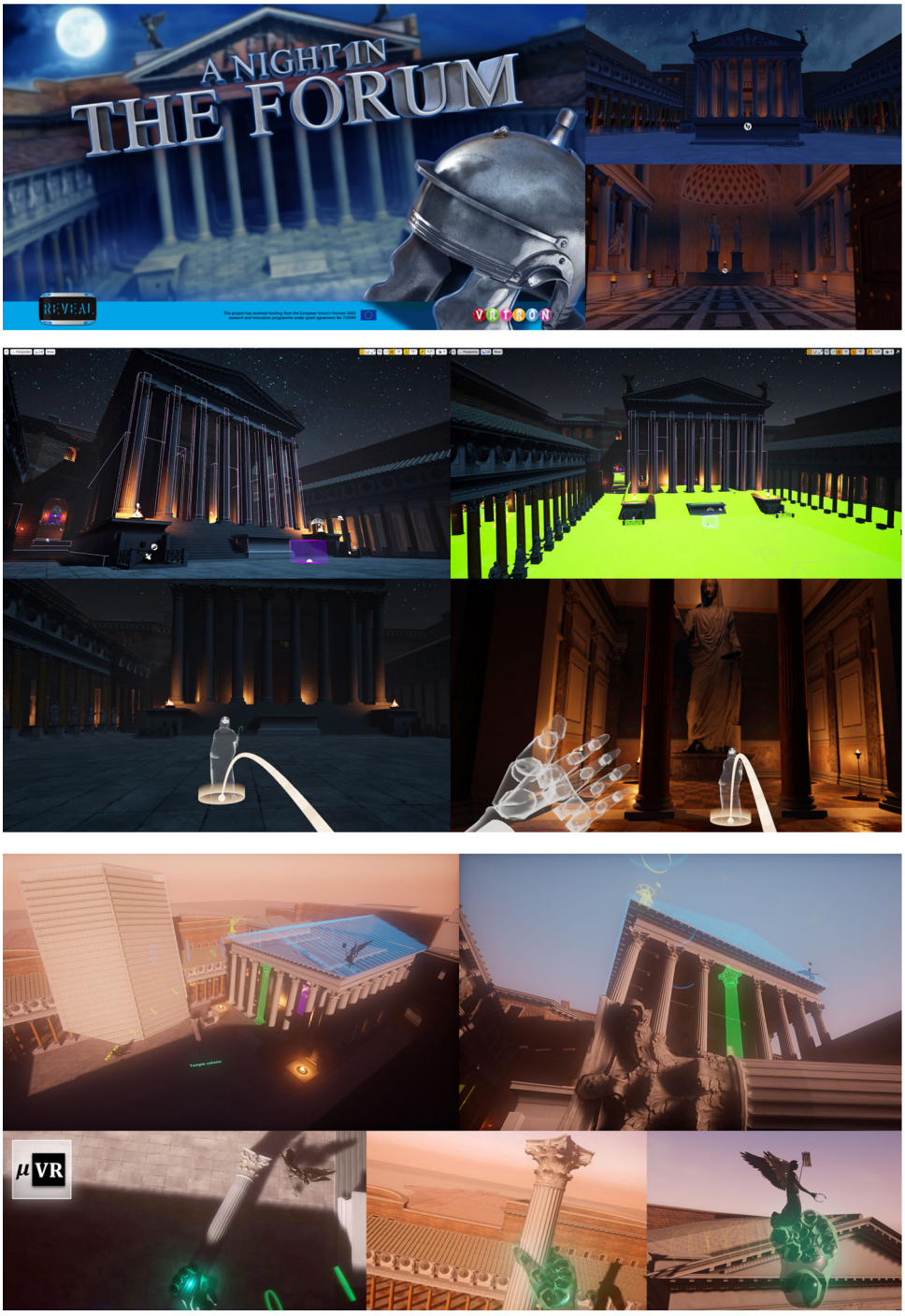

Fig. 10. From top to bottom: (1) "A Night in the Forum" – Cover of the VR game and screenshot of the gameplay; (2) "Forum of Augustus VR" – Definition of basic colliders, locomotion areas (green) inside the game editor and in-game captures while using HMD and VR controllers; (3) "μVR Forum" – Misplacing items inside the game editor and in-game multi-scale manipulation to solve all items.

motion areas (see Fig. 10) were defined inside the game editor through the arrangement of multiple shapes/colliders. A few spatialized sounds were also placed into the virtual scene to create immersive soundscapes.

4.3. μVR Forum

This immersive VR puzzle-game, presented for the first time in TourismA 2019, a fair on archaeology and cultural tourism held in Florence,[24] is based on the μVR game model [29] that combines real walking and multi-scale 6DOF gaming. The model[25] offers users an immersive, physical and engaging re-contextualization challenge within architectural and archaeological contexts. The player has to find multiple misplaced items scattered across the Forum of Augustus and put them back in their original locations by performing basic manipulation tasks (grab and release – using VR controllers).

[24] www.tourisma.it.
[25] http://osiris.itabc.cnr.it/scenebaker/index.php/projects/uvr/.

Once an item is solved (placed in its original position), the virtual space changes scale: this offers the user a new spatial perception of the virtual environment, following a mechanic inspired by the novel "Alice in Wonderland". The game model suits micro- and macro-scale contexts, and minimizes motion sickness by removing artificial locomotion, since each item is solved through physical motions within the tracked area boundaries (for further details see reference paper). For the exhibit, the game exploited the latest 3D reconstruction and assets of Augustus Forum and it was set at sunset (see figure 18). The setup included an Oculus Rift CV1 and a physical tracked area of 2.5×2.5 m in order to deploy the immersive VR game. A collection of items with different sizes was arranged together with a few archaeologists using the game editor for the re-contextualization game: the roof of the temple, a column of the temple, the victory statue, the colossus of Augustus, the main door of the temple and the statue of Mars and Venus.

4.4. Final remarks

The forum was a public space, generally crowded: some sort of crowd simulation is eventually expected for the described VR applications. Several techniques have emerged in the last decade to populate a virtual space, including those dealing with immersive VR products (see [50,22]). For instance in [28] a micro-dynamics model was adopted to populate the reconstruction of ancient *Bononia* and to support the gameplay. We did not include such kind of simulation in our applications for many reasons: philological character modeling targeting immersive VR can be time-consuming ([9]); crowd micro-dynamics are computationally intensive (see for instance [23]); according to historical sources, the access to the forum was forbidden during the times our applications/games are set. Regarding user evaluation, we carried out a preliminary user testing on μVR Forum application ([29]) with high school students and during public events ("TourismA 2019"), in order to study effectiveness of the multi-scale puzzle approach in VR, obtaining encouraging results. Regarding "A night in the Forum" we planned a series of evaluation tests at the Imperial Fora Museum once the applied VR game will be on display (2020), including learning assessment.

5. Conclusions

Virtual reconstruction is a great didactic tool as it improves cognitive processes making the historical and archaeological data easily comprehensible to anyone and within a video game this potential is reinforced by the dynamics of storytelling, and learning-by-doing. However, as emerges from the "picture" described above, the virtual reconstruction of the past imposes many limitations and great effort to ensure the consistency and reliability of the reconstructive hypothesis. The latter indeed prolong the production times, increase costs, require the involvement of experts in various cultural fields and cross-domain professionals, capable of dealing with both computer graphics as well as archaeology worlds.

Another limitation for this class of cultural applications is the creation of the 3D virtual environment. The design of historical architecture and user navigation spaces impose some constraints: while in video games design there is no limit to imagination and script and scenarios are created according to the game needs and logic, in the serious games segment this is not possible. On the contrary, it's the game that has to suit and adapt to the historically validated 3D environment, to maintain consistency.

The research can play a decisive role in helping developers – in particular those without the large funding available to big game entertainment companies – through the creation of collections of cultural assets or supporting them during the application/game development. Furthermore, this can fuel research activities targeting immersive VR segment by providing fertile playground for developers, game designers, researchers and many others, for instance to assess novel interaction models, game mechanics or content creation pipelines.

During last decade, 3D modeling and visualization technologies did prove to enhance cognitive and interpretative processes for a better understanding of archaeological contexts, helping scholars to structure complex sources and test interpretative reasoning in virtual reality models [35]. Indeed many universities and research centers, during their activities, put their effort into the reconstruction of sites and artifacts according to scientific approaches. The creation of libraries that enable the availability of reconstructive models of cultural assets – including linked metadata related to both the characteristics of the object (period, function, cultural context, etc.) and the sources used – could become useful for companies or other researchers to boost up production workflows. We are not only referring to architectural 3D assets, for which this approach is intrinsically limited, especially to dynamic elements commonly referred as props. Architectural 3D assets in fact, are usually unique entities and their re-use can be considered only for some building components (the ones that are typically serialized or obeying specific architectural rules – e.g. capitals or entablatures). In the case of the Forum of Augustus, many props were crafted – tables, chairs, lanterns, braziers, statues, columns – following a philological process which could be re-used in future projects. This logic of sharing, according to a policy to be defined, could follow the ones adopted for the creation of digital heritage collections. The latter bring together contributions from all countries with the purpose of conservation and dissemination thanks to European projects such as Europeana,[26] Carare,[27] 3D Icons[28] and many others.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.culher.2019.12.004.

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[26] https://www.europeana.eu.
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