3D Reconstruction, Digital Twinning, and Virtual Reality: Architectural Heritage Applications

3D Reconstruction, Digital Twinning, and Virtual Reality: Architectural Heritage Applications

Marco Giorgio Bevilacqua*
Dept. of Energy, System, Territory and Construction Engineering, University of Pisa, Italy

Michele Russo‡
Dept. of History, Representation and Restoration of Architecture, Sapienza University of Rome, Italy

Andrea Giordano†
Dept. of Civil, Environmental Engineering and Architecture, University of Padua, Italy

Roberta Spallone§
Dept. of Architecture and Design, Politecnico di Torino, Torino, Italy

ABSTRACT

Virtual Reality proposes different innovative solutions for the fruition of tangible, intangible, or no longer existing Cultural Heritage. The representation of architectural artifacts through virtual 3D models framed in immersive and interactive virtual environments allows building new paths of knowledge. This kind of narrative feeds the fruition, the understanding, and the involvement of the user. The article presents different examples of VR applied in the CH field, highlighting the VR capacities, foreshadowing possible future developments in the specific domain. The first case study describes the reconstructive digital modeling and the prototype application of VR aimed at rendering the interior space of the provisional hall of the First Italian Parliament, no longer existing, for the use of visitors to Palazzo Carignano in Turin. The second case study concerns the Charterhouse of Pisa in Calci and deals with two VR experiences realized for a new visit tour: 3D reconstruction of the illusory space depicted in a quadraturist frescoes and 3D representation of the layout of the cloister in its most important historical phases. The third case study deals with the reconstruction of the Cathedral of Carpi through a 3D interoperable BIM model and the new communication tool called "during time Digital Twin", which uses a combination of VR and AR.

Keywords: Cultural Heritage, virtual architecture, digital twin, museum, knowledge.

Index Terms: Computing methodologies—Computer graphics—Shape modeling—Point-based models; Applied computing—Arts and humanities—Architecture (buildings)—Computer-aided design; Computing methodologies—Computer graphics—Graphics systems and interfaces—Virtual reality

1 INTRODUCTION

Complex knowledge often characterizes Cultural Heritage (CH) buildings. The intersection between the architectural components and the historical transformations makes it challenging to understand the built heritage, not always accessible or still existing. In the last twenty years, the massive application of Information and Communication Technologies (ICT) to tangible and intangible heritage has profoundly changed the access to knowledge, fruition, and enhancement of the CH [1]. Active or passive survey methodologies allow accessing comprehensive, queryable, and interoperable 3D data systems, offering a multi-scale reality-based observation of the context. The integration with bibliographic and iconographic data to understand the architectural transformations and define interpretive 3D models allow to create a virtual replica of the CH assets and the efficient transmission of data, named Digital Twin (DT) [2]. This knowledge model based on 3D digital archives brings significant benefits in analyzing, preserving, communicating, and managing architectural heritage, merging qualitative and quantitative information. In this scenario, defined by accurate virtual models, research interests mainly focus on data management and representation. The interaction and immersion of digital models in virtual worlds have been improved in the last ten years. In the "Real-Virtual Continuum" [3], Virtual Reality (VR) plays an increasingly important role, becoming an established and essential component within the Cultural Computing domain [4]. VR in the CH domain can affect the asset's understanding and time, cost, and quality management, intervening at different scales and moments in designing, knowing, and learning [5]. VR opens new ways of approaching culture. The user is a dynamic actor able to interact and interface more easily with CH, encouraging knowledge dissemination to a broad audience and developing multidisciplinary research.

Virtual reality defines an extended container that converges multiple research topics, significant and challenging in Cultural Heritage: the spatial model reliability, data visualization, digital perception, real-time info extraction, feedback system on virtual experience. These elements are related to 3D model construction, data processing, vision systems, and interaction, moving between cultural aspects about architectures to digital and computer science domains. The content generation in CH is central and critical because it involves experiential and cultural aspects. Behind its definition, there is a traceable process of choices consistent with the VR purpose, which must be reflected in the visualization tools. Comparing different case studies with the cultural aspect as a common denominator reinforces the centrality of the content and better identifies the research areas.

The article proposes different experiences of VR in the CH domain using Digital Twin, highlighting VR as a tool for understanding, reading, and interpreting architectural heritage. The different methodological approaches aim to reach a shared but flexible pipeline that preserves the specific characteristics of the asset and the purpose of the project. These scenarios open a series of considerations about the relationship between digital content, interaction, and immersive tools, helpful for future development.

* email: marco.giorgio.bevilacqua@unipi.it
† email: andrea.giordano@unipd.it
‡ email: m.russo@uniroma1.it
§ email: roberta.spallone@polito.it

2 VR Representation in CH

Since its definition in 1989, VR has shown a wide range of interpretations, displaying many possible applications [6]. It dips users into a synthetic world, enjoying the real environment only through CPU-based representations [7], providing different stimuli to approach an authentic experience [8]. VR in CH is an established practice, presenting multiple research insights offered by the continuous evolution of systems and methodologies for building, managing, and visualizing virtual data.

On the one hand, the focus is the construction of virtual content (DT) and environment, according to the different levels of detail and interpretation concerning the asset and the VR aim. On the other hand, the development of tools to "virtually immerse" the users and make them interact with the architectural spaces plays a fundamental role [9]. Immersion and interaction are crucial aspects for a VR experience in architecture, as they support sensory enrichment for understanding and naturally interacting with space.

VR applications cover several issues, from virtual museums to digital reconstructions, virtual explorations, and edutainment [10][11], offering low-cost content dissemination and communication solutions. The latter has acquired a strategic role in CH in recent times, as evidenced by the most recent literature [12][13] and the foundation of devoted journals. Detractors of VR observed that such technology might relegate cultural content to the background [14], due to the widespread scepticism in ICT and the tendency to deepen multimedia aspects instead of working on contents or specific solutions [15]. However, the adoption of engaging multimedia tools is significant for CH dissemination and promotion among not expert users and younger generations [16]. Virtual environments and attractive cultural paths can bring users with tangible and intangible heritage [17], unveiling hidden underground or lost architectures [18]. A VR classification of applications in the CH domain is suggested by [5]: education, exhibition enhancement, exploration, reconstruction, and virtual museums. These categories intersect or overlap, highlighting VR's trans-disciplinary potential to research content to increase the user's overall knowledge and understanding of the space in which they are immersed. A distributional representation of these categories through a Venn diagram is offered by [19]. In order to supply a contribution in this thematic area, three different case studies are presented in the paper, framing VR in CH with Digital Twins in the following paths:

- Reconstructive digital modelling and VR application for lost architectural heritage (Case Study 1);
- Application of VR in a museum context for understanding the simulated spatiality on frescoed walls and the architectural phases (Case Study 2);
- Architectural data hierarchy and new communication tools: "during time DIgital Twin" (Case Study 3).

3 Case Study 1

The research presented below concerns the provisional hall of the First Italian Parliament, a temporary building which, over the years, held historical and symbolic significance and whose memory is linked to bibliographic, archival and iconographic documentation. The location of this artefact in the courtyard of the 17th-century.

Palazzo Carignano and the closure of the courtyard with the 19th-century specular body, as well as the finding of fragments that probably belonged to it in different locations, make it an interesting case study for different aims:

- The studies on the historical transformations of the architectural and urban layout of the command area in Turin;
- The typological research, including the decorative apparatus, and relations with the provisional hall of Montecitorio, of which the Turin hall was the model;
- The conservation and transmission of the disappeared architectural heritage memory.

Reconstructive digital modelling and immersive fruition through VR technologies took place within the framework of the institutional and scientific collaboration agreement between the Department of Architecture and Design of the Politecnico di Torino and the Piedmont Regional Museums Department, and was carried out by a multidisciplinary team. The building, whose construction had become necessary to accommodate the work of the Lower Chamber, was designed by Amedeo Peyron between 1859 and 1860. The new semicircular hall, made of iron, wood and glass, was built in three months and inaugurated on 18 February 1861. The transfer of the capital of the kingdom to Florence, on 3 February 1865, decreed the end of the hall's use and its inevitable demolition [20].

The virtual reconstruction involved a complex philological and interpretative operation. The main critical points of the 3D modelling work, which was guided by the principles of transparency of reconstruction expressed in the London [21] and Seville [22] charts were:

- The coherence checks and the interweaving of data from bibliographical, textual, and iconographical documents (the latter include views and technical scale drawings);
- The verification of hypotheses regarding the belonging to the building of wooden elements (capitals, balustrades, cornices, doors...) found in the palace storerooms, and of the coats of arms, now part of the decoration of the Subalpine Parliament in the Museum of the Risorgimento;
- The integration of the lacunae.

Modelling was carried out in Rhinoceros following the drafting of two-dimensional plans and sections, using blueprint technique in AutoCAD. Given the nature of the model, it was decided to use a conceptual render to enhance the geometric reconstruction, while the chromatic characteristics have been taken from some textual descriptions and vintage postcards. The prototype level of development of VR made use of personal devices and cardboards. The digital model was reworked according to the type of experience with texture baking techniques for the generation of normal maps and ambient occlusion maps. The model thus generated was inserted in the Sketchfab Web-service for VR use. The platform is particularly suitable for the objectives of the experience. It allows to make changes to the materials, interact with the settings for the ambient and internal lights, use post-processing effects, add textual and iconographic annotations.

Figure 1: Reconstructive model of the First Italian Parliament hall in Palazzo Carignano and VR experience. Modelling: M. Ambrosio.

The reconstructive model is now the first and only product capable of restoring the three-dimensional image of the building and, through an immersive experience, allows the exploration of spaces that no longer exist. It is also foreseeable the integration of an AR experience, which will allow to visualize the disappeared artefact in the courtyard of Palazzo Carignano.

4 Case Study 2

The second case study concerns the monumental complex of the Charterhouse of Pisa in Calci, one of the most significant monasteries in Tuscany. Founded in 1360, the charterhouse is the result of several modifications documented from its founding to the end of the 18th century [23]. Lost its original function in 1962, the Charterhouse hosts today two important museums: the National Museum of the Monumental Charterhouse of Calci and the Natural History Museum of the University of Pisa. The study presented here aims at enhancing visits to the National Museum of the Charterhouse through immersive VR experiences. The study is part of a wider interdisciplinary research project funded by the University of Pisa, aimed at the conservation and enhancement of the Charterhouse. Among the several activities provided by the research project, the 3D digital survey of the whole complex - carried out with LIDAR and 3D photogrammetric methodology - and an in-depth historical analysis represented the basis for the development of the immersive experiences here described. The study provided a first preliminary phase aimed at defining objectives and contents of the new visit tour, focused on the monastery's evolutionary phases, on its most valuable decorative and architectural elements, and on the figures who, over time, had a prominent role in the history of the Charterhouse. Subsequently, a new tour path was elaborated, in order to expand the number of visitable spaces and to increase the immersive involvement.

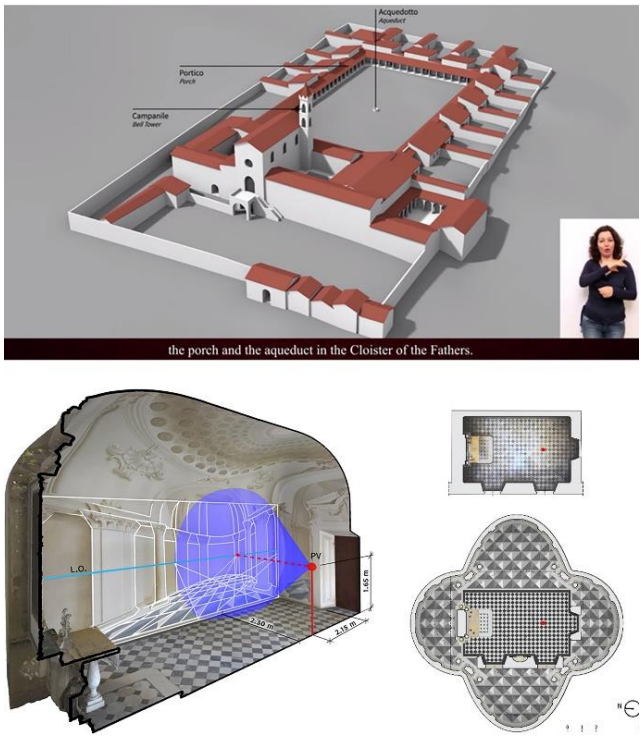

Figure 2: On the top, frame from the introductory video on the various construction phases of the Charterhouse, projected in the chapel of St. Sebastian. On the bottom, left, 3D model of the chapel of St. Anthony; right, comparison between the plans of the real and illusory spaces. Digital elaborations: A. Fedeli.

Vistors are left free to move along the path using audio-video guides on tablets or smartphones. All the spaces are classified into three categories based on the information that will be provided: art and architecture, monastic life, and mixed information. The study, therefore, focused on the development of three VR applications provided in the general plan:

- The introductory video projected at the entrance of the museum, in the Chapel of St. Sebastian, performing a graphic animation of 3D models that reproduce an external view of the various construction phases of the complex, described in Italian by a narrator voice and subtitled in various languages.; The VR experience about the 18th-Century quadraturist frescoes painted by Pasquale Cioffo in the Chapel of St. Antony, aimed at explaining the geometric rules used for the painted composition, providing a 3D reconstruction of the illusory space depicted, inside which visitors are immersed thanks to the use of a VR helmet;
- The VR experience in the Cloister of the Chapter, also to be experienced with a VR helmet, where viewers are immersed in virtual spaces that represent the layout of the cloister in its most important historical phases.

3D Models were developed with the open-source software Blender. Informative texts were processed with Audacity; the final processing was developed in graphic animation software including Adobe After Effects for the introductory video in the Chapel of St. Sebastian, and Unreal Engine, used for the immersive experiences in the Chapel of St. Anthony and in the Cloister of the Chapter.

5 Case Study 3

The urban view of Carpi (second half of the 17th century) by Luca Nasi [24], has raised multiple hypothesis about the geometric genesis and the stylistic-spatial configuration of the cathedral built in this Renaissance city. The problem is that Nasi's map is one of the two surviving documents that show the original idea of the designer, Baldassarre Peruzzi (1481-1537).

This is the central theme of the exhibition organized by the Museum of Palazzo dei Pio in Carpi, entitled "Costruire il TEMPIO. Alla ricerca del progetto di Baldassarre Peruzzi per il Duomo di Carpi" and performed by the Department of Civil, Environmental Engineering and Architecture of the University of Padua. In fact, starting from this precious graphic document, the digital reconstruction of the cathedral was realized, not as a simply instrumental model, but as a critical interpretation tool of the architectural design genesis, verifying it through VR. The virtual model of the church was exhibited in a room that contained real wooden architectural models dating back to the 16th century. Peruzzi made a wooden model by himself to explain to the masons how to build the new church in Carpi; the model disappeared in the mid-17th century. The idea of the exhibition curator, Manuela Rossi, was to create a reconstruction of the lost wooden architectural model so that the visitors could admire it through an app of Augmented Reality loaded on a tablet. A map of the church was printed in large scale and placed on the ground; when visitors framed this map with the tablet, a wooden model faithful to Peruzzi's project appeared on the screen. In this way the observer could virtually compare the lost model of Peruzzi with the wooden models exhibited in the room. In addition, the visitor had at his disposal some explanatory panels that showed the reconstruction process of the virtual model and the archive documents that testified its existence.

From another point of virtual opportunities, a 3D interoperable Building Information Modeling (BIM) model of the church was created, to which structural and configuration data were added. The digital reconstruction in a BIM environment made us able to gather all these features, integrating planar and spatial

information with objective data, obtained through a digital survey of the actual condition of the building. Starting from this 3D model all the transformation of the church over time were represented. In this case, the 3D model, specifically created for the representation of the history of an architectural and cultural heritage, is a geo-referenced entity and, this means that its 3D reconstruction is associated to a virtual geographical system (GIS) in which the buildings are located thanks to common spatial coordinates [25]. Then, this example of augmented reality had the aim of create a system that allows us to analyze and visualize the historical transformations of a place, intending to represent its architectural peculiarity, both at urban and architectural levels. For the development of our system, considering this leading purpose, we decided to introduce, beside the three spatial coordinates (x, y and z), that manage geometry and position of the objects, a fourth one: the temporal dimension. Therefore, assigning to every element two temporal coordinates (the beginning and the end), as these parameters are set in a relational structure with other objects, a simulated condition of change is generated, both at urban and architectural level. To realize this system, we adopted a historical documentation that covers the whole development cycle of the church, relating also to urban transformations of Carpi over time. Then, we achieved a so-called "during time Digital Twin" (dtDT) to perceive and understand with Virtual and Augmented Reality the close relationship between the physical environment and the viewer. The historical and urban transformations over time, dynamically expressed, act as facilitators of scientific – also complex – concepts, dipping the user in simulative virtual activities that stimulate the sense of movement, the only one able to anticipate what is going to happen in the reality [26].

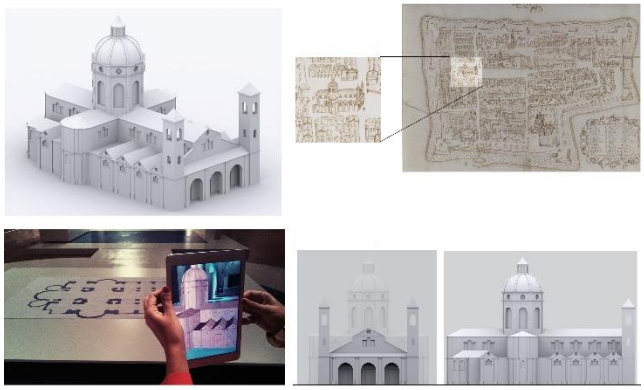

Figure 3: Virtual reconstruction and AR app of the cathedral project by Baldassarre Peruzzi. Carpi view by Luca Nasi, 1677.

6 Conclusion

The three case studies show how VR methodologies can represent new models of knowledge related to the world of architecture and CH through the digital twins. The projects described are testing, but a subsequent validation phase will consider a broader user base. It will undoubtedly analyze the communicative impact and transmission of cultural content through VR, studying criteria for verifying the experience. This process will highlight the pros and cons of cultural transmission, with particular attention to the specificities of the content transmitted. The chance to visualize and understand both the architectural space and the time transformations in an immersive, interactive, and engaging way leads to an improvement in architecture knowledge, expanding the audience of users. The growing interest in VR technologies is demonstrated by many technical reports, which show an exponential growth of research at a global level, thanks to the democratization in VR use. In perspective, the use of VR within the CH can represent an even more valuable bridge of knowledge and understanding between the user and the built environment.

Acknowledgments

The work on the temporary hall of the First Parliament was carried out in the context of a multidisciplinary team (coordinated by R. Spallone) that included digital representation techniques (R. Spallone, F. Natta, M. Ambrosio - DAD PoliTO), architectural history (S. Pace - DAD PoliTO), art history (C. Teolato, former Director of Palazzo Carignano), digital solutions for CH (V. Palma - Shazarch SRL).

The study on VR experiences in the National Museum of the Monumental Charterhouse of Calci is part of a wider interdisciplinary research project for the conservation and enhancement of the Charterhouse of Calci and its Museums, funded by the University of Pisa from 2018 to 2020 and coordinated by M.G. Bevilacqua. LIDAR and digital photogrammetric surveys were developed by the ASTRO Laboratory of the University of Pisa. The historical analysis of the Charterhouse was developed by prof. E. Karwacka of the University of Pisa.

The Augmented Reality app related to Duomo di Carpi was created for the exhibition "Costruire il TEMPIO. Alla ricerca del progetto di Baldassarre Peruzzi per il Duomo di Carpi", Musei di Palazzo dei Pio, Carpi, September 18, 2015 - January 6, 2016. The team was coordinated by A. Giordano, E. Svalduz and M. Rossi (Director of Palazzo Pio Museum).

Appendix

The three researches presented in the article are experiences conducted by different research groups across Italian country. In writing the article, the authors contributed as follows: M.R. was responsible for writing paragraphs I-II, R.S. for paragraph III, M.G.B. for paragraph IV, A.G. for paragraph V. All the authors wrote the conclusions.

References

[1] E. Selmanović, S. Rizvic, C. Harvey, D. Boskovic, V. Hulusic, M. Chahin, and S. Sljivo. Improving Accessibility to Intangible Cultural Heritage Preservation Using Virtual Reality. *J. Comput. Cult. Herit*., 13(2):1-19, June 2020. doi: 10.1145/3377143.

[2] W. Kritzinger, M. Karner, G. Traar, J. Henjes, and W. Sihn. Digital Twin in manufacturing: A categorical literature review and classification. *IFAC*, 51(11):1016-1022, 2018. doi: 10.1016/j.ifacol.2018.08.474.

[3] P. Milgram, and F. Kishino, A taxonomy of mixed reality visual displays. *IEICE Trans. Inf. Syst.*, E77:1321–1329, 1994.

[4] S. Greengard. *Virtual reality*. Mit Press, Cambridge, 2019.

[5] M.K. Bekele, R. Pierdicca, E. Frontoni, E.S. Malinverni, and J. Gain. A Survey of Augmented, Virtual, and Mixed Reality for Cultural Heritage. *J. Comput. Cult. Herit.*, 11: 1-36, 2018. doi: 10.1145/3145534

[6] N.-N. Zhou and Y.-L. Deng. Virtual reality: A state-of-the-art survey. *Int. J. Autom. Comput.*, 6(4):319–325, 2009. doi: 10.1007/s11633-009-0319-9.

[7] J. Carmigniani, B. Furht, M. Anisetti, P. Ceravolo, E. Damiani, and M. Ivkovic. Augmented reality technologies, systems and applications. *Multimedia Tools Appl.* 51(1): 341–377, 2011. doi: 10.1007/s11042-010-0660-6.

[8] Q. Zhao. A survey on virtual reality. *Sci. Chin. Ser. F: Inf. Sci.* 52(3): 348–400, 2009. doi: 10.1007/s11432-009-0066-0

[9] M. Carrozzino, and M. Bergamasco. Beyond virtual museums: Experiencing immersive virtual reality in real museums. *J. Cult. Herit.* 11(4): 452–458, 2010. doi: 10.1016/j.culher.2010.04.001.

[10] C. Christou, C. Angus, C. Loscos, A. Dettori, and M. Roussou. A versatile large-scale multimodal VR system for cultural heritage visualization. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology*, pp. 133–1402006. doi: 10.1145/1180495.1180523.

[11] E. Pietroni, A. Pagano, and C. Rufa. The etruscanning project: Gesture-based interaction and user experience in the virtual reconstruction of the Regolini-Galassi tomb. In *Proceedings of the Digital Heritage International Congress (DigitalHeritage'13)*, 2. IEEE, pp. 653–660, 2013. doi: 10.1109/DigitalHeritage.2013.6744832.

[12] H. Kremers (ed.). *Digital Cultural Heritage*. Cham: Springer, 2020.

[13] M. Duguleană, M. Carrozzino, M. Gams, and I. Tanea (eds.). *VR Technologies in Cultural Heritage. First International Conference*, VRTCH 2018 Brasov, Romania, May 29–30, Springer, Cham, 2018. Doi: 10.1007/978-3-030-05819-7.

[14] F. Cameron, and S. Kenderdine. *Theorizing Digital Cultural Heritage: A Critical Discourse*. Cambridge, Mass.: MIT Press, 2007. doi: 10.7551/mitpress/9780262033534.001.0001

[15] R. Pierdicca, E. Frontoni, E. S. Malinverni, F. Colosi, and R. Orazi. 3D visualization tools to explore ancient architectures in South America. *Virtual Archaeology Review*, 2016. doi: 10.4995/var.2016.5904.

[16] P. Cignoni, and R. Scopigno. Sampled 3D models for CH applications: A viable and enabling newmedium or just a technological exercise? *J. Comput. Cult. Herit.* 1(1):1-23 pages, 2008. doi: 10.1145/1367080.1367082.

[17] L. Manovich. The poetics of augmented space. *Vis. Commun.* 5(2): 219–240, 2006.

[18] P. Clini, E. Frontoni, R. Quattrini, R. Pierdicca, and R. Nespeca. Real/not real: Pseudo-holography and augmented reality applications for Cultural Heritage. In A. Ippolito, and M. Cigola (eds.). *Handbook of Research on Emerging Technologies for Digital Preservation and Information Modeling*, pp. 201-227, 2016. doi: 10.4018/978-1-5225-0680-5.ch009.

[19] H. Heberle, G. Vaz Meirelles, F. R. da Silva, G. P. Telles, and R. Minghim. InteractiVenn: A web-based tool for the analysis of sets through Venn diagrams. *BMC Bioinf.* 16(1): 1-7, 2015. doi: 10.1186/s12859-015-0611-3.

[20] S. Pace. La Vita Nuova. Il 'Risorgimento' di Palazzo Carignano in età contemporanea (1832-1938). In G. Casale (ed.). *Palazzo Carignano*. Istituto della Enciclopedia Italiana fondata da Giovanni Treccani s.p.a., Roma, 2019, pp. 34–44.

[21] The London Charter for the Computer-Based Visualisation of Cultural Heritage. Draft 2.1, 7 February 2009, http://www.londoncharter.org/

[22] Principles of Sevilla. 2012, http://smartheritage.com/sevilleprinciples/seville-principles

[23] M. A. Giusti, and M.T. Lazzarini. *La Certosa di Pisa a Calci*. Pacini Editore, 1993.

[24] E. Rossi, E. Svaludz, and A. Giordano. *Costruire il Tempio. Alla ricerca del progetto di Baldassarre Peruzzi per il Duomo di Carpi*. APM edizioni, Carpi, 2016.

[25] C. Dore, and M. Murphy. Integration of Historic Building Information Modeling (HBIM) and 3D GIS for recording and managing cultural heritage sites. In *18th International Conference on Virtual Systems and Multimedi*a, pp. 369-376, 2012. doi: 10.1109/VSMM.2012.6365947.

[26] T. Haydn. Using *New Technologies to Enhance teaching and learning in History*. Routledge, London, 2013.