Long Paper

Virtual Reconstruction and 3D Modeling for the Auralization of Acoustic Heritage

The Case Study of the Teatro Del Maggio in Florence

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Abstract: The challenge of the AURA project is the creation of multisensory models with reliable performance in acoustics, graphic rendering and virtual reality in order to be used to support and encourage business opportunities related to musical heritage and its communication and dissemination. To achieve this goal, three emblematic European case studies will be examined to test, and develop a methodology for digitization, virtual reconstruction, and auralization of theatrical venues: the Berlin Konzerthaus, the Lviv Opera and Ballet Theater, and the Teatro del Maggio Musicale Fiorentino. The workflow implements different 3D modeling methods for the three case studies based on reality-based digital surveys and semantic classifications of the elements present and their respective materials, in order to study their acoustic characteristics and implement the results within auralization processes, a technique for recreating virtual soundscapes responsive to the acoustics of the real place. The acoustic reconstruction of the various main hall venues will then be combined with virtual reconstruction of 3D models within specific Game Engine platforms, where immersive VR experiences will be developed. The paper will present the first results obtained from the laser-scanning survey and 3D modeling methodologies and activities carried out for the case study of the Teatro del Maggio. Based on these, the paper will attempt to show and investigate the importance and potential offered by new digital documentation technologies and methodologies – such as laser-scanning, SfM photogrammetry, 3D modeling, auralization, and XR systems – for the virtualization and preservation of assets pertaining to both Architectural and Intangible Heritage, such as the acoustic aspects of theatrical venues. The research aims to create a scientific and replicable workflow to create a multisensory immersive experience based on the combination of photorealistic visualization and acoustic rendering simulation with user interaction, in order to develop new ways of communicating and disseminating Cultural Heritage.

Keywords: *Acoustic Model—Soundscapes—Mixed Reality—Digital Survey—Cultural Heritage*

CHNT Reference: Bertocci, S., Cioli, F. and Lumini, A. (2025). 'Virtual Reconstruction and 3D Modeling for the Auralization of Acoustic Heritage: The Case Study of the Teatro del Maggio in Florence', *Proceedings of the 26th International Conference on Cultural Heritage and New Technologies*, Vienna and online, November 2021. Heidelberg: Propylaeum.
doi: 10.11588/propylaeum.1449.c20730.

Introduction

The study that is presented in this paper is a part of the project AURA – Auralisation of Acoustic Heritage Sites Using Augmented and Virtual Reality[1], which is aimed to explore the potential of auralization[2] and virtual experience.The challenge of the AURA project is the creation of multisensory models performing reliably both in acoustics and in graphic rendering, and virtual use, to support and encourage business opportunities related to musical heritage and its communication and dissemination (Bertocci et al., 2021).

To achieve this goal, three highly emblematic case studies at the European level, summarized below, will be examined to test, and develop a methodology for digitization, virtual reconstruction, and auralization of theatrical environments (Figure 1).The project will first delve into the Konzerthaus Berlin case study (Germany), rebuilt after the bombing of the Second World War based on the Schauspielhaus, Karl Friedrich Schinkel's original neoclassical style project from the early 19th century. The second case study is the Lviv Theatre of Opera and Ballet (Ukraine), which was built at the end of the 19th century on the design of Zygmunt Gorgolewski in a Neo-Baroque style with some decorative Art Nouveau elements, stuccoes, statues, and oil paintings. The third case study – the one presented in this paper – is the Teatro del Maggio Musicale Fiorentino, Florence (Italy). Designed by architect Paolo Desideri of ABDR Studio, it represents one of the most relevant contemporary design interventions in the Florentine architectural scene.

Fig. 1. The AURA European project, its partnership and the three case studies: the venues of the Teatro del Maggio in Florence (IT) (© M. Monasta), the Solomiya State Academic Theater of Opera and Ballet in Lviv (UA) (© R. Lytvyn) and the Konzerthaus in Berlin (DE) (© F.L. Sichtkreis).

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[1] AURA is a project co-funded by the Creative Europe program led by the Berliner Gesellschaft für internationale Zusammenarbeit mbH (BGZ), in collaboration with the Hochschule für Technik und Wirtschaft in Berlin (HTW), the Department of Architecture (DIDA) of the University of Florence (UNIFI) and the Lviv Polytechnic National University of Lviv (LPNU, supported by musical institutions such as the Konzerthaus in Berlin and by marketing partners such as Vie en.ro.se. Ingegneria Srl in Florence, the Lviv Tourism Development Center of Lviv (UA) and Magnetic One of Ternopil (UA).

For further information, see the website of the European project https://www.aura-project.eu

[2] Auralization is a technique for recreating virtual sound environments within 3D models to artificially make acoustic experiences audible (Kleiner et al., 1993).

The importance of acoustics in the protection of Cultural Heritage

The evolution of technologies in the investigation and protection of tangible cultural heritage has significantly increased the possibilities of integrating the acquired data. The new LIDAR (light detection and ranging) tools and modeling and rendering methodologies combine to recreate a virtual double of the object investigated, preserving, and protecting its memory and image, allowing not invasive remote studies. Establishing these models – which constitute digital databases rich in information and constantly implementable – requires the collaboration of various specialists who can interact within virtual workspaces. Immersive multimedia systems have always been used as valuable tools for dissemination, communication, and entertainment, starting with the nineteenth-century panoramic paintings, passing through experiments, such as the Sensorama by Morton Heilig[3] (McLellan, 2004), up to the recent technologies that allow the reconstruction of virtual environments, offering new ways to visualize and experience information (Weinzierl and Lepa, 2019).

With the introduction of the concept of Intangible Cultural Heritage (ICH) by UNESCO in 2003 – because of a long debate that began with the Convention on the World Cultural and Natural Heritage of 1972 (Cioli, 2020) – the way was opened for numerous new cultural categories more dynamic and ephemeral, which contribute to preserving the identity of the places and cultural diversity. In 2017, UNESCO introduced the document "The importance of sound in today's world: promoting best practices"[4], highlighting how the acoustic soundscape – the set of sounds, natural and artificial, that characterize a specific place – of existing or historical sites needs documentation, conservation, and scientific study (Katz et al., 2020a). These acoustic features change over time and help structure a place's historical memory, playing a fundamental role in music venues, such as theatres, churches, or auditoriums. The acoustics of architecture is an intangible consequence of its construction, the materials used, and the furniture system, which constitute the tangible aspects of the heritage. The sound perceived within an environment is the result of the direct sound emitted by a source and the reflections within the environment, which constitute the acoustic response.

Modern technologies for creating acoustic spaces increasingly exploit mixed reality (MR) technologies – particularly virtual reality (VR) – integrating the sound aspects to the stimuli generated by visual rendering. Some studies have shown that images influence acoustic characteristics (Katz et al., 2020b) and that the vision in the perception of auditory space contributes to the correct perception of distance (Calcagno et al., 2012). Similarly, sound affects the perception of virtual space, helping to return the sense of balance, breadth, depth, and distance from surfaces and objects. Recording sound sources in anechoic rooms allows capturing only direct sound, which can be inserted within the virtual environment that, if adequately auralized, can restore the acoustics of the real place.

There have been numerous projects financed by European programs relating to the auralization of Cultural Heritage sites in recent years. The ERATO project (2003–2006) was one of the first to use

[3] In 1961, the director Morton Heilig, patented Sensorama, a fully mechanical virtual reality device (a one-person theater) that included three-dimensional color films with sounds, smells, and sensations of movement, as well as the feeling of wind on the face (McLellan, 2004).

[4] The importance of sound in today's world: promoting best practices. Technical report Resolution 39 C / 49, UNESCO (2017). https://unesdoc.unesco.org/ark:/48223/pf0000259172. In particular, it is highlighted how "the sound environment is a key component in the equilibrium of all human beings in their relationship with others and with the world, in its economic, environmental, societal, medical, industrial and cultural dimensions".

cutting-edge modeling and acoustic survey technologies, representing a reference for archaeo-acoustic research. The project aimed to analyze and compare the acoustic properties of ancient Greek and Roman theatres (Rindel, 2011). Another important international project is ECHO, carried out between 2013 and 2018, which addressed the themes of voice, acoustics, and listening by investigating the evolution of various theatres, such as the Théâtre de l'Athénée (Katz et al., 2019), St Germain-des-Prés Abbey and Notre-Dames Cathedral in Paris, through geometric survey, 3D modeling and the development of interactive virtual experiences. Currently underway, the "Past Has Ears" (PHE) project, which began in 2020, aims to document, model, and disseminate the acoustic heritage of three case studies identified for their unique historical, architectural, and heritage characteristics. In particular, the project focuses on three case studies: the Greek theatre of Tindari, which no longer has many of its original apparatuses; the Gothic cathedral of Notre-Dame de Paris, which is inaccessible following the disastrous fire of 15 April 2019; and the House of Commons in London, hardly accessible to the public (Katz et al., 2020a).

The case study methodological workflow: an overview

Based on the project aims related to auralization and virtual reconstruction, the paper will present the first results obtained from the laser-scanning survey and 3D modeling activities carried out for the case study of the Teatro del Maggio. Indeed, the research aims to test the potential offered by 3D models that combine features of excellent visual rendering with excellent acoustic simulation, and how these can be experienced immersively and multisensorally by different categories of users: expert designers and musicians, ordinary users, or students in training courses.

From a methodological point of view, the workflow – mostly common to the three cases – included an initial digital survey using Terrestrial Laser Scanning (TLS), in order to ensure a reliable metric basis for the next step concerning the 3D modeling of the main hall.

At the same time, a semantic subdivision of the furniture and architectural elements that constitute the main hall, together with a classification of the related constructive materials, was also developed. Based on this, each material was also classified acoustically through on-site investigations and studies on technical project documents, and matched with the specific acoustic parameters, in order to develop a parametric acoustic database useful for subsequent auralization processes.

The next phase involved the actual virtual reconstruction of the theatre hall. This was carried out through specific 3D modeling processes based on the morphometric assets developed from the digital survey and the semantic and materials subdivision. The 3D model of the main hall was then subjected to specific mapping and texturing operations in order to optimize its graphical rendering for ArchViz simulation.

Finally, it was placed within a specific Game Engine platform and implemented with different types of data. Primarily, the optimized 3D model has been interacted with RGB range-based data related to the external areas of the main hall, so that the entire theatre complex can also be navigated, albeit in the form of a colored point cloud. Secondly, each surface/material was associated with its acoustic parameters and based on these, auralization processes were carried out.

These methodological steps made possible the development of an immersive, multisensory VR experience intended for different types of users. In this regard, the last step involved precisely testing activities on users to verify the effective contribution of auralization of 3D models[5].

Digital survey for the virtual reconstruction and visualization of the Teatro del Maggio Musicale Fiorentino

The technological development in laser imaging detection allows the creation of highly descriptive three-dimensional data combinable with Augmented and Virtual Reality (AR and VR) technologies. The joint application of these technologies offers the opportunity to develop tools for disseminating data collected in scientific research and improves the classic workflow between researchers, providing realistic 3D models that are implementable and usable remotely. The 3D laser-scanner survey has developed a lot in recent years, allowing to process high-precision point clouds and providing increasingly reliable and descriptive data thanks to the integration of high-resolution cameras that acquire the given color, thus providing a photorealistic appearance. Thanks to the improvement and diffusion of AR and VR technologies, now easily accessible to the public, the large amount of data detected by laser-scanning can be used to create virtual environments and process the large volume of data acquired by LIDAR to visualize the dataset in a realistic and immersive way using different devices such as smartphones or tablets (Mures et al., 2016). The above workflow can significantly improve research work in cultural heritage conservation, archaeology, architecture, and engineering and offers opportunities for disseminating culture in a widespread and more accessible way.

The project's first step is digitizing the built heritage, which requires a preliminary analysis of the architecture and its urban and environmental context to plan digital survey campaigns, conducted using modern 3D laser-scanner technologies. The three case studies identified – the Berlin Konzerthaus, the Lviv Theatre of Opera and Ballet, and the Teatro del Maggio Fiorentino – have architectural and functional differences that influence the choice of the methodology of analysis and the technical tools to be applied.

The two historic venues in Berlin and Lviv required the integrated use of the laser-scanner survey and SfM photogrammetry. The first methodology allows the creation of the laser-scanning colored point cloud for morphological reconstruction and establishing a virtual environment within the VR application. The photogrammetric survey provides a photorealistic 3D model for exporting photographic ortho-images of the surfaces necessary for the model surfaces mapping.

The digitalization workflow of the third case study – the Teatro del Maggio Musicale Fiorentino – included a digital laser scanner campaign and a photographic campaign for the material classification. In fact, given the recent construction and the presence of contemporary and repetitive materials (Figure 2), the documentation procedure required a photographic sampling to recreate textures necessary for mapping the surfaces of the 3D model.

For the Teatro del Maggio Musicale Fiorentino survey, the great hall and the external spaces of the theatre were considered, with the forecourt and the entrance, to create a path that allows users to move around the complex (Figure 3, 4). The planning of the digital survey campaign considered the

[5] These activities will be carried out by Vie en.ro.se. Ingegneria S.r.l., Italian consultancy firm specialized in acoustics and partner of AURA project.

furnishing and decorative elements present in the interiors to establish a complete and detailed point cloud. A significant number of scans was necessary to avoid the formation of shadow cones on the surfaces, and consequently a lack of data.

Fig. 2. The main hall of the Teatro del Maggio Musicale Fiorentino (© Michele Monasta).

The digital survey of the Teatro del Maggio Fiorentino required the use of two instruments: a laser scanner Z+F 5016 for the exteriors, the entrance and the monumental environment of the main hall, and a Faro Focus M70 for the service areas, the corridors, and the areas of connection with the galleries.

The overall point cloud required the acquisition of 177 color scans using a Z+F 5016 laser scanner and 109 scans made with the Faro Focus M70. The data obtained, registered through visual alignment processes using the *Leica Geosystems Cyclone*[6] software, produced a colored point cloud of the entire complex and the surrounding environment, well balanced in representing the original color of the elements and, therefore, highly descriptive (Cioli and Ricci, 2020). This first global point cloud – the reliability of which has been verified through the analysis of the registration error ratio[7] – includes a large amount of improperly generated data due to the nature of materials such as glass, metal, and shiny materials that can cause uncontrolled reflection and distortions of the laser pulse. For these reasons specific data filtering operations were carried out.[8] This latter filtering activity thus made it possible to obtain a three-dimensional asset from which both morphometric and chromatic-material information could be extracted and used for the development of graphical-technical supports necessary for the subsequent modeling and auralization steps.

[6] https://leica-geosystems.com/products/laser-scanners/software/leica-cyclone

[7] The error was verified by analyzing the report generated at the end of the survey recording process in the Leica Geosystems Cyclone software and manually creating section plans to check for any misalignments in the section line (slice).

[8] Data filtering was first performed automatically: for the Z+F 5016, the scan filtering process was used in the Z+F LaserControl software; for the Faro Focus M70, the filtering took place directly during the import phase within the Leica Cyclone software. After the overall point cloud registration, a manual cleaning phase was carried out by creating section plans and eliminating the points generated improperly.

Furthermore, the model was used as a background setting to create an immersive VR experience to avoid lengthy modelling processes in virtual environments. *Lidar Point Cloud* plugin for *Unreal Engine 4*[9], now included in UE5, changes the usual workflow for the digitization and virtualization of the architectural asset. The plugin allows importing, visualizing, and processing the colored point clouds acquired by laser scanning devices and modifying the points' quantity, size, and shape (Cioli and Ricci, 2020). By establishing a virtual experience within the 3D model, it is possible to develop dissemination tools of the results that entail an optimization in the use of data without the need for further stages of modeling and rendering.

Fig. 3. Panoramic view of the colored point cloud of the theatre's external environment (© Andrea Lumini).

Fig. 4. Panoramic view of the colored point cloud of the main hall (© Federico Cioli).

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

3D Modeling for acoustic auralization and multisensory virtualization

The semantic and acoustic classification of the elements and their materials

In order to guide the 3D modeling and acoustic simulation processes required by the project, a semantic classification of the architectural and decorative elements, and the furniture present in the theatre's main hall was carried out. The hall has been thus divided according to its constructive components and segmented according to materials and specific typological categories. This segmentation process was conducted manually by the research team through visual examinations carried out on site, focusing on both acoustic relevance and the materials with which the various elements are characterized. In support of visual inspections, the classification criteria also considered the acoustic design principles outlined by the Müller-BBM Studio[10], the engineering company that dealt with the structural and environmental acoustic design.

The first element to be analyzed acoustically was the ceiling of the hall, designed to ensure uniform sound diffusion from the stage towards the stalls, the gallery, and the first and second-order boxes. Characterized by numerous narrow and rectangular lighting bodies, the ceiling is made of plasterboard sheets painted with dark colors to highlight the luminous reflections. The proscenium, whose shape has been studied with geometric radius checks, is divided into five inclined reflectors to optimally distribute the sound produced on the stage and in the orchestra pit towards the audience. The structuring of the sidewalls is another fundamental factor for the environmental acoustic distribution, which are made up of rounded pear wood panels at the level of the stalls. An acoustically invisible metal net conceals the remaining side surfaces. This element allows both to manage the architectural shape regardless of the acoustic and to host and hide many acoustic reflectors that can generate reflections towards the stage and directing the sound energy to the stalls' last seats. Finally, the flooring was also studied. It is structured using a specific wooden filigree that allows the sound energy to be spread from the stage to the public through characteristic vibrations. The sounds are thus perceived not only through the air to the ears, but also from the floor to the rest of the body (Reinhold and Conta, 2012).

Based on these constructive and acoustic considerations, a specific subdivision of the elements was carried out, and on its basis, the workflow then focused on quantifying the values of specific acoustic parameters associated with the materials of the various components. The parameters for developing the auralization processes of the model within the chosen Game Engine platform, as it will be seen in the next paragraphs, are essentially three: sound absorption[11], transmission frequencies[12], and scattering[13]. The investigation and assignment of values to the acoustic parameters was carried out

[10] On the 39th National Conference of the AIA (Italian Association of Acoustics) held in Rome in July 2012, the two project managers and acoustic designers of Müller-BBM, Jürgen Reinhold and Simone Conta, exhibited the main acoustic characteristics of the various structural components and some results of acoustic measurements carried out to determine the values of the sound reverberation times (Reinhold and Conta, 2012).

[11] The amount of sound that a given material absorbs at different frequencies (low, medium, and high) and has a domain of values ranging from 0 to 1. For example, if the high-frequency absorption coefficient is set to 1, it means that the material absorbs all the high-frequency sounds that reach it.

[12] It specifies how much sound the material transmits at different frequencies (low, medium, and high), always within limited values between 0 and 1—for example, setting the high-frequency transmission frequency to 0 means that no sound is high frequency passes through the material.

[13] By means of scattering values, it specifies how "rough" the surface is when it reflects sound. Characters with a high diffusion value randomly reflect sound in all directions; surfaces with a low value, on the other hand, reflect the sound in a specular way.

by the Department of Industrial Engineering (DIEF) of the University of Florence, part of UNIFI partner of the AURA project, in charge of the acoustic survey[14].

As mentioned above, the methodology of attributing the acoustic absorption and diffusion coefficients of the different materials in the theatre's main hall was based on visual examinations of the architectural components (Pompoli and Prodi, 2000) supported by extracts of the acoustic report of the architectural project. In particular, the main acoustically significant materials and interior finishes were listed and attributed to each the acoustic characteristics – in terms of scattering and average coefficient of sound absorption and diffusion at low, medium, and high frequencies – relying on data found in the acoustic design extracts, scientific publications, and acoustic simulation software such as *Odeon*[15] and *Ramsete*[16] (Bartalucci et al., 2018).

This methodological classification process led to the creation of an acoustic parametric database, in the form of an information table, containing the coding of the various architectural elements subdivided by single material, a count of the number and areas of the multiple instances, a localization image of the element, and the acoustic parameters associated with the various materials (Figure 5). As it will be seen in the next paragraph, it's important to underline that also the 3D modeling processes were conducted by referring to this semantic classification of the architectural components, namely by structuring for the various elements specific layers with assigned codes and materials corresponding to the acoustic ones.

3D Modeling methodology

The processing and post-production phase of the acquired data was developed by pursuing two complementary and methodologically propaedeutic objectives for the auralization of the Teatro del Maggio acoustic heritage. The first aimed at creating a highly descriptive 3D model of the main hall based on the geometric results of the laser-scanner survey (Figure 6a). The second one aimed at the semantic subdivision of the various architectural elements, in order to enrich the morphological contents with information relating to the investigated acoustic parameters.

The preparatory phase for 3D modeling involved the creation within *Autodesk AutoCAD*[17] environment of two-dimensional drawings through a careful data discretization[18] from the global point cloud developed by laser-scanner survey (Figure 6b).[19]

[14] These investigations were carried out by PhD Eng. F. Borchi of DIEF, under the supervision of Prof. PhD M. Carfagni.

[15] https://odeon.dk

[16] http://www.ramsete.com

[17] https://www.autodesk.it/products/autocad/overview

[18] By "data discretization" is meant the action/process performed by the architect-surveyor, in this case manually and in a critical and rational manner – according, thus, to his architectural composition knowledge – and without the use of specific automated algorithms or AI, of extrapolating from the laser-scanner's massive data acquisitions only the geometric data useful for the virtual reconstruction of the surveyed object.

[19] The interoperability of Autodesk Recap Pro and AutoCAD software was chosen for this process. The point cloud registered on Cyclone was thus exported in .e57 format and then imported within Recap Pro, thus creating an interchange .rcp file. The latter was then inserted into the CAD environment, where it was possible to work by acting directly on the point cloud, through section planes and limit boxes.

ACOUSTIC DATABASE

ID	Element description	TYP	Element Type / Component description	MAT	Material description	POS	NUM	SRFE	SRFT	LFA	MFA	HFA	S	LFT	MFT	HFT
AP	Acoustic Panel	A	Acoustic panel with horizontal stripes - 50x100	apa-01	Acoustic panel 01		53	0,50	26,50	0,08	0,30	0,50	0,60	0,00	0,00	0,00
		B	Acoustic panel with vertical stripes - 50x100	apa-02	Acoustic panel 02		82	0,50	41,00	0,08	0,30	0,50		0,00	0,00	0,00
		C	Curved acoustic panel with 1 m radius - 150x45	apa-03	Acoustic panel 03		30	0,68	20,40	0,08	0,01	0,15	0,30	0,00	0,00	0,00
		D	Curved acoustic panel with 1 m radius - 50x100	apa-03	Acoustic panel 03		45	0,45	20,25	0,08	0,01	0,15	0,30	0,00	0,00	0,00
SE	Seat	A	Metal seat structure	met-04	Metal 04			0,3	537,90	0,10	0,05	0,04	0,50	0,00	0,00	0,00
		B	Wooden seat structure	wod-08	Wood 08		1793	0,52	932,36	0,10	0,05	0,04	0,50	0,00	0,00	0,00
		C	Seat fabric lining	fab-01	Fabric 01			1,60	2.868,80	0,55	0,70	0,65	0,50	0,00	0,00	0,00
ST	Stairs	A	Audience wooden main steps	wod-01	Wood 01		-	-	277,24	0,15	0,08	0,05	0,30	0,00	0,00	0,00
		B	Audience wooden steps	wod-02	Wood 02		-	-	840,17	0,15	0,08	0,05	0,30	0,00	0,00	0,00
		C	Shell 01 wooden main steps	abg-01	Wood 01		-	-	195,47	0,15	0,08	0,05	0,30	0,00	0,00	0,00
		D	Shell 01 wooden steps	wod-02	Wood 02		-	-	505,09	0,15	0,08	0,05	0,30	0,00	0,00	0,00

DATABASE LEGEND

Fig. 5. Screenshot of the processed acoustic database (© Andrea Lumini).

These vectorized drawings (floor plans, sections, and elevations) were then imported within *McNeel Rhinoceros*[20] modeling software where they were used as metric reference for the creation of the 3D model of the main hall and each of its components, exploiting the management and precision potential of NURBS[21] geometries. Indeed, these made it possible to exploit the polylines and curves present in the inserted .dwg files to model individual constructive elements through specific reconstruction commands, such as extrusions along curves, 1- or 2-rails sweeps, or lofts. For some instances with complex geometry, such as the large planar structure housing the first-order boxes, a portion of the decimated point cloud was imported directly, and from it, through specific algorithms and cross sections, the three-dimensional surface was extracted (Figure 6c). The volumes and solids belonging to the 3D model have been geometrically simplified in some points due to construction irregularities, with a reliability level of a max of 5 cm compared to the point cloud.

Very important for subsequent acoustic processing, in addition to the architectural elements of the hall, the entire system of acoustic reflectors, such as scattering panels or acoustic curtains, was also modeled (Figure 6d). The modeling methodology applied here, as these elements were hidden by the wire net and consequently not entirely captured by the laser-scanner beams, referred to the technical documentation made available by the theatre's technical department.

[20] https://www.rhino3d.com/

[21] The Non-Uniform Rational Basis Spline (NURBS) are a class of geometric curves used in computer graphics to represent curves and surfaces. They are essentially mathematical representations of 3D geometry, which accurately define any shape: from a simple line to a circle, arc, or curve, to the most complex 3D free-form or organic solid or surface. Thanks to these geometric properties, in these cases, they allow maintaining a high level of correspondence between surveyed and modeled data.

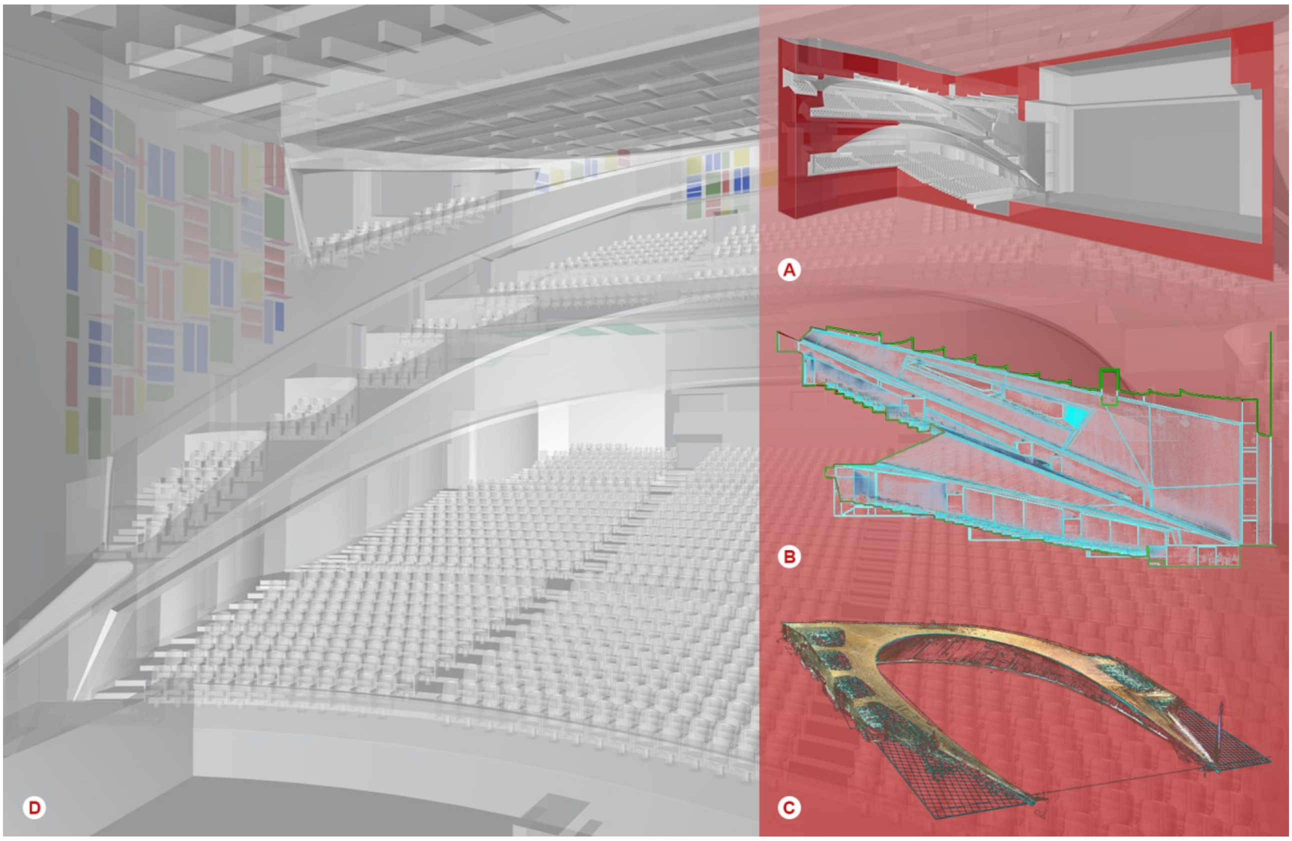

Fig. 6. Graphical elaborations describing the 3D modeling workflow based on CAD drawings and range-based data (© Andrea Lumini)

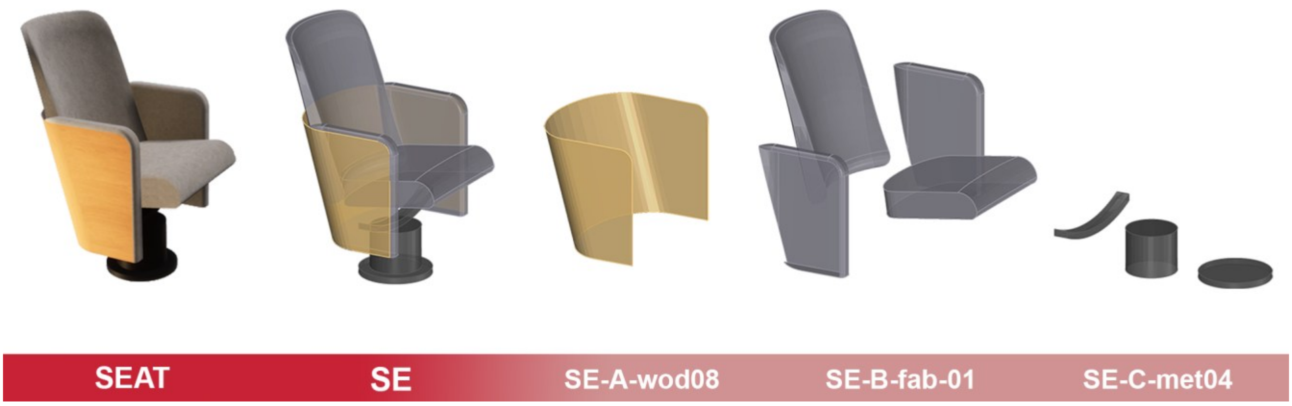

Fig. 7. Example of coding and semantic subdivision according to the constructive components and their materials (© Andrea Lumini).

Finally, special attention was given to the furnishing elements, such as benches and seats, since their significant presence (over 1700 instances) is highly relevant in the acoustic study of the hall and, consequently, in the auralization processes. In conclusion, each element was assigned a pre-defined and coded virtual material to complete the instances' informatization (Figure 7).

Interaction of different assets to create photorealistic and multisensory virtual environment

The research required several tests to develop a multisensory virtual experience of the Teatro del Maggio that could simulate visual and acoustic reality simultaneously. The focus was thus directed toward graphics rendering engines that would allow graphical optimization of 3D models, virtual experience of architectural spaces, and also the simultaneous readability of acoustic metadata associated with geometries.

Regarding the first aspect related to the Architectural Visualization and the texturing of the model, the potentialities of the *Twinmotion*[22] software have been exploited.

Through a specific interchange plugin *Datasmith Importer*, it's possible to link the model created within *Rhinoceros* to the *Twinmotion* graphic engine, maintaining the accuracy of geometries and the related materials information.

Since the actual materials of the main hall were sampled through a photographic survey, within *Twinmotion* a custom photorealistic texture was created for each of these and coded with the same ID as the materials present in the model developed on *Rhinoceros* and in the parametric acoustic database. These, then, were replaced with the newly created ones and, after calibration on the surfaces of the various architectural components of the model, they guaranteed an absolutely true-to-real texture mapping, creating the first virtualization environment (Figure 8).

The further methodological steps for developing an immersive and acoustically simulated virtual environment have required the use of a real Game Engine platform. In this regard, many tests were carried out during this first phase of the research project (still ongoing), the results of which identified *Unreal Engine 4* as the most suitable virtual platform for this sort of real-time applications.

In fact, this platform allows – through specific plugins – both the interaction between different types of assets, such as 3D models and point clouds, and their spatialization and acoustic characterization through the setting of acoustic sources and materials.

First, again through the plugin *Datasmith Importer*, the *Twinmotion* graphically optimized 3D model was inserted within *Unreal Engine*, so that the first navigable virtual environment was set up. Since the model represented the main hall only, as previously mentioned, the *Lidar Point Cloud* plugin was tested, in order to enrich the visual experience and the perception of the architectural environment of the theatre through the interaction of colored point clouds with the three-dimensional model.

Before importing the colored point clouds, data filtering operations were carried out, keeping only the scans necessary to visualize the spaces outside the hall. In this way, only range-based data relative to the pedestrian area in front of the theatre and the entrance foyer areas have been selected to create a visiting path. In the virtual experience, the user can thus visit the main hall by following an equal path to the real one.

Once the point cloud was decimated and exported in .las format to optimize its size, it was inserted into *Unreal Engine* through the above-mentioned plugin, which also allows to define the number, shape, and display mode of the point cloud (RGB in this case). Finally, one last operation was necessary to freely navigate the point cloud on *Unreal Engine*: the collision enabling, so that the points were effectively recognized as interactive geometric elements and responsive to actions performed on them (such as the possibility of walking on the ground).

[22] https://www.twinmotion.com/

The interaction between the two 3D assets, overlaid by sharing the same reference system and visually coherent to reality thanks to faithful texturing, thus made it possible to create a highly photorealistic virtual environment in which the user can freely move from a point cloud to modeled surfaces (Figure 9).

Fig. 8. Perspective view of the textured 3D model for the virtualization of the theater main hall (© Andrea Lumini).

Fig. 9. Real-time ArchViz experimentation using colored point clouds for the theater's exterior environment (© Andrea Lumini).

As for the next steps in the methodological workflow, these will be carried out by the University of Applied Sciences of Berlin (HTW) project partners[23], who, thanks to their IT and acoustic skills, will develop the auralization processes of the 3D model and its actual multisensory virtualization (Droste et al., 2020).

Although these activities are still ongoing by HTW-Berlin partners, an overview of the auralization processes to be developed within the virtual platform is presented below.

Unreal Engine provides built-in 3D sound simulation options that can be activated and adjusted using specific parameters, thus creating spatialized audio. However, developing auralization processes require more than these simple acoustic adjustments, since they do not consider how the geometry of a room and its materials affect the sound of the source. As a result, it was necessary to rely on specific plugins to develop these processes. Many tests were carried out and identified *Steam Audio*[24] as the most suitable software for the purposes of this research, as it is most accurate for adding 3D audio and creating environmental effects[25].

However, before developing auralization processes, some preliminary steps are necessary.

First, a multitrack audio source recorded in an anechoic chamber (Böhm et al., 2018, pp. 977–984) was imported into the *Steam Audio* plugin. Here, each individual track was associated with the respective musical instrument, which was previously placed in the virtual environment in the form of a musician avatar.

Secondly, the plugin needs each surface of the 3D model that is intended to be acoustically active during auralization to be tagged as “phonom geometry”. In this way, the plugin acoustically calculates the environmental effects relative to the various surfaces and accordingly activates the proper response to the audio source during auralization.

Finally, each geometry tagged according to that term has been associated with a “phonom material”, which is an acoustic material that allows the input of specific properties based on the acoustic parameters previously investigated. In this way, based on the semantic/material classification and the respective data stored in the developed acoustic database, values related to the sound absorption and transmission frequencies and the scattering will be set appropriately.

In this way, the main hall of the theatre will be auralized and its various elements, divided by acoustic materials and activated geometrically, will respond acoustically to the waves coming from the source just as they do in reality, enabling a sound simulation as close as possible to the real thing.

Conclusions and further goals

The solution proposed as part of the AURA project – and presented in this paper for the case study of the Teatro del Maggio in Florence – involves not only developing multisensory 3D models based on reliable metric-morphological supports, but more importantly, creating a scientific and replicable

[23] These acoustic and informatic elaborations will be developed by computer scientist S. Schauer of HTW under the supervision of Prof. PhD J. Sieck.

[24] https://valvesoftware.github.io/steam-audio/

[25] Steam Audio offers an end-to-end spatial audio solution that integrates room and listener simulation. Physics-based sound propagation completes auditory immersion by coherently recreating the way sound interacts with the virtual environment.

methodology of a workflow based on element classification and virtual reconstruction aimed at auralization processes.

The evolution of technologies for the investigation and protection of tangible cultural heritage has greatly increased the possibilities. New LIDAR tools and modeling and rendering methodologies have combined to recreate a digital twin of the surveyed object, preserving and protecting its memory and image.

The project thus set out to test an integrated and immersive approach that combines photorealistic visualization and acoustic rendering with direct, simulated user interaction, with the goal of developing significantly new ways of communicating and disseminating Cultural Heritage.

These results will allow the user to experience, through Virtual Reality applications, a multisensory perceptual experience, combining an immersive visual representation with an acoustic simulation. Indeed, the user will be able to move freely in the external virtual environment, realistically reproduced in the form of a point cloud[26], and then enter the theatre, moving from the foyer to the auditorium. Here, inside, the user will be able to choose the listening position and perceive the sound sequence of the music piece equivalently as if he or she were in that place in the theatre.

Through the integration of auralization and a reliable and realistic visual experience, based on data acquired with integrated TLS digital surveying and Structure from Motion (SfM) photogrammetry techniques, it is further possible to investigate the mutual influence that visual and acoustic stimuli have in the perception of the virtual experience.

The first future goals of the experimental virtual reconstruction presented in this paper lead primarily to the development of model auralization processes on the basis of semantic and material classification.

Further studies on information and parametric modeling can be brought forward. Scan-to-NURBS modeling and the creation of information databases has been experimented within the project. Subsequent phases will involve the development of case studies in which modeling will enhance the Scan-to-BIM methodology to directly associate acoustic parameters with individual elements, creating an information infrastructure, shared and embedded of the object of study.

Finally, based on the results obtained from the project, efforts will be made to develop new user opportunities through the involvement of expert and non-expert users, promoting innovation and cross-sector collaboration to build new audiences, business models, practices performance and immersive experiences.

Funding

The AURA project was co-funded by the Creative Europe Programme of the European Union (Grant Agreement n. 101008547).

Conflict of Interests Disclosure

The authors subscribe that there is no conflict of interest in the research presented within this paper.

[26] The experimental use of point clouds has made it possible to reduce time-consuming modeling processes of complex virtual environments, focusing the actual 3D modeling only on elements with which the user interacts in a multisensory way.

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