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# Deliverable 3.2

## Technical description of the 3D modelling of the three venues in Berlin, Florence and Lviv

AURA

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**Project Information**

"AURA - Auralisation of Acoustic Heritage Sites Using Augmented and Virtual Reality" (project no. 101008547)

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Auralisation – the technique of creating virtual soundscapes in 3D models to provide the same immersive sound experience as the music performed in the real venue. AURA will explore exciting new opportunities that auralisation opens up for music performing arts and their traditional and new audiences.

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# 1. Introduction

The Cultural and Creative Industries (CCI) are increasingly moving towards the implementation of modern technologies to explore new commercial horizons and attract new audiences (Bertocci et al., 2021). This impulse has been accelerated in the last two years by the pandemic of COVID-19, which has highlighted the urgency of developing alternative proposals for the fruition of Artistic and Cultural Heritage.

This study is part of the project AURA – Auralisation of Acoustic Heritage Sites Using Augmented and Virtual Reality, co-funded since 2021 by the Creative Europe call, whose objective is to explore the potential of auralisation – a technique to simulate the acoustics of a given place within models (Kleiner et al., 1993) – by combining it with visual representations of the virtual world, in order to create a multisensory experience that reflects the appearance and acoustics of the real place.

The evolution of technologies in the field of investigation and protection of tangible cultural heritage has significantly increased the possibilities of integrating the acquired data. The new LIDAR tools and modelling and rendering methodologies combine to recreate a virtual double of the object investigated preserving and protecting its memory and image, allowing non-invasive remote studies. The establishment of 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 (McLellan, 2004), up to the recent technologies that allow the reconstruction of virtual environments, offering new ways to visualise and experience information (Weinzierl and Lepa, 2019).

With the introduction of the concept of Intangible Cultural Heritage (ICH) by UNESCO in 2003 – as a result 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 particular, in 2017, UNESCO introduced the document “The importance of sound in today’s world: promoting best practices” (UNESCO, 2017), 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 to structure the historical memory of a place, 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 that occur within the environment itself, 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, in particular, 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 makes it possible to capture only direct sound, inserted within the virtual environment. If properly auralised, it can restore the acoustics of the real place.

There have been numerous projects financed by European programs relating to the auralisation of Cultural Heritage sites in recent years. The ERATO project (2003-2006) was one of the first to use cutting-edge technologies in modelling and acoustic survey, representing a reference for archaeo-acoustic research. The project’s goal was to analyse and compare the acoustic properties of ancient Greek and Roman theatres (Rindel et al., 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 modelling 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 Greek theatre of Tindari is investigated, 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).

As part of the AURA project, great attention was paid to investigating the relationship between virtualisation of architecture and auralisation through the development of digital laser-scanner and SfM photogrammetry surveying campaigns that allow to set up highly reliable and descriptive 3d models. These models were tested during the testing phases on ordinary and expert users to verify the actual contribution of the virtual environment in the auralisation. In particular, the AURA project aims to create multi-sensory models, reliable and performing both in terms of graphic rendering and virtual experience and acoustics, also exploiting the integration of point clouds within the gaming technologies. This allows reducing the lengthy modelling processes of complex virtual environments, modelling only the elements the user interacts within a multisensory way.

To reach AURA's goal, three emblematic European case studies were examined – the Konzerthaus in Berlin (DE), the Teatro del Maggio Musicale Fiorentino in Florence (IT) and the Opera and Ballet Theatre in Lviv (UA) – for each of which an appropriate methodology dedicated to digitization and virtual reconstruction was conceived, to obtain reliable assets on which to set the subsequent auralisation processes and, following these, to develop multi-sensory 3D models, reliable and performing both in terms of graphic rendering and virtual fruition, and in terms of acoustics.

The choice of three different case studies from an acoustic, functional, and architectural point of view is fundamental in order to define a methodology applicable at an international level. The project investigates a contemporary building, the Teatro del Maggio Musicale Fiorentino, which addresses many of the material and technological problems that can be encountered in new auditoriums and recently built theatres. A building affected by a reconstruction in neoclassical style, the Konzerthaus in Berlin, which allows the AURA team to address the problems relating to the combination of different materials, such as reinforced concrete structures and the wood and stucco decorative elements, typical of nineteenth-century theatres. Finally, the Opera and Ballet Theatre in Lviv (UA) represents a typical example of an Italian-style theatre in the neo-baroque style, an architectural typology present throughout Europe, and which addresses various issues related to architectural and decorative structures and their acoustic responses.

The methodology linked to the digitization of cultural heritage is therefore declined based on the architectural characteristics of the individual case study and the aims of the project, defining an innovative approach on the international scene.

*Fig. 01 – The three case studies within AURA project: Berlin Konzerthaus, Teatro del Maggio Musicale Fiorentino, Lviv Opera House*

# 2. The AURA workflow: from digital survey to 3D modelling for the auralisation of three European theatre halls

Within the next sections, the preliminary steps of the AURA Project related to the digital surveying and 3D modelling activities of the three case studies considered will be discussed.

This methodological workflow, mostly common to the three cases, included an initial phase dedicated to digital surveying using terrestrial laser-scanner (TLS) instrumentation and, in one case, also through Structure from Motion (SfM) photogrammetry techniques. These activities were necessary both to ensure a reliable metric basis for the next step concerning the 3D modelling of the main halls and to obtain a highly descriptive representation of the current state of the buildings and their interior spaces.

In parallel, a series of on-site studies were carried out on the constructive materials and their acoustic properties, investigating in particular the values of specific acoustic parameters[1] related to them and needed for subsequent auralisation processes. Along with these studies, a series of photographic surveys of the various materials present were also carried out for their sampling intended for the creation of photorealistic textures for mapping the 3D models.

The second phase aimed precisely at the virtual reconstruction of the theatre halls through specific 3D modelling processes based on NURBS geometries and corresponding operations of mapping and texturing of the surfaces of the various constructive elements present.

The latter, moreover, underwent a series of semantic subdivision and material classification processes in order to create a parametric and coded database within which the various elements and their respective constructive materials could be associated with the values of the acoustic parameters identified in the preliminary on-site studies.

This preparatory phase thus allowed that in the 3D model each surface of each element could be associated with both the corresponding textured material and its acoustic parametric values, supporting and facilitating consequently the next processes of auralisation and graphical *ArchViz* simulations.

The latter operations of graphic and acoustic virtualisation - which, however, will not be explored in depth within these sections - were carried out by exploring the multiple potentials offered by Unity software. Indeed, this Game Engine platform allows both the creation of virtual and immersive 3D environments and, through a specific plugin[2], their auralisation, through the setting of music sources and sound materials associated to the values of the acoustic parameters investigated and to the respective surfaces of the imported 3D models.

The following table (tab. 01) summarises for each case study the various activities of the methodological workflow adopted for the AURA Project, including these preliminary steps dedicated to digital surveying and 3D modelling, each of which will be fully explored in the next paragraphs.

[1] The acoustic parameters considered for auralisation are essentially three: sound absorption and transmission frequencies (low, medium and high) and scattering.

[2] Valve Steam Audio

| | | KHB | | TOF | | LVI | |
|---|---|---|---|---|---|---|---|
| | | int | ext | int | ext | int | ext |
| **DIGITAL SURVEY** | | | | | | | |
| **ACQUISITION** | TLS digital survey | ■ | ■ | ■ | ■ | ■ | ■ |
| | SfM photogrammetric survey | | | | | ■ | |
| | On-site study on acoustic parameters | ■ | ■ | ■ | ■ | ■ | ■ |
| | On-site photographic survey for materials sampling | | | ■ | | | |
| **PROCESSING** | Scans registration | ■ | ■ | ■ | ■ | ■ | ■ |
| | SfM photogrammetric processes | | | | | ■ | |
| **RESULTS** | RGB & B/W range-based point cloud | ■ | ■ | ■ | ■ | ■ | ■ |
| | RGB photogrammetric 3D model | | | | | ■ | |
| | 2D CAD graphical drawings | ■ | ■ | ■ | ■ | ■ | ■ |
| **3D MODELLING** | | | | | | | |
| **VIRTUAL RECONSTRUCTION** | Morphological transformations on existing assets | ■ | | | | | |
| | NURBS 3D modelling processes | | | ■ | | ■ | |
| | Projection of photogrammetric data onto 3D model | | | | | ■ | |
| | Mapping and texturing processes | | | ■ | | | |
| **PREPARATORY PHASE** | Elements semantic subdivision | ■ | | ■ | | ■ | |
| | Materials classification | ■ | | ■ | | ■ | |
| | Creation of an acoustic parametric database | ■ | | ■ | | ■ | |
| **AURALISATION** | | | | | | | |
| **PRELIMINARY PHASE** | Importing musicians' avatars in Unity | ■ | | ■ | | ■ | |
| | Importing of audio anechoic sources | ■ | | ■ | | ■ | |
| | Association of audio sources to musicians' avatars | ■ | | ■ | | ■ | |
| **AURALISATION PHASE** | Creation of specific parametric acoustic materials | ■ | | ■ | | ■ | |
| | Association of acoustic materials to 3D model surfaces | ■ | | ■ | | ■ | |
| | Spatialization and acoustic simulation | ■ | | ■ | | ■ | |
| **VIRTUALISATION** | | | | | | | |
| **VR APPLICATION** | Setting of specific interactive hearing hotspots | ■ | | ■ | | ■ | |
| | Creation of a multisensorial experience | ■ | | ■ | | ■ | |

*Tab. 01 – The AURA methodological workflow - Panoramic view of the coloured point cloud of the exterior area of the Berlin Konzerthaus*

Before proceeding to the discussion, it is necessary to specify that the contents and the notes of the next sections (3, 4, 5) regarding the activities carried out for the three case studies, sharing most of the methodological workflow, may sometimes appear the same.

However, these repetitions were made voluntarily, as it was considered more informative that the processes related to the various case studies were treated equally for each of them, so that even the reading of the activities conducted for a single case study could be complete with all the information.

The reader in this way will be able to read the entire document and get a general overview of the methodological workflow of activities related to the digital survey and 3D modelling of theatres, or just read the case study in which he or she is interested and get the same complete information.

# 3. Berlin Konzerthaus

The Berlin Konzerthaus is a neoclassical building initially built after the design of the architect Karl Friedrich Schinkel on the site of the National Theatre of Carl Gotthard Langhans, destroyed by a fire in 1817. It was built as a drama theatre in the centre of Gendarmenmarkt, a large square in the Mitte district characterized by the presence of two symmetrical churches, the Deutscher Dom and the Französischer Dom. Destroyed by bombing during World War II, the building was rebuilt and reopened only in 1984 as a concert hall. The twentieth-century renovation faithfully retained the exterior elevations but significantly altered the interiors, with the disappearance of the Italian-style theatre hall, replaced by an enlarged copy of the former auditorium (Steffens 2004).

Within the AURA Project, as anticipated, a series of digital documentation activities intended for the development of a highly reliable 3D model of the main hall both from the metric-morphological and visual rendering points of view have been carried out, so that it can be used for the development of the auralisation processes and for the creation of the multisensory acoustic-visual experience.

The following paragraphs will focus on the discussion of the various activities related to the 3D digital documentation of the main hall of the Berlin Konzerthaus (fig. 02).

*Fig. 02 – Panoramic view of the coloured point cloud of the exterior area of the Berlin Konzerthaus*

# 3.1. Digital Survey

## 3.1.1 Acquisition and processing of laser-scanner survey data

The documentation activities were carried out during a research mission which was held in Berlin from August 28 to September 3, 2021, by the working team of the Department of Architecture of Florence (DIDA-UNIFI) under the scientific guidance of Prof. S. Bertocci.

The activities included laser scanning surveys of the exterior of the Konzerthaus building and its surrounding in Gendarmenmarkt Square, the foyer and the main hall of the theatre.

The laser scanner survey has provided highly reliable metric data, which have been subsequently processed by specific software, thus constituting a three-dimensional database that will serve as a support basis for the development of the 3D model.

For the laser-scanner survey of the Konzerthaus, two different TLS instruments were used, a Z+F Imager 5016 and a Faro CAM$^2$ Focus$^M$ 70, both with phase difference technology, through which about 500 scans were taken. Specifically, the first instrument was used to acquire 220 RGB colour scans related to the exterior environments of the Konzerthaus, its foyer and main hall, while the second one was used to acquire data from the corridors, stairwells and service areas, developing 300 B/W scans (fig. 03).

*Fig. 03 – TLS digital survey acquisition phase*

The large amount of data obtained from the laser-scanner survey campaign was in fact subsequently imported and processed within a specific point cloud management software, Leica Geosystems Cyclone, through which the main phases of filtering, registration, certification and processing of the global point cloud were developed.

The first step involved the process of filtering out noise due to massive instrumentation acquisitions, by which the point clouds were thus cleaned of excess data, mainly due to the nature of materials such as glass, metal, and shiny materials that can cause uncontrolled reflection and distortions of the laser pulse.

Next, the filtered point clouds were registered by a visual alignment procedure, whereby, through a series of rigid rototranslations between adjacent point clouds, their homologous points are identified in order to determine their alignment. This cloud-to-cloud registration thus made it possible to obtain a single global point cloud of the Konzerthaus complex that included all the data acquired during the instrumental survey.

The next step involved verifying the reliability of the developed survey; during this phase any misalignment errors present in the registered point cloud were checked. To support this verification, the polygonal closure of the scanning locations was previously planned in the acquisition phase, so as to obtain a global cloud formed by scans that were all well constrained to each other.

The check was carried out through sections performed on the global point cloud, both by horizontal and vertical cut planes, verifying that the distance between the section wireframes of the different aligned point clouds was below the tolerance set by the scale of representation (in this case, accuracy limits were set with a tolerance of ±12 mm). The results of this verification were positive, with maximum errors of less than a 10 mm, thus establishing the clear reliability of the TLS survey developed and making it a reliable morphometric support for the digital drawings and its virtual 3D reconstruction (fig. 04).

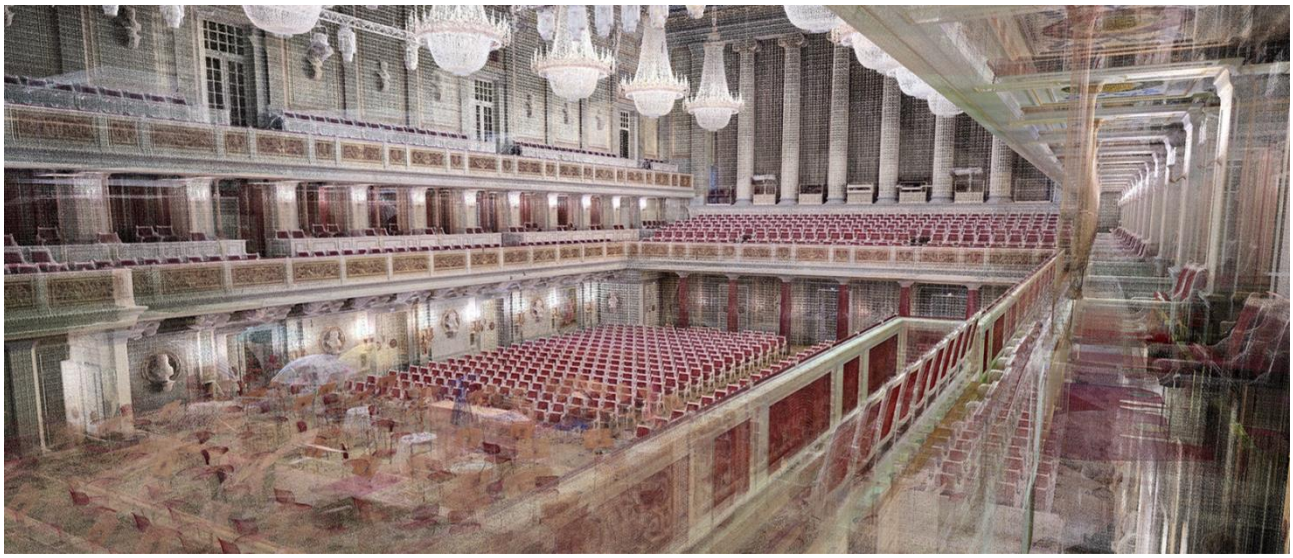


*Fig. 04 – Panoramic view of the coloured point cloud of the Berlin Konzerthaus' main hall*

In order to be able to work more smoothly on the global point cloud, only the portion related to the theatre's main hall was considered. Its point cloud was thus unified, decimated and exported to .e57 format so that it could be imported back within other software and be used as a metric support for the 3D model (fig. 05).

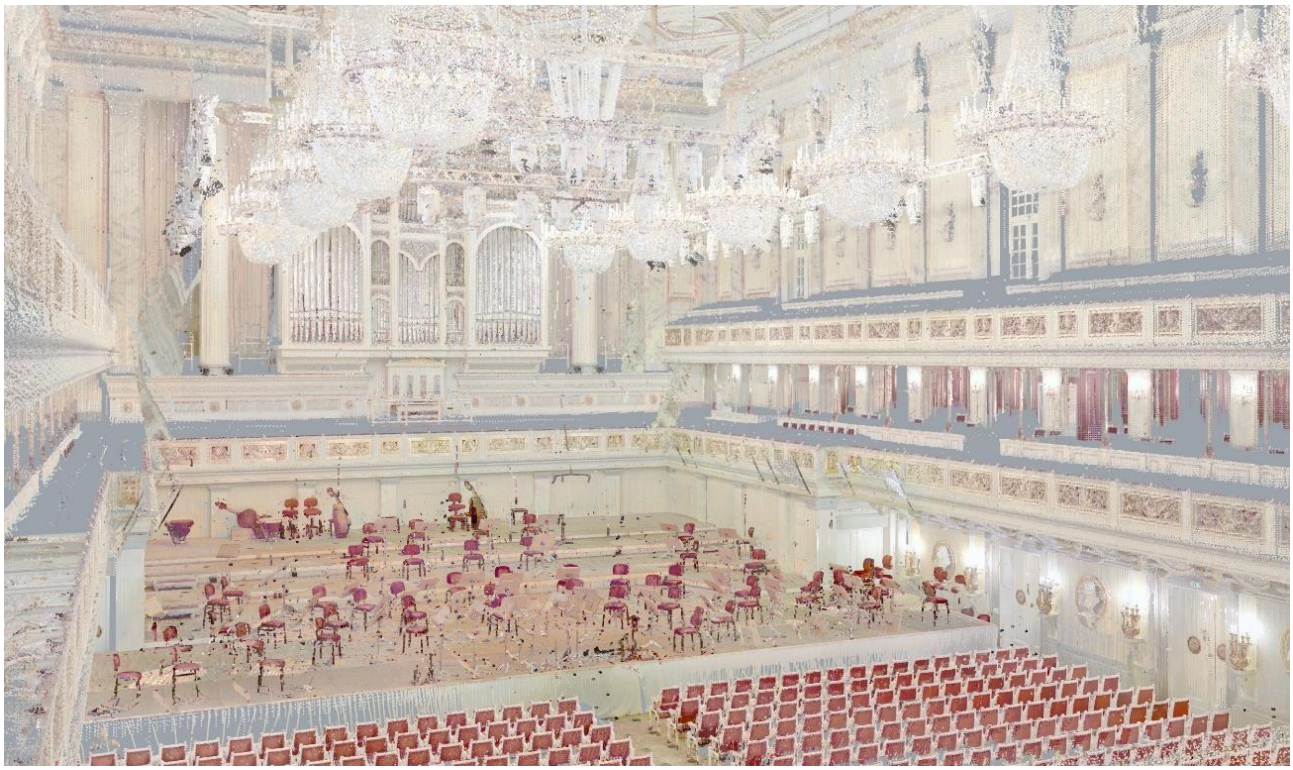


*Fig. 05 – Decimated point cloud of the main hall inserted within the 3D modelling software*

### 3.1.2 On-site study on acoustic parameters

In parallel to these digital data documentation activities, the methodological workflow included a series of on-site studies on the constructive materials and their acoustic properties, investigating the values of the above-mentioned acoustic parameters related to them and needed for subsequent auralisation processes.

As previously stated, the parameters for developing the auralisation processes of the model within specific IT applications are essentially three: sound absorption[3] and transmission[4] frequencies, and scattering[5].

The investigation and assignment of values to the acoustic parameters was carried out by the working team of 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, under the scientific guidance of Prof. M. Carfagni.

The methodology of attributing the acoustic absorption and diffusion coefficients of the different materials present in the theatre's main hall was based on a visual examination of the architectural components (Pompoli and Prodi, 2000) supported, in some cases, by an extract of the acoustic report of the architectural project.

For this case study, however, these studies were not concretely carried out, but rather the results related to the studies conducted on the materials present in the case study of the Teatro del Maggio Musicale Fiorentino[6] were taken into consideration and adapted to the same respective ones present in the Konzerthaus' main hall.

## 3.2. 3D Modelling

### 3.2.1. The digital survey as a metric basis for the use of an existing 3D model

Unlike the other case studies, for this Berlin theatre an existing 3D model was used. In fact, as a partner of the AURA project, the Konzerthaus institution provided a textured 3D model of the main hall, previously elaborated for another project (fig. 06).

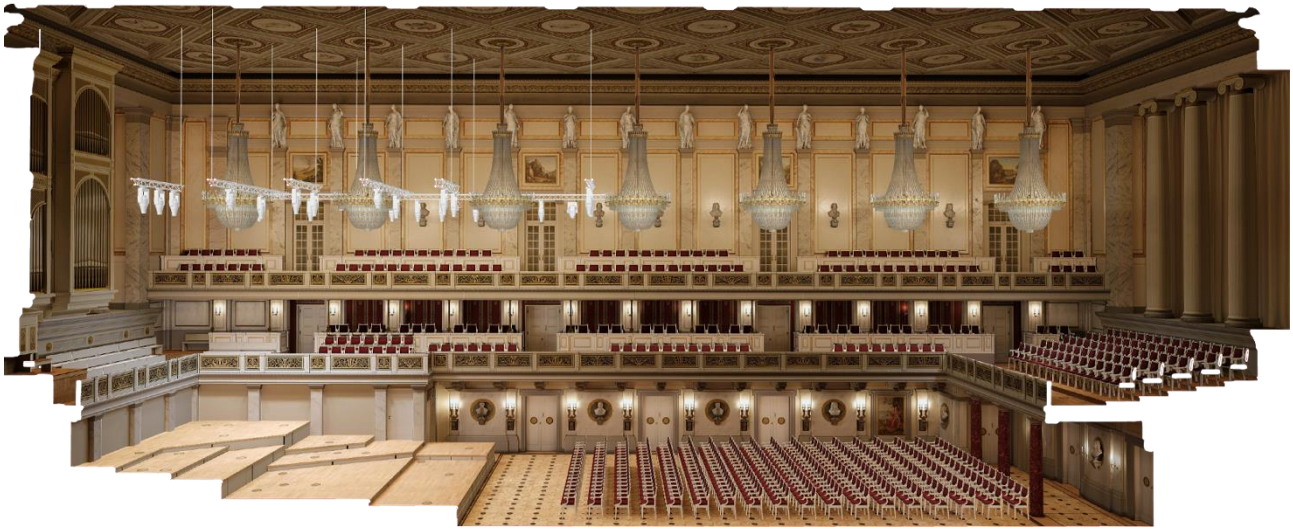


*Fig. 06 – Longitudinal section of the existing 3D model of the Konzerthaus' main hall*

[3] 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.

[4] 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.

[5] By means of scattering values, we specify 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.

[6] See paragraph 4.1.2

However, following specific morphological analyses conducted, it turned out that this 3D model did not metrically reflect the real dimensional aspects of the complex, making some morphological modifications based on the more reliable point cloud necessary.

To accomplish these adjustments, the potentials offered by McNeel Rhinoceros 3D management and modelling software were exploited. Thus, both the 3D asset provided by the Konzerthaus and the portion of the point cloud of the main hall developed from the laser-scanner surveys in .e57 format were imported into it.

Once inserted into the Rhinoceros environment, the 3D model was initially oriented according to the spatial coordinate system of the point cloud, and then morphologically modified by specific transformation commands, until the two different assets were matching (fig. 07).

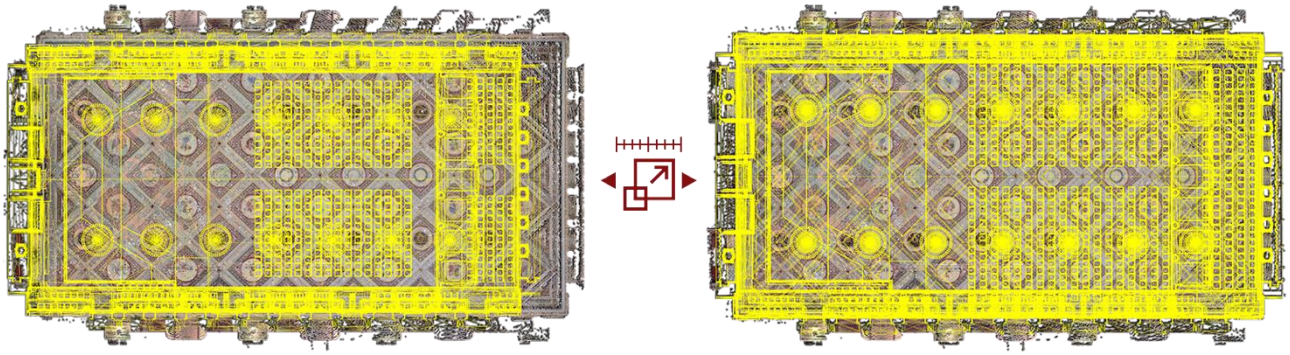


*Fig. 07 – Morphological transformations performed on the existing 3D model based on the most reliable point cloud*

In this way, a visually and metrically reliable 3D model of the Konzerthaus main hall was obtained (fig. 08) although not yet exactly ready to be exploited for subsequent auralisation processes. The next paragraphs will, in this regard, discuss further operations to prepare the 3D model for subsequent acoustic activities.

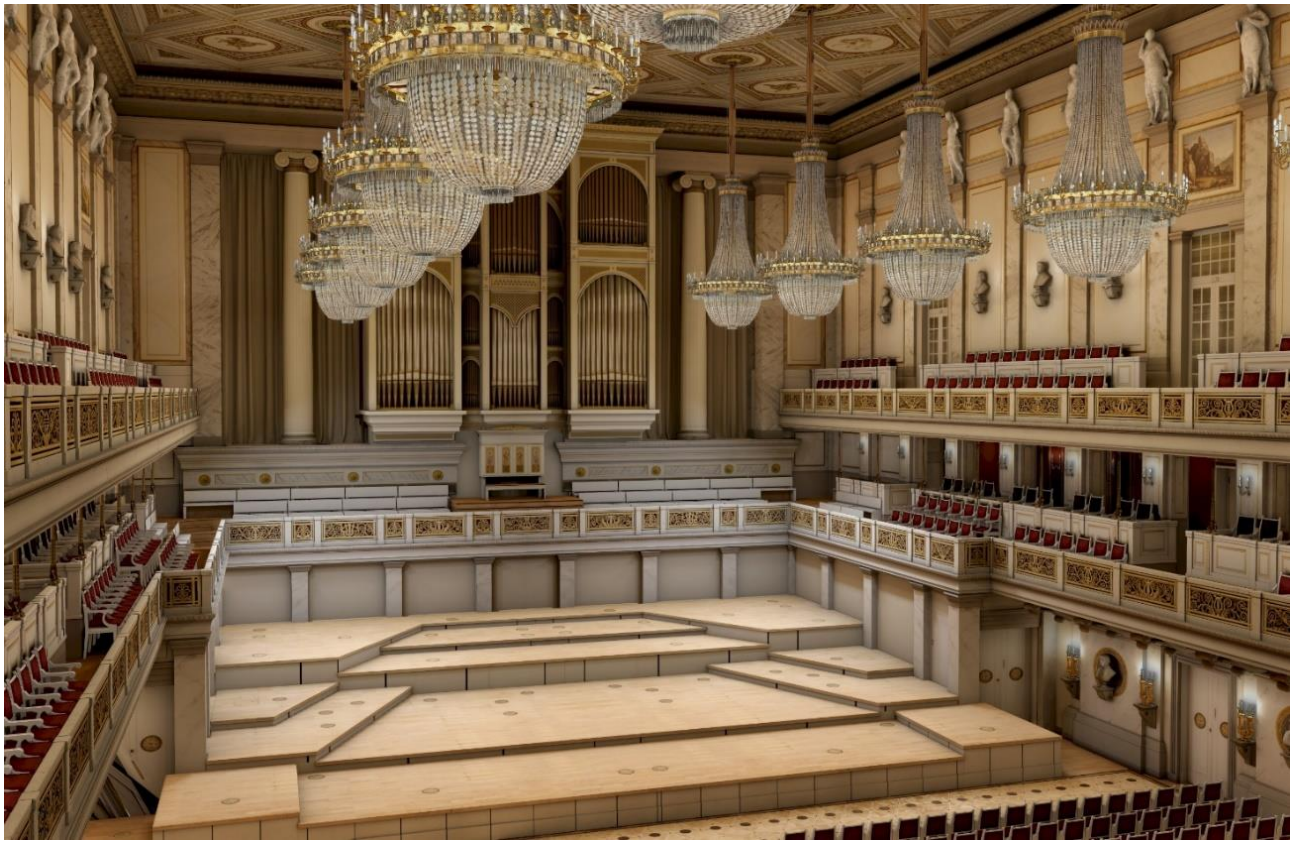


*Fig. 08 – Panoramic view of the "new" main hall 3D model metrically reliable*

### 3.2.2. Elements semantic subdivision, materials classification and creation of an acoustic parametric database

Given the acoustic simulation purposes that the virtualisation project envisaged, in preparation for the auralisation phase, a semantic classification of the individual elements present in the theatre main hall was developed.

The hall has been divided according to its constructive components and segmented according to materials and specific typological categories. The methodological approach with which this division was conducted was based both on the acoustic relevance and materials of which the various elements are characterized, and on the results of the preliminary on-site acoustic studies.

Based on these constructive and acoustic considerations, a specific subdivision of the elements was then carried out, focusing on quantifying the values of specific acoustic parameters associated with the materials of the various components (fig. 09).

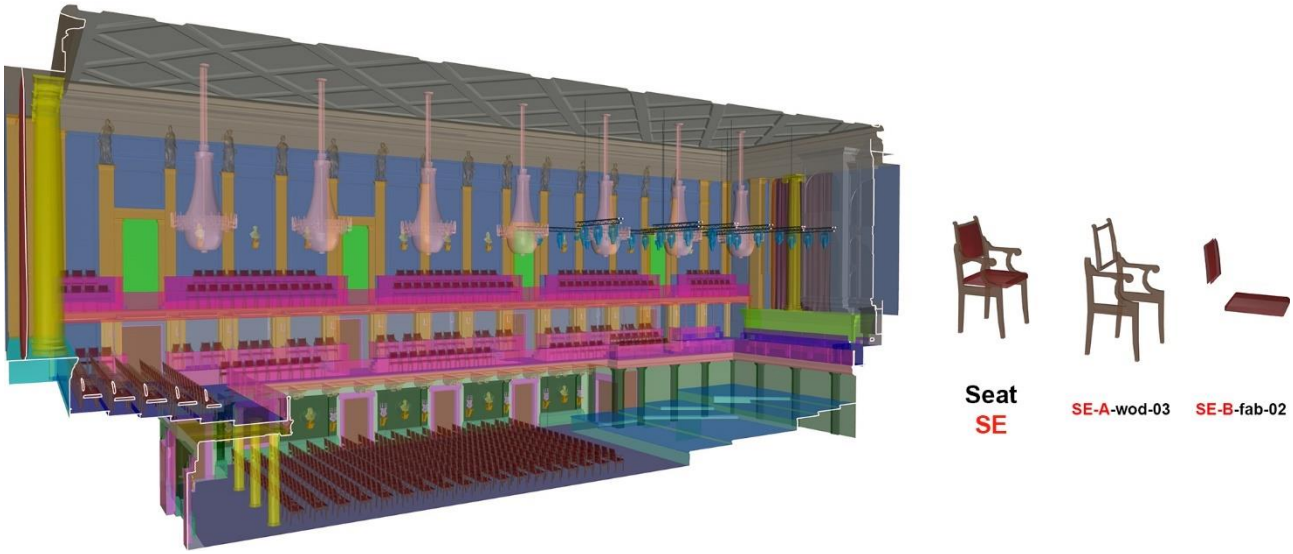


*Fig. 09 – Different visualisations of the 3D model subdivided into coded component elements (each represented by a different colour)*

This methodological 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 picture of the element, and the acoustic parameters associated with the various materials.

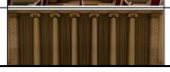
It is important to underline that also the 3D modelling processes were conducted by referring to the semantic subdivision of the architectural components, namely by structuring for the various elements, specific layers with assigned codes and materials corresponding to the acoustic ones inserted within the database (tab. 02).

For this latter, the main acoustically significant materials and interior finishes were listed and attributed to each the acoustic characteristics in terms of average coefficient of sound absorption and transmission at low, medium, and high frequencies and the average coefficient of acoustic scattering based on databases of materials taken from scientific publications and acoustic simulation software such as Odeon and Ramsete (Bartalucci et al., 2018).

Since the specific characteristics of many of the materials in the hall, as well as their construction methods (glued coating, on supports, etc.) are not known, general assumptions were made, and average coefficients related to each specific material were assigned.

As for transmission coefficients, they were set equal to 0 (no transmission of sound through the element) for all boundary elements, as it was not necessary to know the level transmitted outside the main hall.

Each value of the acoustic parameters investigated was thus associated with the respective architectural element and its characteristic material, thus facilitating the development of the subsequent auralisation processes, which require the subdivision of the elements of the 3D model according to its materials in order to create specific acoustic assets.

| ACOUSTIC DATABASE | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | Element description | TYP | Element Type / Component description | MAT | Material description | Material RGB code | IMG | NUM | SRFE | SRFT | LFA | MFA | HFA | S | LFT | MFT | HFT |
| BE | Bench | A | Wooden bench | ben-01 | Bench 01 | 139,139,0 | | 12 | 125,0 | 0,36 | 0,15 | 0,30 | 0,40 | 0,30 | 0,00 | 0,00 | 0,00 |
| CE | Ceiling | A | Balcony 01 lower ceiling | cei-01 | Ceiling 01 | 142,47,47 | | - | - | 1.598,14 | 0,15 | 0,05 | 0,04 | 0,10 | 0,00 | 0,00 | 0,00 |
| | | B | Balcony 02 lower ceiling | cei-02 | Ceiling 02 | 103,15,15 | | - | - | 19,71 | 0,15 | 0,05 | 0,04 | 0,10 | 0,00 | 0,00 | 0,00 |
| | | C | Main hall ceiling | cei-03 | Ceiling 03 | 63,0,0 | | - | - | 304,95 | 0,15 | 0,05 | 0,04 | 0,10 | 0,00 | 0,00 | 0,00 |
| CN | Cornice | A | Balcony 01 cornice | cor-01 | Cornice 01 | 204,204,0 | | - | - | 105,06 | 0,15 | 0,05 | 0,04 | 0,10 | 0,00 | 0,00 | 0,00 |
| | | B | Balcony 02 cornice | cor-02 | Cornice 02 | 79,127,63 | | - | - | 135,10 | 0,15 | 0,05 | 0,04 | 0,10 | 0,00 | 0,00 | 0,00 |
| | | C | Main hall cornice | cor-03 | Cornice 03 | 191,63,63 | | - | - | 105,06 | 0,15 | 0,05 | 0,04 | 0,10 | 0,00 | 0,00 | 0,00 |
| | | D | Door cornice | cor-04 | Cornice 04 | 255,191,255 | | - | - | 135,10 | 0,15 | 0,05 | 0,04 | 0,10 | 0,00 | 0,00 | 0,00 |
| CU | Curtain | A | Curtain | cur-01 | Curtain 01 | 139,121,94 |  | - | - | 343,30 | 0,10 | 0,40 | 0,60 | 0,10 | 1,00 | 1,00 | 1,00 |

*Tab. 02 – Screenshot of the processed acoustic parametric database for the Konzerthaus*

### 3.2.3. The setting of a photorealistic virtual environment

For this case study, unlike the other ones, the 3D model made available by the Konzerthaus institution was already perfectly adequate for its visual virtualisation, and in fact no mapping or texturing process of the 3D model was necessary.

The only operations to set up the photorealistic virtual environment involved morphological changes to the main hall carried out to adapt the original 3D model to its real size based on the digital survey, which also included resizing the textures applied to the various surfaces in order that they, too, would be at the correct metric scale.

The correctly sized 3D asset, visually coherent with the reality, semantically subdivided by constructive elements and made up of surfaces with materials that can be associated with the various acoustic parameters was thus made available – through exporting its geometries in .fbx format – for subsequent activities related to auralisation processes and the development of multisensory virtual experiences, which will be conducted within the Game Engine Unity platform (fig. 10).

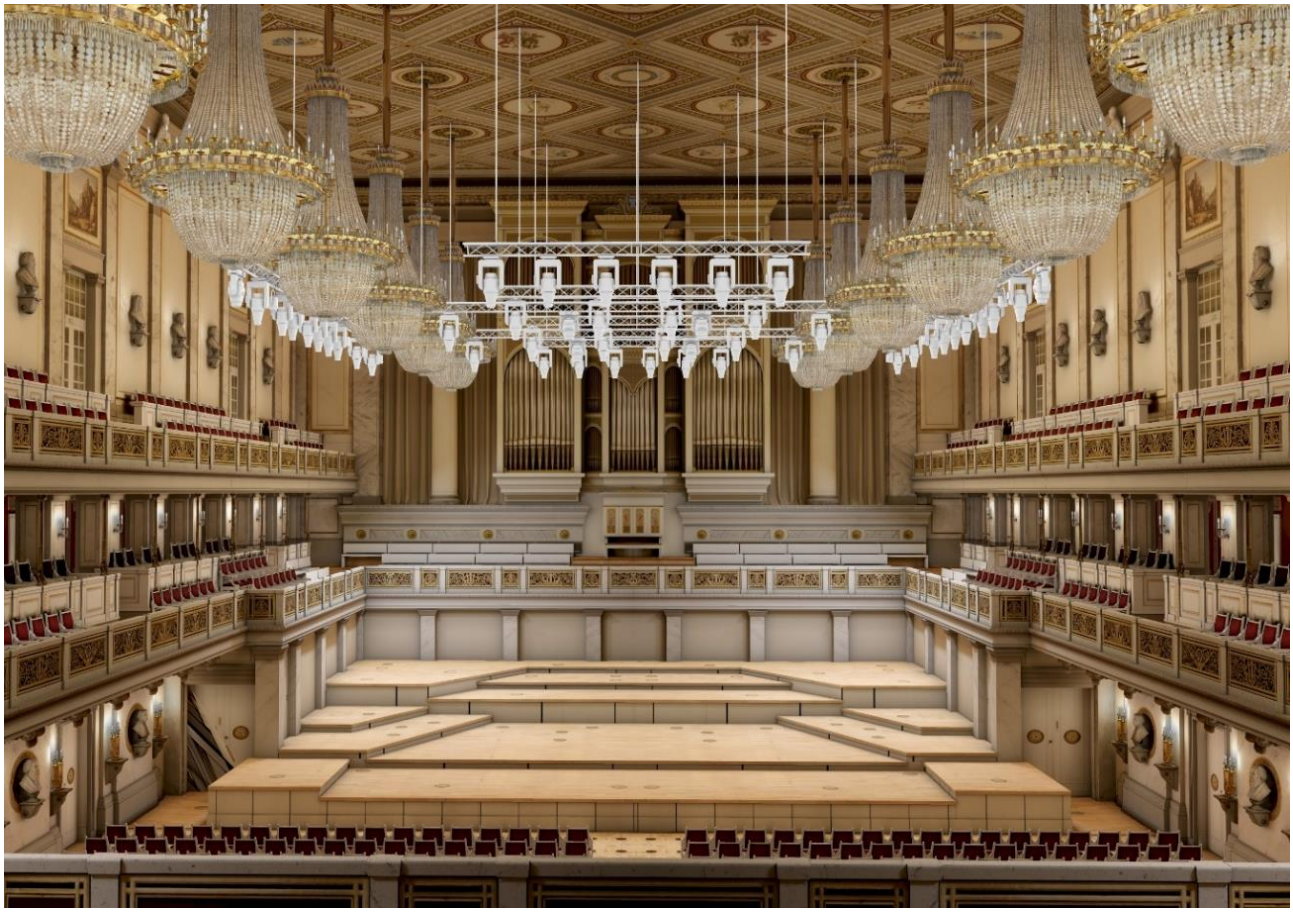


*Fig. 10 – Panoramic view of the subdivided and textured 3D model ready for the auralisation processes and for its virtualisation*

# 4. Teatro del Maggio Musicale Fiorentino in Florence

The Teatro del Maggio Musicale Fiorentino (or Teatro dell'Opera di Firenze), designed by architect Paolo Desideri of ABDR studio and opened in December 2011, represents one of the most relevant contemporary design initiatives in the Florentine architectural scene. Inside it hosts, in addition to numerous smaller rooms, three large theatrical venues: a recently opened auditorium, an open-air cave and the main hall of the opera house, enclosed within a stereometric volume in the shape of a " horse-shoe" (Reinhold and Conta, 2012).

Within the AURA Project, as anticipated, a series of digital documentation activities intended for the development of a highly reliable 3D model of the main hall both from the metric-morphological and visual rendering points of view have been carried out, so that it can be used for the development of the auralisation processes and for the creation of the multisensory acoustic-visual experience.

The following paragraphs will focus on the discussion of the various activities related to the 3D digital documentation of the main hall of the Teatro del Maggio Musicale Fiorentino in Florence (fig. 11).

*Fig. 11 – Panoramic view of the coloured point cloud of the exterior area of the Teatro del Maggio Musicale Fiorentino in Florence*

# 4.1. Digital Survey

## 4.1.1. Acquisition and processing of laser-scanner survey data

The documentation activities were carried out in Florence in the early months of 2021, by the working team of the Department of Architecture of Florence (DIDA-UNIFI) under the scientific guidance of Prof. S. Bertocci.

The activities included laser scanning surveys of the exterior of the Maggio building and its surrounding in Vittorio Gui Square, the foyer and the main hall of the theatre.

The laser scanner survey has provided highly reliable metric data, which have been subsequently processed by specific software, thus constituting a three-dimensional database that will serve as a support basis for the development of the 3D model.

For the laser-scanner survey of the Teatro del Maggio, two different TLS instruments were used, a Z+F Imager 5016 and a Faro CAM$^2$ Focus$^M$ 70, both with phase difference technology, through which about 300 scans were taken. Specifically, the first instrument was used to acquire 180 RGB colour scans related to the exterior environments of the Maggio, its foyer and main hall, while the second one was used to acquire data from the corridors, stairwells and service areas, developing 110 B/W scans (fig. 12).

*Fig. 12 – TLS digital survey acquisition phase*

The large amount of data obtained from the laser-scanner survey campaign was in fact subsequently imported and processed within a specific point cloud management software, Leica Geosystems Cyclone, through which the main phases of filtering, registration, certification and processing of the global point cloud were developed.

The first step involved the process of filtering out noise due to massive instrumentation acquisitions, by which the point clouds were thus cleaned of excess data, mainly due to the nature of materials such as glass, metal, and shiny materials that can cause uncontrolled reflection and distortions of the laser pulse.

Next, the filtered point clouds were registered by a visual alignment procedure, whereby, through a series of rigid rototranslations between adjacent point clouds, their homologous points are identified in order to determine their alignment. This cloud-to-cloud registration thus made it possible to obtain a single global point cloud of the Maggio complex that included all the data acquired during the instrumental survey.

The next step involved verifying the reliability of the developed survey; during this phase any misalignment errors present in the registered point cloud were checked. To support this verification, the polygonal closure of the scanning locations was previously planned in the acquisition phase, so as to obtain a global cloud formed by scans that were all well constrained to each other.

The check was carried out through sections performed on the global point cloud, both by horizontal and vertical cut planes, verifying that the distance between the section wireframes of the different aligned point clouds was

below the tolerance set by the scale of representation (in this case, accuracy limits were set with a tolerance of ±12 mm). The results of this verification were positive, with maximum errors of less than a 10 mm, thus establishing the clear reliability of the TLS survey developed and making it a reliable morphometric support for the digital drawings and its virtual 3D reconstruction (fig. 13).

In order to be able to work more smoothly on the global point cloud, also for this case study, only the portion related to the theatre's main hall was considered. Its point cloud was thus unified, decimated and exported to .e57 format so that it could be imported back within other software and be used as a metric support for the 3D model.

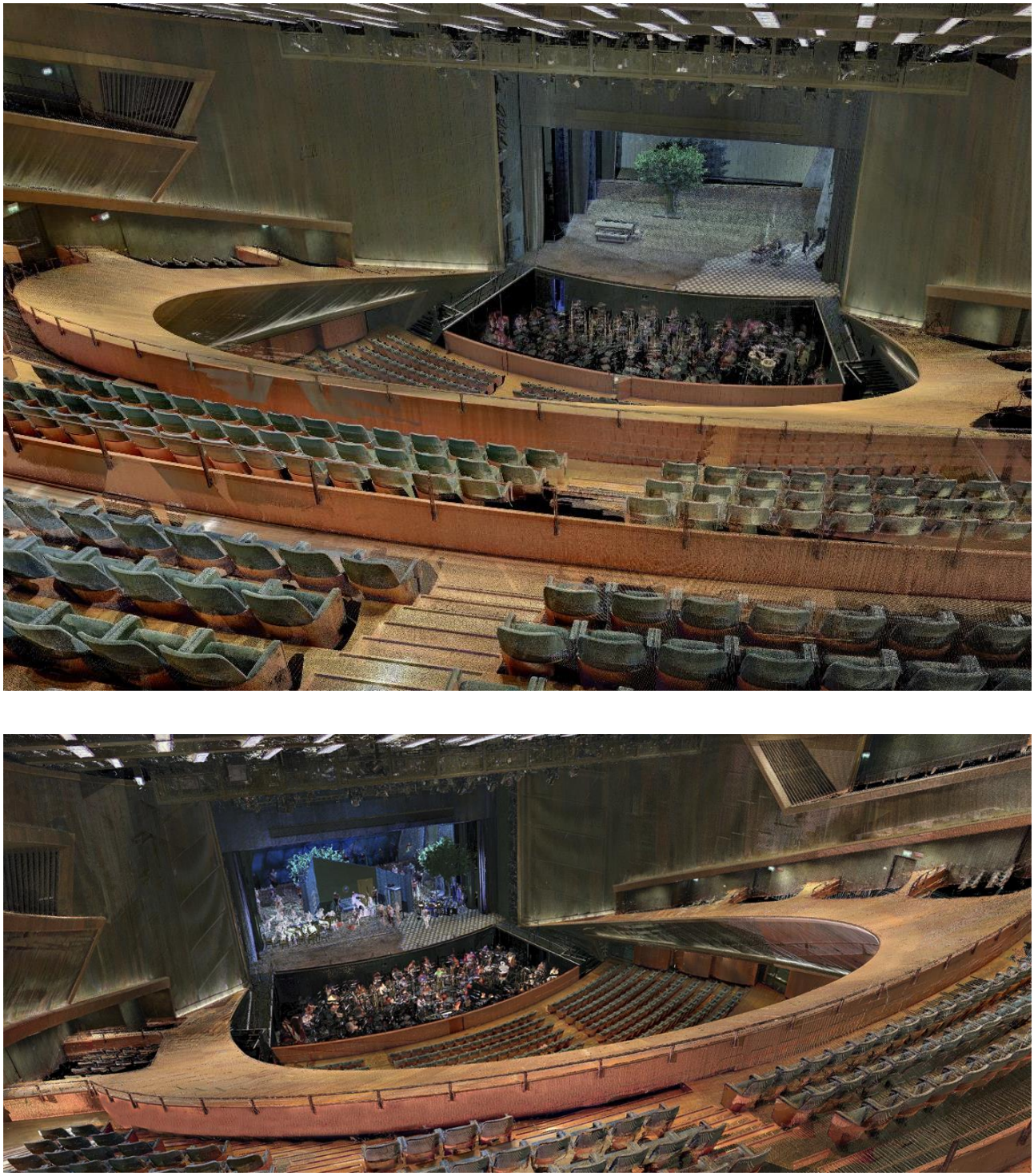


*Fig. 13 – Panoramic views of the coloured point cloud of the Maggio's main hall*

### 4.1.2 On-site study on acoustic parameters

In parallel to these digital data documentation activities, the methodological workflow included a series of on-site studies on the constructive materials and their acoustic properties, investigating the values of the above-mentioned acoustic parameters related to them and needed for subsequent auralisation processes.

As previously stated, the parameters for developing the auralisation processes of the model within specific IT applications are essentially three: sound absorption[7] and transmission[8] frequencies, and scattering[9].

The investigation and assignment of values to the acoustic parameters was carried out by the working team of 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, under the scientific guidance of Prof. M. Carfagni.

The methodology of attributing the acoustic absorption and diffusion coefficients of the different materials present in the theatre's main hall was based on a visual examination of the architectural components (Pompoli and Prodi, 2000) supported, just in this case, by an extract of the acoustic report of the architectural project, in which some acoustic characteristics were listed. In addition, the acoustic design principles outlined by the Müller-BBM studio, the engineering company that dealt with the structural and environmental acoustic design, were also considered.[10]

The primary element for the theatre's acoustics is the hall's ceiling, designed to ensure uniform diffusion of sound 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 was made of plaster-board sheets painted with dark colours to highlight the luminous reflections. The proscenium, whose shape has been studied with geometric radius checks, is a structure divided into five inclined reflectors to optimally distribute the sound produced on the stage and in the orchestra pit towards the audience.

Another fundamental factor for the environmental acoustic distribution lies in the structuring of the sidewalls, which are made up of rounded pear wood panels at the level of the stalls. At the same time, the remaining side surfaces are concealed by an acoustically invisible metal net that allowed both to manage the architectural form regardless of the acoustic format and the housing of numerous acoustic reflectors capable of generating reflections towards the stage and directing the sound energy that would be lost in the last places of the stalls.

Finally, the flooring was also studied and structured using a specific wooden filigree that allowed the sound energy to be spread from the stage to the public through characteristic vibrations, thus making the sounds perceived not only through the air to the ears also from the floor to the rest of the body.

These studies conducted on the materials and the constructive components of the Maggio Theatre's main hall were used as the basis also for the other two case studies, adapting the results to the materials – often the same – found in the Berlin Konzerthaus or in the Lviv Opera House.

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[7] 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.

[8] 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.

[9] By means of scattering values, we specify 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.

[10] With over 400 highly skilled employees, Germany-based Müller-BBM GmbH is a leading engineering company for consulting, testing, and planning services in all fields of acoustics, building physics, and environmental protection. On the occasion of the 39th National Conference of the AIA (Italian Association of Acoustics) held in Rome in July 2012 (Reinhold, J., Conta, S., 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.

# 4.2. 3D Modelling

## 4.2.1. The digital survey as a metric basis for the creation of a NURBS 3D model

The processing and post-production phase of the acquired data was developed by pursuing two complementary and methodologically propaedeutic objectives for the auralisation of the Maggio Theatre's 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. The second concerns the semantic subdivision of the various architectural elements to enrich the morphological contents with information relating to the investigated acoustic parameters.

The preparatory phase for 3D modelling involved the creation in CAD environment of two-dimensional drawings through careful discretization of data extracted from the portion of point cloud developed from the laser-scanner surveys (fig. 14). These drawings were then imported within McNeel Rhinoceros modelling software where they were used as metric support for the creation of the 3D model of the hall and each of its components, exploiting the management and precision potential of Nurbs geometries.

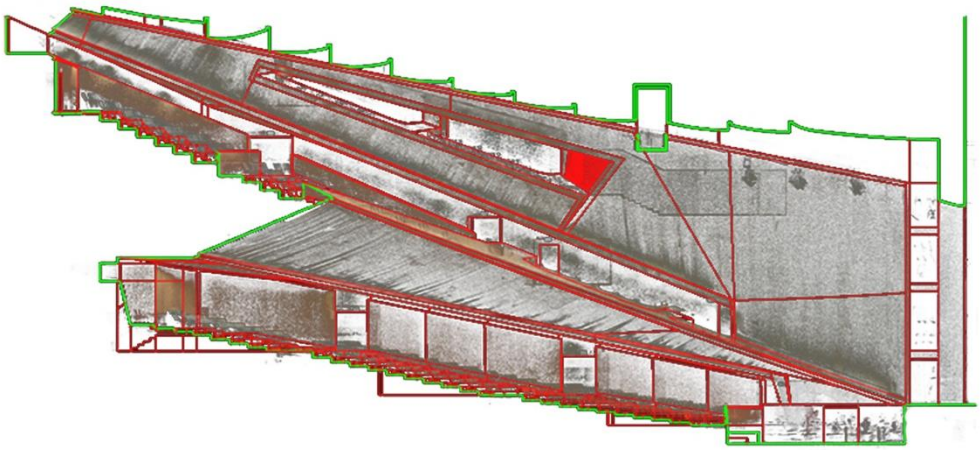


*Fig. 14 – 2D graphical elaborations processed within CAD environment*

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 surfaces were extracted (fig. 15). The volumes and solids belonging to the 3D model were geometrically simplified in some places, due to construction irregularities, but a level of adherence to reality of max 5 cm was maintained with respect to the point cloud.

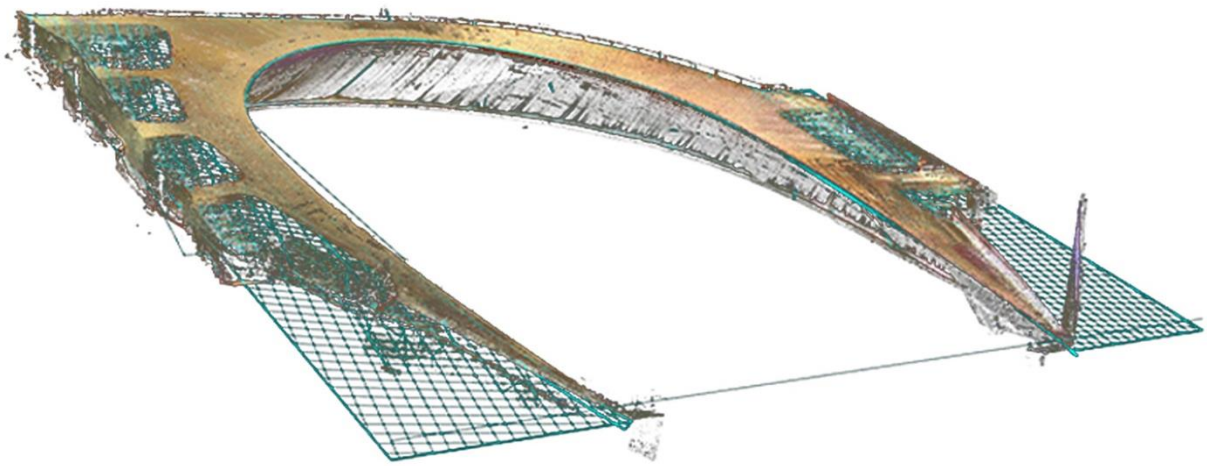


*Fig. 15 – Surface extraction directly from the decimated point cloud*

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 modelled (fig. 16). The modelling 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.

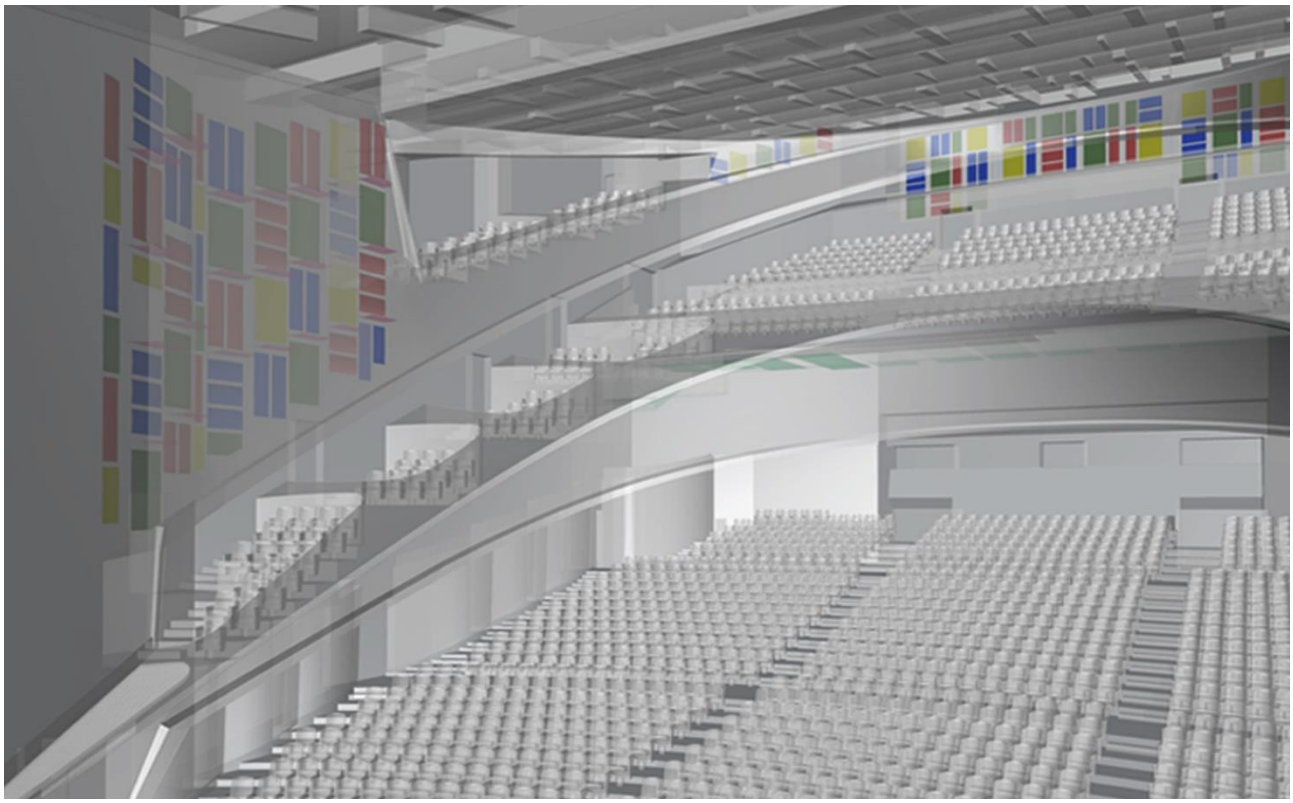


*Fig. 16 – 3D modelling of the entire system of acoustic reflectors, such as scattering panels or acoustic curtains*

Finally, special attention was given to furniture elements, such as benches and seats, as their wide presence (more than 1700 instances) is extremely relevant in the acoustic study of the venue and consequently in the auralisation processes.

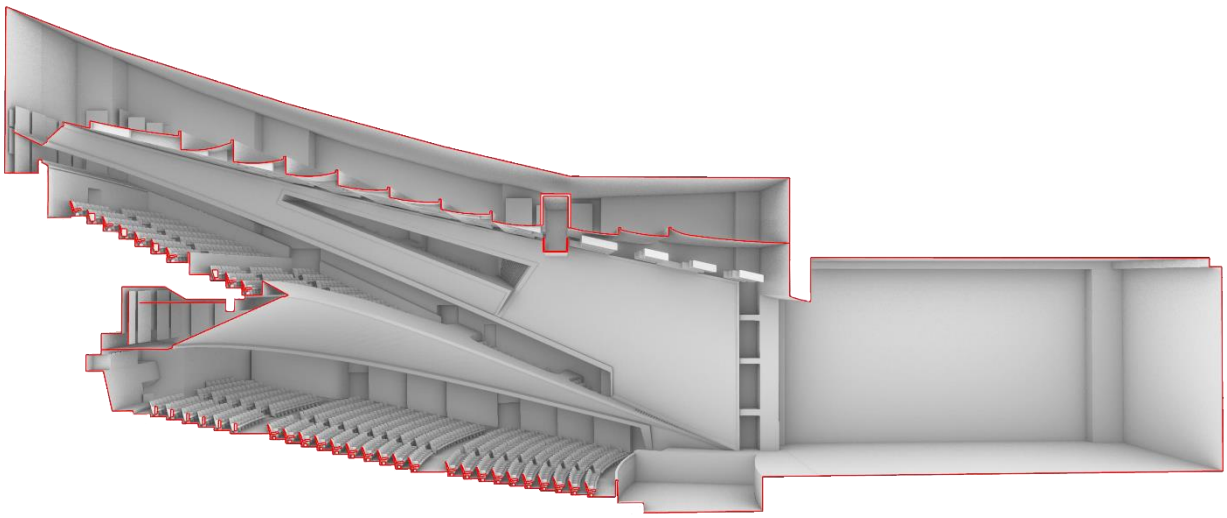


*Fig. 17 – Longitudinal section of the untextured 3D model of the Maggio's main hall*

### 4.2.2. Elements semantic subdivision, materials classification and creation of an acoustic parametric database

Given the acoustic simulation purposes that the virtualisation project envisaged, in preparation for the auralisation phase, a semantic classification of the individual elements present in the theatre main hall was developed.

The hall has been divided according to its constructive components and segmented according to materials and specific typological categories. The methodological approach with which this division was conducted was based both on the acoustic relevance and materials of which the various elements are characterized, and on the results of the preliminary on-site acoustic studies.

Based on these constructive and acoustic considerations, a specific subdivision of the elements was then carried out, focusing on quantifying the values of specific acoustic parameters associated with the materials of the various components (fig. 18).

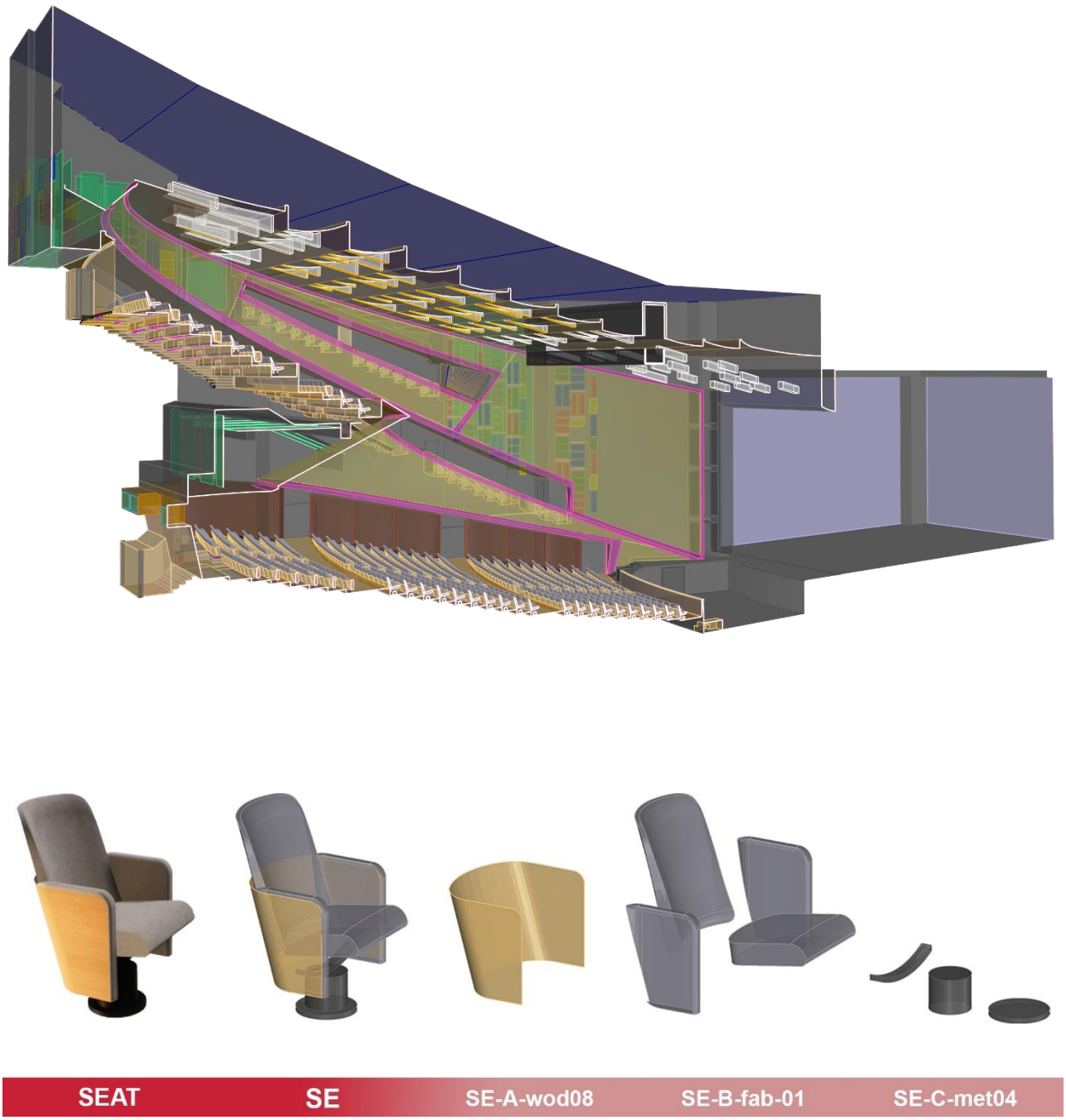



*Fig. 18 –Visualisation of the 3D model subdivided into coded component elements (each represented by a different colour)*

This methodological 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 picture of the element, and the acoustic parameters associated with the various materials.

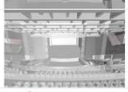
It is important to underline that also the 3D modelling processes were conducted by referring to the semantic subdivision of the architectural components, namely by structuring for the various elements, specific layers with assigned codes and materials corresponding to the acoustic ones inserted within the database (tab. 03).

For this latter, the main acoustically significant materials and interior finishes were listed and attributed to each the acoustic characteristics in terms of average coefficient of sound absorption and transmission at low, medium, and high frequencies and the average coefficient of acoustic scattering based on databases of materials taken from scientific publications and acoustic simulation software such as Odeon and Ramsete (Bartalucci et al., 2018).

Since the specific characteristics of many of the materials in the hall, as well as their construction methods (glued coating, on supports, etc.) are not known, general assumptions were made, and average coefficients related to each specific material were assigned.

As for transmission coefficients, they were set equal to 0 (no transmission of sound through the element) for all boundary elements, as it was not necessary to know the level transmitted outside the main hall, while for the metal net, which it has to be considered acoustically invisible, the transmission coefficient was set equal to 1 (complete transmission of sound through the element).

Each value of the acoustic parameters investigated was thus associated with the respective architectural element and its characteristic material, thus facilitating the development of the subsequent auralisation processes, which require the subdivision of the elements of the 3D model according to its materials in order to create specific acoustic assets.

| ACOUSTIC DATABASE | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | Element description | TYP | Element Type / Component description | MAT | Material description | Material RGB code | POS | NUM | SRFE | SRFT | LFA | MFA | HFA | S | LFT | MFT | HFT |
| AB | Acoustic Background | A | Stage 01 vertical acoustic background | abg-01 | Acoustic background 01 | 191,191,255 | | - | - | 873,44 | 0,30 | 0,50 | 0,70 | 0,50 | 0,00 | 0,00 | 0,00 |
| | | B | Stage 01 fly acoustic background | abg-02 | Acoustic background 02 | 63,63,255 | | - | - | 374,12 | 0,50 | 0,70 | 0,90 | 0,50 | 0,00 | 0,00 | 0,00 |
| | | C | Shell 01 wooden surfaces acoustic background | abg-03 | Acoustic background 03 | 0,0,255 | | - | - | 8,72 | 0,15 | 0,07 | 0,05 | 0,10 | 0,00 | 0,00 | 0,00 |
| | | D | Shell 02 slanted walls acoustic background | abg-04 | Acoustic background 04 | 0,0,191 |  | - | - | 10,50 | 0,15 | 0,07 | 0,05 | 0,10 | 0,00 | 0,00 | 0,00 |
| | | E | Hall cover acoustic background | abg-05 | Acoustic background 05 | 0,0,127 | | - | - | 1.473,10 | 0,03 | 0,05 | 0,08 | 0,10 | 0,00 | 0,00 | 0,00 |
| AC | Acoustic Curtain | A | Vertical acoustic curtain | acu-01 | Acoustic curtain 01 | 63,191,127 | | - | - | 343,30 | 0,10 | 0,40 | 0,60 | 0,10 | 1,00 | 1,00 | 1,00 |
| | | B | Horizontal acoustic curtain | acu-02 | Acoustic curtain 01 | 127,255,191 | | - | - | 150,10 | 0,10 | 0,40 | 0,60 | 0,10 | 1,00 | 1,00 | 1,00 |
| | | A | Acoustic panel with horizontal stripes - 50x100 | apa-01 | Acoustic panel 01 | 204,204,0 | | 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 | 79,127,63 | | 82 | 0,50 | 41,00 | 0,08 | 0,30 | 0,50 | 0,60 | 0,00 | 0,00 | 0,00 |

*Tab. 03 – Screenshot of the processed acoustic parametric database for the Teatro del Maggio*

### 4.2.3. The setting of a photorealistic virtual environment

The need to develop a digital twin of the Maggio Theatre that would simulate its architectural reality led to the search for a software solution that would allow the setting of a photorealistic virtual environment based on the newly developed 3D model.

Initially, the possibility of processing mapping and texturing operations also within McNeel Rhinoceros was tested, but this first attempt did not produce a satisfactory result. While the software allows excellent 3D management and modelling operations using NURBS geometries, it does not respond in speed and simplicity to accurate realism in model mapping.

The search therefore shifted to graphics rendering engines that would allow such texturing operations intended for realistic ArchViz. Thus, the potential of the Twinmotion software was exploited, which allows, through a specific Datasmith Importer interchange plugin, to link the 3D model created within Rhinoceros with the Twinmotion graphics engine, maintaining both the actual geometries and the various materials associated with them through the layers. One of the main operational features of Twinmotion is the ability to quickly perform a replacement of the materials present in the imported model with others present in the system library or in the user's customizable library. In this regard, it should be mentioned that, prior to the graphic elaborations, a series of photographic survey campaigns were conducted, through which the main real materials present in the venue were sampled.

Based on these therefore, 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 provided an absolutely faithful mapping of them to the real one.

This 3D asset, visually coherent with the reality thanks to the faithful texturing, semantically subdivided by constructive elements and made up of surfaces with materials that can be associated with the various acoustic parameters was thus made available – through exporting its geometries in .fbx format and its textures in .jpg format – for subsequent activities related to auralisation processes and the development of multisensory virtual experiences, which will be conducted within the Game Engine Unity platform (fig. 19).

*Fig. 19 – Panoramic view of the subdivided and textured 3D model ready for the auralisation processes and for its virtualisation*

# 5. Lviv Opera House

The Opera and Ballet Theatre in Lviv, Ukraine, was built at the end of the 19th century following a major competition held by the city, which at that time was the Austro-Hungarian capital of Galicia. The winning project was the one presented by Zygmunt Gorgolewski, who proposed the placement of the theatre right in the centre of the city, despite the environmental impediment of the Poltva River, planning to bury it in the area of construction of the new complex and providing for this one of the first examples in Europe of reinforced concrete foundations. The theatre, built in neo-baroque style with some Art Nouveau elements, and enriched with stuccos, statues and oil paintings, hosts a large highly decorated Italian-style hall and concludes, outside, a long tree-lined avenue that over the years has become the centrepiece of the historic centre, now under UNESCO protection (Sajo, 2013).

Within the AURA Project, as anticipated, a series of digital documentation activities intended for the development of a highly reliable 3D model of the main hall both from the metric-morphological and visual rendering points of view have been carried out, so that it can be used for the development of the auralisation processes and for the creation of the multisensory acoustic-visual experience.

The following paragraphs will focus on the discussion of the various activities related to the 3D digital documentation of the main hall of the Lviv Opera House (fig. 20).

*Fig. 20 – Panoramic view of the coloured point cloud of the exterior area of the Lviv Opera House*

# 5.1. Digital Survey

## 5.1.1. Acquisition and processing of laser-scanner survey data

The documentation activities were carried out in Lviv in two different temporal tranches: the first one in early 2021, by the working team del Department of Higher Geodesy and Astronomy of Lviv (HGA-LPNU) under the scientific guidance of Prof. I. Savchyn, while the second one, from October 18 to 22, 2021, by the working team of the Department of Architecture of Florence (DIDA-UNIFI) under the scientific guidance of Prof. S. Bertocci.

During the first digital survey campaign, the internal geometric data of the hall, foyer, corridors, stairwells and service areas were acquired with 160 B/W scans using a Leica C10 laser-scanner instrument, while the chromatic ones – just of the main hall – were obtained through SfM photogrammetric surveys, which, however, will be discussed in the next paragraph.

During the second digital survey campaign, instead, another 160 scans, coloured this time, descriptive of the outdoor areas, including the adjacent streets of Svobody Ave and Knyazya Yaroslava Osmomysla Square, and again, of some interior spaces (such as the main hall, foyer and corridors), were acquired through a Faro CAM$^2$ Focus$^M$ 70 laser-scanner instrument, in order to ensure a homogeneous global coverage of range-based RGB data (fig. 21).

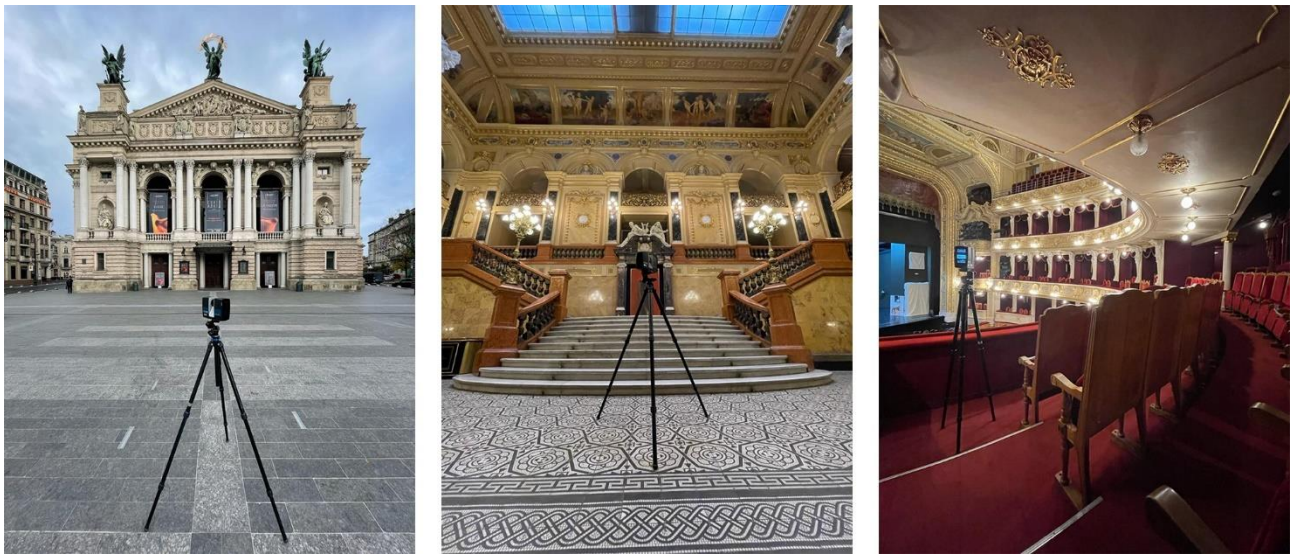


*Fig. 21 – TLS digital survey acquisition phase*

The laser-scanner surveys have thus provided highly reliable metric data, which have been subsequently processed by specific software, thus constituting a three-dimensional database that will serve as a support basis for the development of the 3D model.

The data obtained from the two digital survey campaigns were processed with different timelines and methodologies and were also exploited for different purposes.

The first scans acquired by the HGA-LPNU working team were processed in early 2021 and registered within Autodesk Recap Pro software, through which a global B/W point cloud of only the theatre's interior spaces was developed (fig. 22).

This 3D asset, geometrically highly defined and temporally available earlier, will be used, as will be seen in the next paragraphs, for the development of the 3D NURBS model of the theatre's main hall and for all consequent auralisation and virtualisation processes.

In particular, in order to be able to work more smoothly on the global point cloud, only the portion related to the theatre’s main hall was considered. Its point cloud was thus unified, decimated and exported to .e57 format so that it could be imported back within other software and be used as a metric support for the 3D model (fig. 23).

*Fig. 22 – Panoramic view of the coloured point cloud of the Lviv Opera House's main hall*

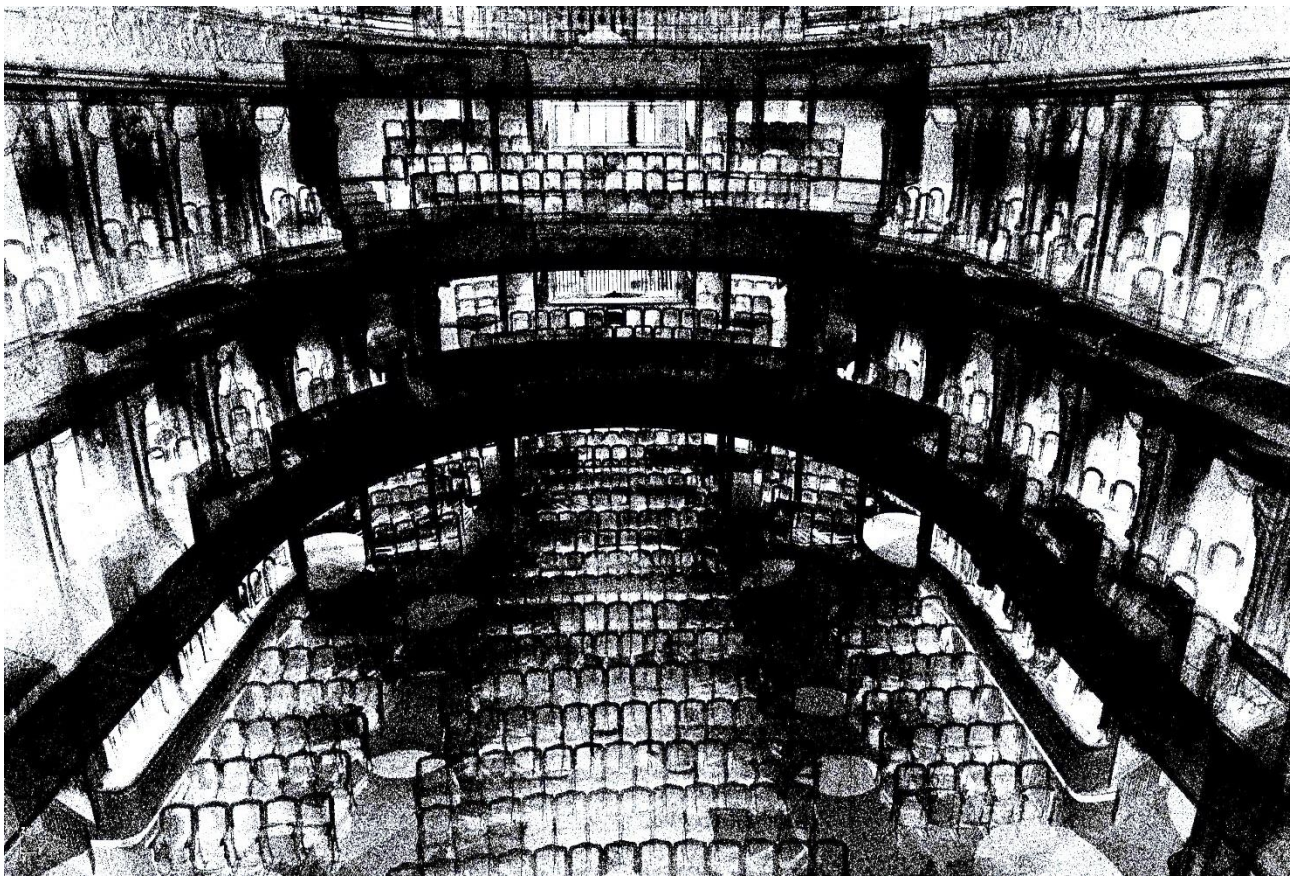


*Fig. 23 – Decimated point cloud of the main hall inserted within the 3D modelling software*

The large amount of data obtained from the second laser-scanner survey campaign conducted by DIDA-UNIFI working team at the end of 2021, was instead imported and processed within a specific point cloud management software, Leica Geosystems Cyclone, through which the main phases of filtering, registration, certification and processing of the global point cloud were developed.

The first step involved the process of filtering out noise due to massive instrumentation acquisitions, by which the point clouds were thus cleaned of excess data, mainly due to the nature of materials such as glass, metal, and shiny materials that can cause uncontrolled reflection and distortions of the laser pulse.

Next, the filtered point clouds were registered by a visual alignment procedure, whereby, through a series of rigid rototranslations between adjacent point clouds, their homologous points are identified in order to determine their alignment. This cloud-to-cloud registration thus made it possible to obtain a single global point cloud of the Lviv Opera House complex that included all the data acquired during the instrumental survey.

The next step involved verifying the reliability of the developed survey; during this phase any misalignment errors present in the registered point cloud were checked. To support this verification, the polygonal closure of the scanning locations was previously planned in the acquisition phase, so as to obtain a global cloud formed by scans that were all well constrained to each other. The check was carried out through sections performed on the global point cloud, both by horizontal and vertical cut planes, verifying that the distance between the section wireframes of the different aligned point clouds was below the tolerance set by the scale of representation (in this case, accuracy limits were set with a tolerance of ±12 mm). The results of this verification were positive, with maximum errors of less than a 10 mm, thus establishing the clear reliability of the TLS survey developed.

This second 3D asset, which was developed later than the first one, made it possible to obtain a true digital twin of the venue in the form of a point cloud, which is both geometrically reliable and visualisable, as it contains colour data of both the theatre's exterior and interior spaces.

The data from this digital asset, as anticipated, were not used for the creation of the 3D model, but were necessary firstly to obtain, as for the other case studies, a coloured point cloud of the entire venue and its adjacent areas for digital documentation and safeguarding purposes, and secondly to have a morphological basis with colorimetric properties that would facilitate the photogrammetric alignment processes, as will be seen in the next paragraph (fig. 24).

*Fig. 24 – Panoramic views of the coloured point cloud of the Lviv Opera House's main hall*

### 5.1.2. Acquisition and processing of photogrammetric survey data

During the first digital survey campaign, the HGA-LPNU working team carried out, in parallel to the laser-scanning activities, an extensive photogrammetric acquisition of the main hall of the venue. The massive acquisition (approximately 1600 photos) was carried out to ensure a wide overlap between the various pictures taken, so that their alignment during the photogrammetric processes would be facilitated.

However, the data acquired through various instrumentation and photographic optics by the Ukrainian working team were processed later by the DIDA-UNIFI one through specific photogrammetric processes, outlined below.

The Structure from Motion (SfM) photo-modelling software chosen for photogrammetric data processing was Agisoft Metashape Pro, within which not only the photographic acquisitions were imported, but also a coloured and structured point cloud portion related to the main hall in .57 format, including some of the scans developed during the second laser-scanner survey.

The first step involved the alignment of the photographic data only. The software then, through image-matching processes, initially identified homologous points between the pictures and reconstructed their position and orientation for each. These procedures thus made it possible to process an initial alignment between the acquired images in the form of a sparse cloud (fig. 25).

In order to obtain a highly morphologically defined photogrammetric model, to this first sparse cloud obtained from the pictures, the inserted scans were also processed, aligning them in the form of "Depth Maps" with the former, thus generating a new sparse cloud integrated with the geometric data developed by the laser-scanner and oriented according to the latter's coordinate system. [11]

Subsequently, through further specific DSM algorithms, this new sparse cloud was subjected to densification through the use of all the pixels in the images, resulting in the so-called dense cloud, which is a 3D asset in the form of a point cloud that is highly reliable in terms of morphology and visual rendering compared with the real one. The dense cloud points were subsequently triangulated and polygonised, creating a 3D mesh model (fig. 26).

The subsequent process aimed at processing the photogrammetric 3D model of the main hall, and in particular its mapping with the texture created from the photographic data, will be discussed next in paragraph 5.2.3.

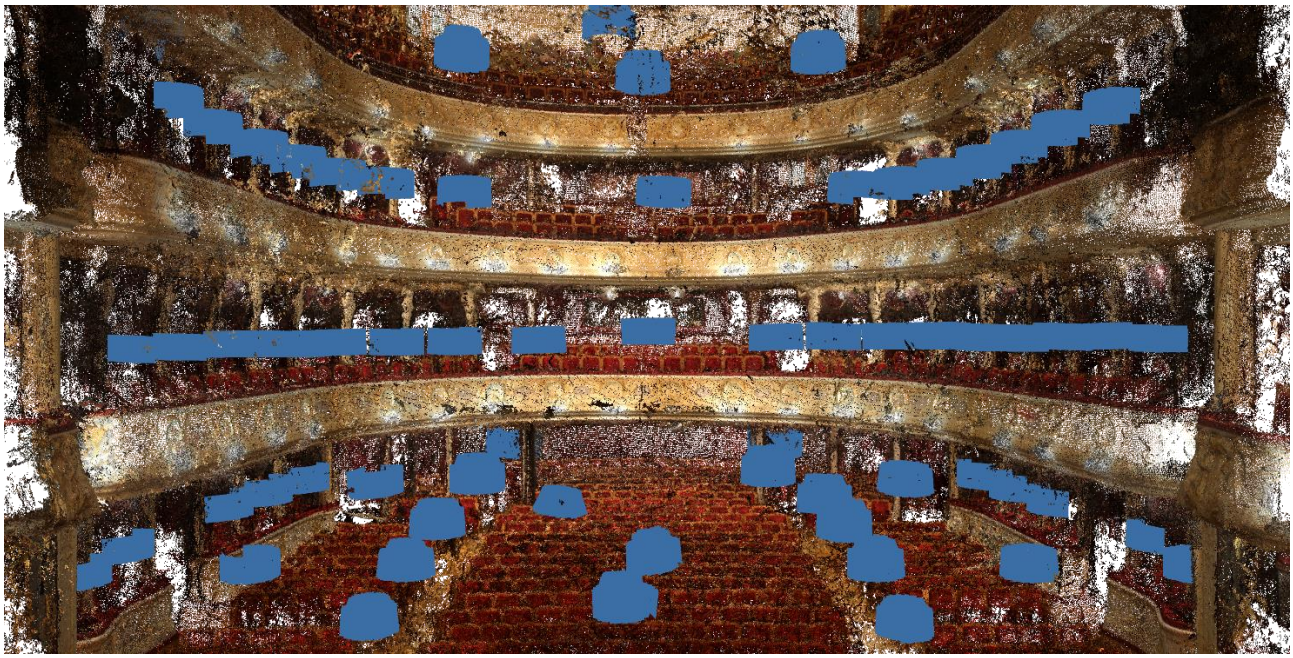


*Fig. 25 – Photogrammetric digital survey acquisition phase*

[11] This coordinate system was set according to the same orientation and origin of the one of the point cloud processed as a result of the first laser-scanner survey, and on the basis of which the 3D model will be developed. In this way, as will be seen, both the photogrammetric model of the main hall and the 3D NURBS model will share the same coordinate system, thus making them integrable.

*Fig. 26 – Photogrammetric 3D model of the Lviv Opera House's main hall*

### 5.1.3 On-site study on acoustic parameters

In parallel to these digital data documentation activities, the methodological workflow included a series of on-site studies on the constructive materials and their acoustic properties, investigating the values of the above-mentioned acoustic parameters related to them and needed for subsequent auralisation processes.

As previously stated, the parameters for developing the auralisation processes of the model within specific IT applications are essentially three: sound absorption[12] and transmission[13] frequencies, and scattering[14].

The investigation and assignment of values to the acoustic parameters was carried out by the working team of 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, under the scientific guidance of Prof. M. Carfagni.

The methodology of attributing the acoustic absorption and diffusion coefficients of the different materials present in the theatre's main hall was based on a visual examination of the architectural components (Pompoli and Prodi, 2000) supported, in some cases, by an extract of the acoustic report of the architectural project.

For this case study, however, these studies were not concretely carried out, but rather the results related to the studies conducted on the materials present in the case study of the Teatro del Maggio Musicale Fiorentino[15] were taken into consideration and adapted to the same respective ones present in the Lviv Opera House's main hall.

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[12] 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.

[13] 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.

[14] By means of scattering values, we specify 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.

[15] See paragraph 4.1.2

# 5.2. 3D Modelling

## 5.2.1. The digital survey as a metric basis for the creation of a NURBS 3D model

The processing and post-production phase of the acquired data was developed by pursuing two complementary and methodologically propaedeutic objectives for the auralisation of the Lviv Opera House's 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. The second concerns the semantic subdivision of the various architectural elements to enrich the morphological contents with information relating to the investigated acoustic parameters.

The preparatory phase for 3D modelling involved the creation in CAD environment of two-dimensional drawings through careful discretization of data extracted from the B/W portion of the point cloud developed from the first laser-scanner survey (fig. 27). As with the Maggio case study, these drawings were then imported within McNeel Rhinoceros modelling software where they were used as metric support for the creation of the 3D model of the hall and each of its components, exploiting the management and precision potential of Nurbs geometries.

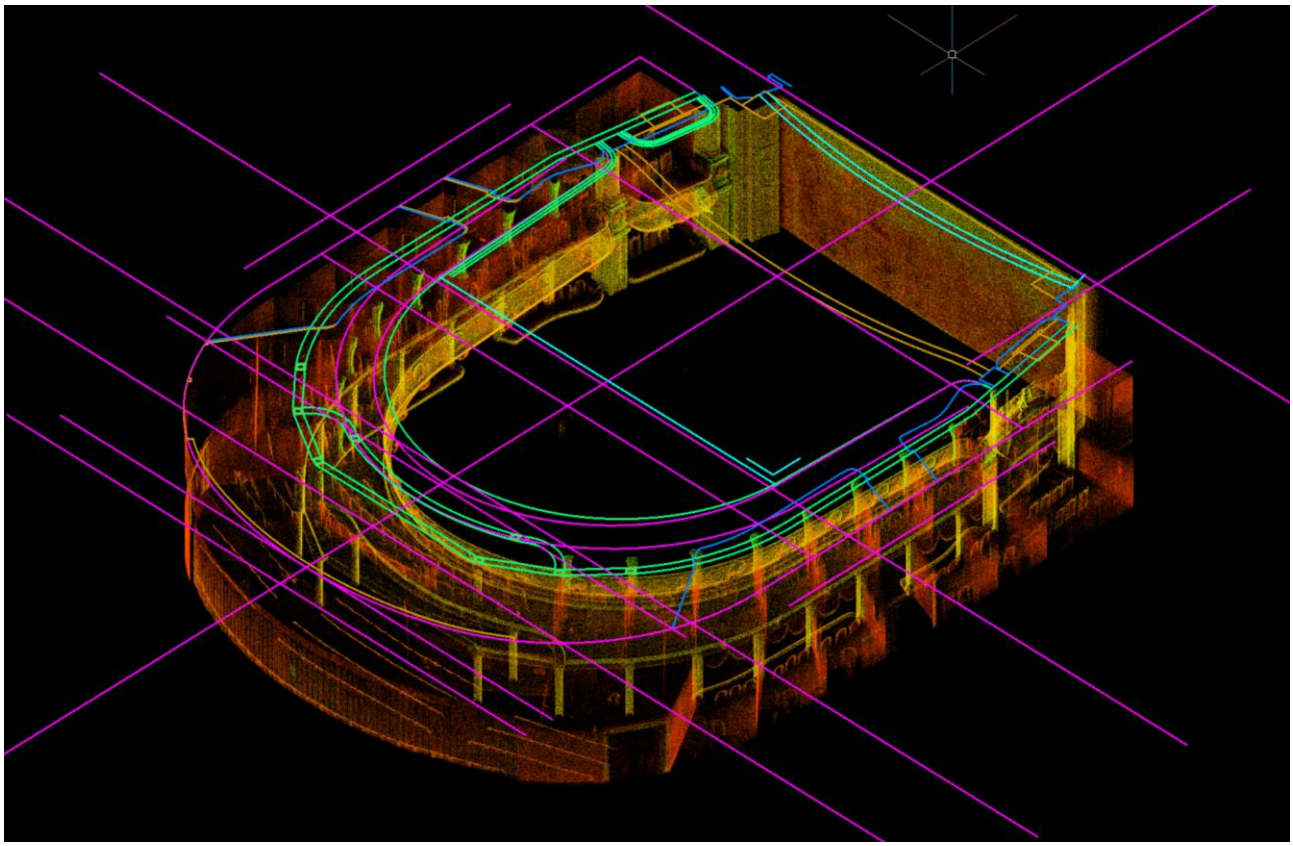
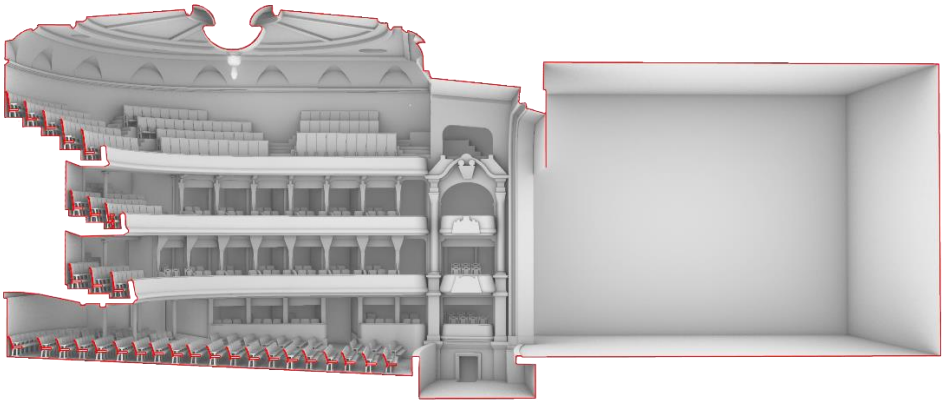
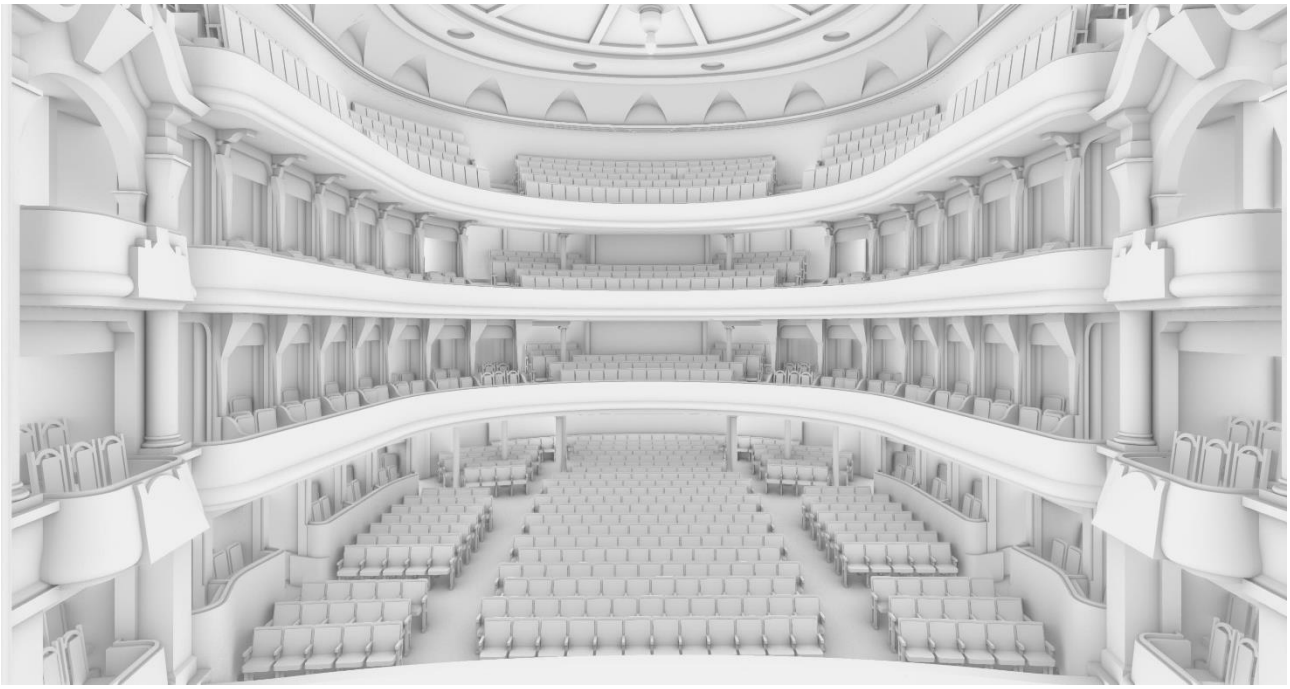


*Fig. 27 – 2D graphical elaborations processed within CAD environment*

The volumes and solids belonging to the 3D model were obviously geometrically simplified in some places, due to construction irregularities, but a level of adherence to reality of max 5 cm was maintained with respect to the point cloud.

Finally, special attention was given to furniture elements, such as the seats, as their wide presence, also for this case study, is extremely relevant in the acoustic study of the venue and consequently in the auralisation processes.





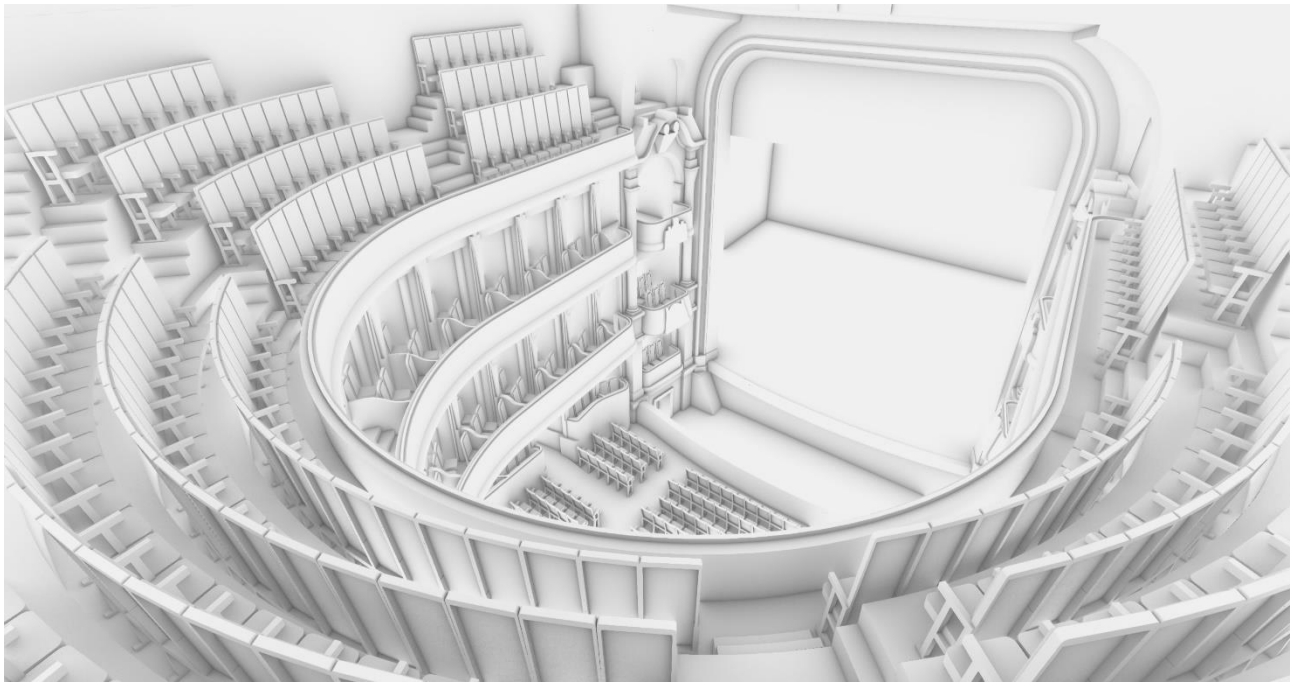


*Fig. 28 – Longitudinal section and panoramic views of the untextured 3D model of the Lviv Opera House's main hall*

### 5.2.2. Elements semantic subdivision, materials classification and creation of an acoustic parametric database

Given the acoustic simulation purposes that the virtualisation project envisaged, in preparation for the auralisation phase, a semantic classification of the individual elements present in the theatre main hall was developed.

The hall has been divided according to its constructive components and segmented according to materials and specific typological categories. The methodological approach with which this division was conducted was based both on the acoustic relevance and materials of which the various elements are characterized, and on the results of the preliminary on-site acoustic studies.

Based on these constructive and acoustic considerations, a specific subdivision of the elements was then carried out, focusing on quantifying the values of specific acoustic parameters associated with the materials of the various components (fig. 29).

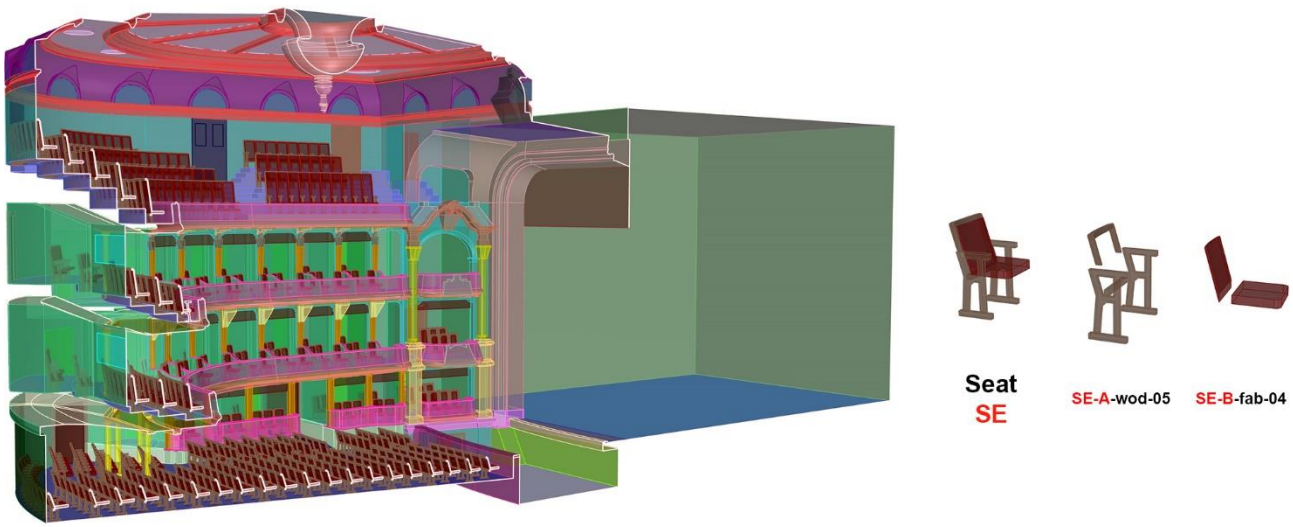


*Fig. 29 – Different visualisations of the 3D model subdivided into coded component elements (each represented by a different colour)*

This methodological 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 picture of the element, and the acoustic parameters associated with the various materials.

It is important to underline that also the 3D modelling processes were conducted by referring to the semantic subdivision of the architectural components, namely by structuring for the various elements, specific layers with assigned codes and materials corresponding to the acoustic ones inserted within the database (tab. 04).

For this latter, the main acoustically significant materials and interior finishes were listed and attributed to each the acoustic characteristics in terms of average coefficient of sound absorption and transmission at low, medium, and high frequencies and the average coefficient of acoustic scattering based on databases of materials taken from scientific publications and acoustic simulation software such as Odeon and Ramsete (Bartalucci et al., 2018).

Since the specific characteristics of many of the materials in the hall, as well as their construction methods (glued coating, on supports, etc.) are not known, general assumptions were made, and average coefficients related to each specific material were assigned.

As for transmission coefficients, they were set equal to 0 (no transmission of sound through the element) for all boundary elements, as it was not necessary to know the level transmitted outside the main hall.

Each value of the acoustic parameters investigated was thus associated with the respective architectural element and its characteristic material, thus facilitating the development of the subsequent auralisation processes, which require the subdivision of the elements of the 3D model according to its materials in order to create specific acoustic assets.

| ACOUSTIC DATABASE | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | Element description | TYP | Element Type / Component description | MAT | Material description | Material RGB code | IMG | NUM | SRFE | SRFT | LFA | MFA | HFA | S | LFT | MFT | HFT |
| CE | Ceiling | A | Balconies lower ceiling lined with plaster | cei-01 | Ceiling 01 | 139,139,0 | | - | - | 1.598,14 | 0,15 | 0,05 | 0,04 | 0,10 | 0,00 | 0,00 | 0,00 |
| | | B | Balconies lower ceiling lined with fabric | cei-02 | Ceiling 02 | 255,255,220 | | - | - | 19,71 | 0,15 | 0,05 | 0,04 | 0,10 | 0,00 | 0,00 | 0,00 |
| | | C | Stage ceiling | cei-03 | Ceiling 03 | 132,132,117 | | - | - | 304,95 | 0,15 | 0,05 | 0,04 | 0,10 | 0,00 | 0,00 | 0,00 |
| | | D | Proscenium arch ceiling | cei-04 | Ceiling 04 | 145,44,238 | | - | - | 415,51 | 0,15 | 0,05 | 0,04 | 0,10 | 0,00 | 0,00 | 0,00 |
| | | E | Cloister vault with lunettes ceiling | cei-05 | Ceiling 05 | 139,0,139 | | - | - | 304,95 | 0,15 | 0,05 | 0,04 | 0,10 | 0,00 | 0,00 | 0,00 |
| | | F | Main hall ceiling | cei-06 | Ceiling 06 | 255,191,255 | | - | - | 19,71 | 0,15 | 0,05 | 0,04 | 0,10 | 0,00 | 0,00 | 0,00 |
| CN | Cornice | A | Balconies cornice | cor-01 | Cornice 01 | 255,127,127 | | - | - | 105,06 | 0,15 | 0,05 | 0,04 | 0,10 | 0,00 | 0,00 | 0,00 |
| | | B | Main hall ceiling cornice | cor-02 | Cornice 02 | 255,63,63 | | - | - | 135,10 | 0,15 | 0,05 | 0,04 | 0,10 | 0,00 | 0,00 | 0,00 |
| | | C | Door cornice | cor-03 | Cornice 03 | 139,121,94 | | - | - | 105,06 | 0,15 | 0,05 | 0,04 | 0,10 | 0,00 | 0,00 | 0,00 |

*Tab. 04– Screenshot of the processed acoustic parametric database for the Teatro del Maggio*

### 5.2.3. The setting of a photorealistic virtual environment through photogrammetric data

For this case study, unlike the others, the 3D asset developed by Nurbs modelling processes was mapped and textured through a different operational methodology, namely by exploiting photogrammetric data processed within Agisoft Metashape Pro software.

The first step involved exporting the Nurbs model created within McNeel Rhinoceros in the form of a mesh in .fbx format. Sharing the same coordinate system, it was possible to import that mesh model within Agisoft Metashape Pro, replacing the one previously processed and based on the photographic data, and perform the remaining photogrammetric processes regarding the texturing.

Specifically, the photogrammetric data associated with the photos were projected onto the new mesh, obtaining a 3D photogrammetric model that is faithful both morphologically to the one made through Rhinoceros, and visually since it is mapped with the textures from the photos. It should be specified, however, that such 3D asset, in the form of a mesh, corresponds only morphologically to the one realized on Rhinoceros through Nurbs geometries, and possesses in comparison with this one a substantial difference: it is not subdivided by elements, and therefore possesses only visual potential and not exploitable for auralisation purposes.

In this way, for the immersive virtualisation project of the main hall, it was planned to experiment with the interaction between two different assets, inserting within the same Unity virtual environment – and according to the same coordinates – both the 3D model featured with the surfaces divided by components that can be associated with the acoustic parameters of each material, and the textured mesh model, which possesses a highly faithful visuality.

At this point, once the various auralisation processes are performed on the subdivided 3D model, this can be overlaid with the textured one, and turned invisible during the virtual experience. This will ensure both the environmental acoustic simulation developed by the auralisation of the 3D model, and the realistic graphical rendering of the theatre complex (fig. 30).

*Fig. 30 – Panoramic view of the subdivided and textured 3D models ready for the auralisation processes and for its virtualisation*

# 6. Technology Transfer: designing a multi-disciplinary university workshop programme on auralisation

As architectural design of music venues is impossible without joining acoustics into the pursuit of optimal audience/listening experience, the possibility to explore the music halls and to test the acoustic in the preliminary stages of design process has become an indispensable element in the design. It allows the designer to choose the better materials and technological solutions. The relation between architectural design and audience experience has been the object of many studies.

One of the aims of the AURA project is to investigate the possible use of auralised 3D models in the context of architectural and acoustic design, for this reason the project has foreseen the organisation of a multidisciplinary university workshop on auralisation theme which has involved 20 students of the Department of Architecture of the University of Florence (fig. 31).

The workshop was developed through a series of 6 meetings starting from 16 March 2022, with the involvement of the AURA consortium. DIDA-UNIFI took care of the part relating to the digital survey and 3D modelling aimed at auralisation; DIEF-UNIFI and Vie en.ro.se illustrated the basic principles of acoustics for the classification of materials; HTW demonstrated the steps for the implementation of models in virtual environment and auralisation techniques. Due to the restrictions of the COVID-19 pandemic, the teaching activity was carried out in a mixed mode, both for theoretical and applied form.

- *Theoretical activity*: in order to allow a correct approach to problems related to auralisation, theoretical and in-depth lessons has been held.
- *Application activity*: the practical part of the workshop provides the study of the three theatres through the creation of bidimensional drawings based on the digital survey and the creation of simplified 3d models in groups or individually. The field activity took place at the Teatro del Maggio Musicale Fiorentino and provides the acquisition of the data necessary for the 3D modelling and the study of the material for the classification.

The students involved took an active part in the transfer of knowledge phase, helping to define an approach to the dissemination of the methodological steps to a user of technicians and architects. In particular, the methodologies adopted have proved to be a possible integration into acoustics and digital survey classes, training a new generation of architects and construction engineers sensitive to issues connected with the acoustic heritage. These issues are linked to those of B.I.M. (Building Information Modelling) and collaborative approaches to design, offering the possibility of connecting design skills with IT skills to create immersive experiences useful in the conception and development phases of the architectural project.

*Fig. 31 – Workshop program*

# 7. Conclusions

These three very different case studies allow to investigate and develop a set of methodological workflows that can be replicated and applied at the European level for other venues as well.

The solution proposed within the AURA project for the three case studies of the Berlin Konzerthaus, Lviv Opera House and Teatro del Maggio Musicale in Florence foresees not only to develop multisensory 3D models based on reliable metric-morphological supports but also to create a scientific and replicable methodology of the workflow of the elements classification and virtual reconstruction aimed at auralisation.

The project started experimenting with the possibility of collaborating specialists who can interact within virtual workspaces and immersive multimedia systems, starting to investigate the possibilities of using the data produced as valuable tools for dissemination and communication and entertainment. By integrating auralisation and a reliable and realistic visual experience based on data acquired through integrated TLS digital survey and Structure from Motion (SfM) photogrammetric techniques, it is possible to investigate the mutual influence that visual and acoustic stimuli have on the perception of the virtual experience. These outputs will allow the user to experience, through Virtual Reality applications, a perceptually multisensory experience, associating an immersive visual representation with an acoustic simulation. The user has the opportunity to choose the listening position and will be able to perceive the sound sequence of the musical track equivalently as if he were really in that place in the theatre.

This integrated and immersive approach, in which photorealistic visualisation and acoustic rendering are combined with direct and simulated user interaction, aims to significantly develop new ways of communicating and disseminating cultural heritage.

The future goals of the experimentation of virtual reconstruction lead not only to the process of auralisation of the model, based on the semantic and material classification realized, but also to further studies on informative and parametric modelling. If in this case it has been tested the Scan-to-NURBS modelling and the creation of informative databases, the following steps will involve the development of case studies in which the modelling will take place through Scan-to-BIM methodology to directly associate the acoustic parameters to individual elements, creating an informative, shared, and embedded infrastructure of the object of study.

The goal of the project is to develop new opportunities for fruition through the engagement of expert and non-expert users, promoting innovation and cross-sector collaboration to build new audiences, business models, performance practices, and engaging experiences (Bertocci et al. 2021).

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