POLITECNICO DI TORINO

Department of Architecture and Design

Master's Degree in Architecture for Sustainability

HBIM and immersive virtual reality applied to cultural heritage: Digital modeling of the Parliament Hall in Palazzo Carignano

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Abstract

In recent years, Historical Building Information Modeling (HBIM) and Virtual Reality (VR) technologies have become transformative tools in cultural heritage preservation, enabling the documentation of critical historical data and enhancing public engagement with architectural heritage. This research presents an innovative HBIM-to-VR workflow that addresses two major challenges: modeling complex curved spaces without relying on advanced scanning technologies and facilitating accessible information transfer from HBIM to VR for users without programming expertise. Using Rhino.Inside.Revit, a detailed HBIM model of the curved Parliament Hall in Palazzo Carignano, Turin, was created by combining Rhino's advanced surface modeling capabilities with Revit's BIM environment, incorporating historical and material data. Element information from Revit schedules was exported as CSV files and dynamically updated using Power Query in Excel. The processed data was then visualized in Unity through a custom C# script generated with GPT assistance, enabling real-time interaction and exploration. The proposed workflow minimizes technical barriers while effectively preserving and presenting cultural heritage in an interactive VR environment.

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1. Introduction

This research aims to explore the application of Historical Building Information Modeling (HBIM) and Virtual Reality (VR) technologies in cultural heritage preservation through the modeling and VR production of the Parliament Hall in the Palazzo Carignano in Turin, showcasing its unique architectural value and historical significance. The research highlights the process of constructing a BIM model of the elliptical room through the utilization of technical drawings and photographic documentation. HBIM enhances the value of heritage assets by enabling the integration of cultural information into BIM models. Furthermore, a novel HBIM-to-VR workflow is proposed, not only enabling the visualization of model data within a VR environment but also leveraging VR interactive design to enhance the accessibility and immersive engagement of cultural heritage sites.

Cultural heritage is defined as the legacy of both tangible and intangible elements transmitted across generations, preserved in the present, and safeguarded for the benefit of future generations (UNESCO, n.d.). It encompasses tangible aspects, such as buildings, archival materials, books, works of art, and artifacts as well as intangible elements, including traditions, language, folklore, and knowledge (UNESCO, 2003). However, not all remnants of the past qualify as "heritage." Instead, it is the cultural significance and societal values attributed to specific elements that determine their recognition and elevation to the status of heritage (Logan, 2007). Palazzo Carignano, it is part of the UNESCO serial site Residenze Sabaude. It was the historic seat of the Subalpine Parliament (1848-1861) and of the first Parliament of the Kingdom of Italy (1861-1864).

Building Information Modeling (BIM) was introduced by van Nederveen and Tolman in 1992 as a method for digitally representing design information (van Nederveen & Tolman, 1992). Its widespread adoption began in the 2010s, driven by technological advancements and the need for efficient construction workflows (Lucchi, 2023). It is defined as "a digital representation of physical and functional characteristics of a facility" and serves as a centralized knowledge base, supporting decision-making throughout a facility's lifecycle (National BIM Standard Project Committee et al., 2007). Mainly used in the Architectural, Engineering, and Construction (AEC) sectors, BIM integrates data collected during construction to create virtual models for managing and maintaining built structures (Alizadehsalehi et al., 2020).

The BIM concept in the heritage sector was developed in 2009, referred to as Heritage Building Information Modeling (HBIM) (Murphy et al., 2009). The HBIM system serves as a comprehensive management platform for heritage structures, enabling the storage of integrated 3D models alongside their associated historical and semantic information. This system plays a pivotal role in consolidating diverse historical data, including archival documents, structural details, monitoring records, and the current state of the building, within a comprehensive 3D environment (Heesom et al., 2020).

This research utilizes existing sectional drawings, photographs, and historical archives to manually model the Parliament Hall, adding essential structural, material, and historical data within Revit. Due to the complex curved geometry of the hall's interior, Rhino is used for advanced surface modeling, which is then imported into Revit through Rhino.Inside.Revit to refine and embed historical context and structural material attributes, creating an HBIM model. While limitations in data sources may affect the model's precision and detail, this approach provides a way for digitizing historic buildings lacking high-precision data.

After completing the basic model construction, the research further imported the model into Unity to implement interactive design within a VR environment. VR development in Unity allows users not only to visualize the HBIM model data but also to access information about its historical context, architectural style, and furniture data through interactive elements. This study designed various interactive features in Unity, such as virtual buttons, information panels, and rotation, enabling users to explore the history and model data of the parliament hall within a virtual environment. Through the immersive VR experience, users can gain a comprehensive understanding of the cultural heritage's significance, enhancing their appreciation of the architectural value.

Particularly in the post-pandemic era, VR technology has broken spatial limitations and promoted the importance of cultural heritage. It not only makes cultural heritage more accessible, enriching cultural education with deeper insights and richer experiences, but also supports the preservation and digital documentation of heritage, ensuring that cultural heritage continues to be passed down in a more vibrant way in contemporary society.

1.1 Heritage Preservation

Preserving historic buildings and sites is essential for maintaining cultural legacies and shared heritage (Gazzola et al., 1964). Heritage conservation involves both a technical aspect, focusing on the physical preservation of historical structures, and a social aspect, which emphasizes disseminating heritage within society to ensure its ongoing protection (Naeyer et al., 2000).

The Nara Document on Authenticity (1994) describes preservation as encompassing all efforts to understand cultural heritage, recognize its historical and cultural significance, safeguard its physical condition as needed, and restore and enhance its presentation. It views cultural heritage as including monuments, groups of buildings, and culturally significant sites, as outlined in Article 1 of the World Heritage Convention (World Heritage Committee and ICOMOS, 1994).

Responsibility for cultural heritage and its management initially rests with the cultural community that created it, and subsequently with those entrusted with its care (World Heritage Committee and ICOMOS, 1994). Italy’s principal legislative framework for cultural heritage is Legislative Decree No. 42 of 2004, known as the Codice dei Beni Culturali e del Paesaggio (Cultural Heritage and Landscape Code). This comprehensive legislation regulates the preservation, protection, and promotion of Italy’s cultural and natural heritage, reflecting their intrinsic interconnectedness. Moreover, Italy aligns its efforts with international conventions like the UNESCO World Heritage Convention and incorporates principles from key charters such as the Venice Charter (1964) and the Charter of Krakow (2000). These frameworks underscore Italy’s dedication to preserving cultural heritage not only as a national treasure but also as a shared global responsibility, ensuring its continued protection for future generations.

The Athens Charter for the Restoration of Historic Monuments (1931) was the first international document to address the restoration and preservation of historic patrimony. Building on this, the Venice Charter (1964) introduced concepts such as "historic sites" and "modest works" while emphasizing aspects like color, scale, and volume. Italy’s Carta di Restauro (1972) required a clear distinction between original and reconstructed elements, emphasizing stylistic unity (Marconi, 1993). The Charter of Krakow, the most recent, highlights the importance of education and training in heritage conservation and introduces the concept of preserving historic towns and villages (Naeyer et al., 2000). The ICOMOS Guide to Recording Historic Buildings (1990) suggests that documentation of a historic site should include not only the building’s physical attributes, such as materials, structure, and pathologies, but also its cultural significance and value (International Council on Monuments and Sites, 1990).

To address the preservation of digital heritage, UNESCO issued its Guidelines for the Preservation of Digital Heritage in 2003, emphasizing that digital materials, particularly those in the public domain, should remain accessible without unreasonable restrictions (Webb, 2003).

In conclusion, the HBIM methodology must thoughtfully consider the comprehensive body of knowledge and regulatory frameworks that have been developed through widespread consensus and are highly regarded by heritage stakeholders. This integration ensures that HBIM effectively supports the preservation, management, and dissemination of cultural heritage while adhering to established principles and practices.

1.2 BIM

BIM is a transformative methodology that integrates multidisciplinary data to create a comprehensive digital representation of a building's lifecycle. It facilitates the planning, design, construction, and operation phases of a project through intelligent 3D modeling. Unlike traditional 2D methods, BIM offers a dynamic environment where data is interconnected, enabling stakeholders to collaborate efficiently (Eastman et al., 2011).

Azhar (2011) noted that BIM represents a paradigm shift in the architecture, engineering, and construction (AEC) industry, offering capabilities such as 3D visualization, simulation, construction sequencing, conflict detection, and forensic analysis. Furthermore, Azhar, Khalfan, and Maqsood (2012) emphasized that BIM is not merely software or technology; it represents a process that necessitates significant changes in workflows and project delivery methods in design and construction.

A key characteristic of BIM is its ability to achieve interoperability, which ensures seamless information exchange among various stakeholders throughout the lifecycle of a building project. Interoperability enables diverse software platforms and multidisciplinary teams to collaborate effectively without the risk of data loss or miscommunication. This ensures projects are delivered safely, efficiently, and with high quality. BIM achieves interoperability at the software level by utilizing standardized exchange formats such as Industry Foundation Classes (IFC) and BIM Collaboration Format (BCF). These open standards allow data to be shared across different software applications, including design, analysis, and construction management tools. This reduces redundancy, prevents errors, and ensures consistency in data transfer (Eastman et al., 2011). Beyond software, interoperability fosters collaboration among multidisciplinary teams, including architects, engineers, contractors, and facility managers. By maintaining a unified digital model, BIM ensures that all participants are aligned toward a common goal, streamlining communication and enhancing decision-making throughout the project lifecycle (Azhar, 2011).

The integration of the Building Information Model (as a data repository) with the processes of Building Information Modeling (as a collaborative methodology) exemplifies the power of interoperability. This integration bridges data representation and real-time collaboration, leading to enhanced project coordination, reduced rework and errors, and improved efficiency and overall project outcomes. As emphasized by Eastman et al. (2011), interoperability is the cornerstone of BIM's success in enabling data-driven decision-making and multidisciplinary collaboration.

The adoption of BIM as a transformative methodology has significantly impacted the AEC industry, necessitating the establishment of regulatory frameworks to standardize its application. Recognizing BIM's potential to improve efficiency, foster collaboration, and support informed decision-making throughout a project's lifecycle, various governments and organizations have introduced guidelines and mandates to facilitate its integration into construction processes. These regulatory efforts aim to provide consistent standards for data management, interoperability, and multidisciplinary coordination, reinforcing BIM’s critical role in advancing the built environment.

In Italy, the implementation of BIM has been regulated through Decree DM 560/2017, commonly referred to as the “BIM Decree.” This legislation sets forth a phased adoption strategy for BIM in public procurement projects. Effective from January 28, 2018, the regulation mandates a gradual integration of BIM based on project value:

- From January 1, 2019, for projects exceeding €100 million;
- From January 1, 2020, for projects exceeding €50 million;
- From January 1, 2021, for projects exceeding €15 million;

- From January 1, 2022, for projects exceeding thresholds defined in Article 35 of Italy's Public Contracts Code;
- From January 1, 2023, for projects exceeding €1 million;
- By January 1, 2025, for all public works, regardless of value (Ministero delle Infrastrutture e dei Trasporti, 2017).

The decree underscores the Italian government's commitment to fostering digital transformation in the construction sector. It also aligns with broader European directives, such as Directive 2014/24/EU on public procurement, which encourages the use of digital tools like BIM to improve efficiency and transparency in public works. Additionally, Italian standards such as UNI 11337 provide detailed guidance on BIM implementation, addressing aspects like model structure, data management, and interoperability requirements. These regulations ensure a standardized and progressive approach to adopting BIM across Italy's construction industry.

1.3 HBIM

HBIM incorporates the principles of BIM, a digital modeling and information management methodology, into the preservation and management of historically significant assets, collectively known as Cultural Heritage (CH) (Heritage, 2023). First introduced by Maurice Murphy in 2009, HBIM combines advanced digital modeling techniques with historical research to create detailed parametric 3D models of heritage structures (Murphy et al., 2009; Dore & Murphy, 2012). Unlike conventional BIM, HBIM is tailored to address the specific challenges posed by historic buildings, such as irregular geometries and complex material characteristics (Murphy et al., 2009).

HBIM enables the development of dynamic databases for historic structures, facilitating the documentation and management of geometry, spatial relationships, material properties, and construction methods. This methodology fosters collaboration among multidisciplinary teams, providing a robust foundation for informed decision-making in restoration and conservation projects (Volk et al., 2014; Dore & Murphy, 2012).

The integration of all construction phases into a single, comprehensive 3D model is one of HBIM's most significant contributions, offering a deeper understanding of a building's historical and structural context and thereby supporting more effective conservation efforts (Oreni et al., 2014). Additionally, HBIM's advanced 3D visualization tools significantly enhance communication and collaboration among stakeholders, including clients, by presenting clear and accessible representations of proposed designs and facilitating meaningful contributions to the decision-making process (Zekavat et al., 2014).

The HBIM methodology is structured into three stages: data acquisition, data processing and modeling, and management. The data acquisition phase employs techniques such as laser scanning, photogrammetry, and total station measurements to gather geometric data, alongside historical, architectural, material, and condition assessments as non-geometric data. Comprehensive documentation ensures all relevant information is captured for model development (Penjor et al., 2024). In the second phase, data processing and modeling, collected data is verified for accuracy and relevance before geometric data is used to create a 3D model in BIM software. Non-geometric data is either embedded in the 3D model or linked through external databases, ensuring a holistic information model. Finally, the management stage utilizes the HBIM model to guide conservation strategies and plan interventions. New information generated during this phase is processed and integrated to maintain the model's accuracy and relevance for heritage management (Pinti & Bonelli, 2022; Castellano-Román & Pinto-Puerto, 2019).

A critical challenge in applying BIM to historical buildings lies in ensuring the reliability of the recorded measurements and information. Research and survey activities often fail to provide fully comprehensive datasets, leading to difficulties in accurately reconstructing the heritage structures. Therefore, ensuring the transparency and reliability of HBIM models is crucial.

These issues related to the reliability of the data were introduced by referring to the concept of transparency of the state of art model as early as 2009 with the London Charter and then, subsequently integrated in 2012 in the Seville Principles, even though these were mainly aimed at the world of archaeology. The foundations of these arguments were laid in any case as early as 2003 with the UNESCO Charter on the Preservation of Digital Heritage.

The London Charter emphasizes methodological principles for ensuring accurate and reliable digital visualization and dissemination of cultural heritage information. Key principles include:

- Implementation: Developing clear and well-defined methodologies for digital modeling.
- Research Sources: Highlighting the importance of transparency in digital models and associated data.
- Documentation: Establishing procedures for organizing and processing information from data collection to visualization, ensuring reproducibility and scientific rigor (London Charter, 2009).

Building on these foundations, the Seville Principles focus on "scientific transparency." They require that visualized data be verifiable and open to scrutiny, enabling conclusions to be confirmed, challenged, or refined by other researchers. Additionally, these documents introduce the concept of *paradata*, which refers to metadata that documents the interpretive processes behind creating digital models, offering a framework for interpreting the critical analysis of artifacts conducted by experts (Seville Principles, 2012).

The second phase for modelling methodologies used in HBIM can be categorized into three main approaches: conventional BIM authoring tools, alternative technologies, and bespoke systems.

Conventional BIM tools, such as Revit and ArchiCAD, are widely used in heritage documentation and modeling. Parametric modeling allows BIM objects to be reused with slight modifications, making them versatile for various projects. Despite the time and expertise required to create detailed parametric objects, the World Heritage List (WHL) provides a property-based framework that integrates seamlessly into parametric workflows. The Medina of Marrakech (Gomih, Leporelli, Martino, & Santi, 2021). showcases this application effectively. Using Graphisoft Archicad for parametric modeling and Agisoft Metashape for photogrammetry, the project created a semantically enriched HBIM model to document the 15th-century riad's architectural and historical elements. Metadata, including material properties and historical references, were embedded in the model, and objects were exported in OBJ and IFC formats, ensuring compatibility for reuse in future projects and software. This project demonstrates how parametric modeling, supported by WHL's standardized attributes and advanced modeling tools, can effectively document and preserve complex heritage structures, providing a valuable proof of concept for HBIM applications.

While BIM authoring tools enable future edits and standardized data integration, they lack the advanced capabilities of CAD software, making manual modeling for heritage projects time-intensive and technically demanding. The Tusculum sanctuary project illustrates these challenges. Using Agisoft Metashape, a photogrammetric survey captured the site's irregularities, which were manually reconstructed in Autodesk Revit. Revit's limited tools required significant skill to interpret and model complex geometries, while semantic data, such as materials and conservation history, was added for future updates. However, unique elements modeled "in place" were project-specific and non-reusable. This case highlights the strengths of manual modeling for detailed documentation but emphasizes BIM tools' limitations in handling heritage irregularities (Guerrero Vega & Pizzo, 2021).

Alternative technologies, including NURBS (Non-Uniform Rational B-Splines), Mesh-to-BIM, and CAD offer advanced methods for capturing and representing complex geometries in heritage documentation, each with unique strengths and limitations in precision, flexibility, and data integration. NURBS models are easy and simple to create due to their well-established modeling technique, allowing for the accurate representation of complex shapes. However, they cannot be edited once imported into BIM authoring tools. This capability was effectively demonstrated in the Baptistery of San Giovanni case study by Bartolini et al. (2024). Using Rhinoceros, researchers modeled the intricate geometries of the Baptistery based on high-resolution point cloud data from laser scanning, showcasing NURBS' strength in precision and simplicity. However, as NURBS models inherently lack depth of information, secondary software such as Grasshopper and ArchiCAD was needed to integrate metadata and organize semantic information within an HBIM framework. Once imported into the HBIM environment, the NURBS-based models were static and could not be parametrically adjusted or edited, reinforcing the limitations of this approach for iterative processes. This case highlights both the efficiency and the limitations of NURBS models, aligning with the observation that while they excel in geometric accuracy, they rely on additional tools for enrichment and result in static representations within BIM environments.

Mesh-to-BIM models provide an effective means of representing point clouds, accurately capturing the surface geometry of structures. Depending on the project's Level of Detail (LOD), surface meshes can often suffice for specific objects without the need for further modeling, showcasing the utility of mesh-to-BIM workflows in achieving dimensional accuracy and tracking changes over time. The San Pietro di Deca Conventazzo project (Barrile, Bernardo, & Bilotta, 2022) illustrates the utilized photogrammetry, laser scanning, and UAV technologies to generate high-resolution mesh models from dense point clouds, which were then imported into BIM software like Revit. While the meshes successfully detailed the intricate architectural elements, they became static and non-editable within the BIM environment. Furthermore, the computational demands of high-resolution meshes created interoperability and performance challenges. This case underscores both the strengths and constraints of mesh-to-BIM workflows in heritage documentation and conservation.

CAD tools excel in modeling complex and irregular shapes, as demonstrated in the Old-Segeberg Town House project, where AutoCAD with the PointCloud plugin was used to create detailed geometric models from laser scan and photogrammetric data. CAD enabled the reconstruction of intricate architectural features with precision, highlighting its flexibility for non-standard geometries. However, a key limitation is the lack of bidirectional integration with BIM tools. CAD models cannot be directly added to BIM object libraries or parametrically edited, becoming static upon import and requiring additional workflows for semantic enrichment (Kersten et al., 2014).

Bespoke systems are designed to address unique project needs, providing tailored solutions for complex challenges. However, their advantages are often limited to individual projects and lack universal applicability. The absence of standardization frequently leads to interoperability challenges between tools. The Santa Croce Basilica Cloister project in Florence (Campari & D'Uffizi, 2017) exemplifies these challenges. Utilizing a bespoke workflow to design a new lighting system, the project employed advanced BIM tools, such as Revit, for precise lighting simulations. While this approach effectively addressed the cloister's specific requirements, the reliance on multiple platforms created interoperability issues, and the separation of historical and modern elements limited seamless integration.

The accurate identification and classification of heritage building elements are essential due to their varying geometries, conditions, and historical significance. Semantic decomposition and classification within BIM tools enhance data management by assigning unique identifiers to components. For instance, Autodesk Revit employs progressive "identification numbers" (IDs) (Adami et al., 2018). In parametric modeling, Non-Uniform Rational B-Splines (NURBS) are used to represent curves, and Rhino serves as a 3D modeling platform for their classification. Grasshopper, integrated with Rhino, provides a robust visual programming environment that supports third-party extensions and facilitates the seamless transfer of Rhinoceros-modeled elements into BIM software like Autodesk Revit, thereby enhancing workflow efficiency and flexibility.

The HBIM workflow integrates a wide range of specialized software tools, each playing a crucial role in different stages of heritage conservation. Visualization and presentation tools, such as 3D rendering and virtual reality software, empower stakeholders to explore restoration scenarios in detail and effectively convey plans to non-technical audiences, fostering greater understanding and collaboration. At the same time, collaborative platforms and project management tools ensure seamless communication and efficient information sharing among architects, engineers, conservators, and policymakers, maintaining alignment with the project's goals and preserving the integrity of the conservation effort.

The approaches analyzed so far share a common goal: to create accurate, editable, and information-rich historical models. These models typically rely on advanced data acquisition techniques, such as photogrammetry and laser scanning, to capture precise geometric and surface details. As summarized in Table 1, each approach has its own distinct features and inherent limitations. In cases where advanced data acquisition techniques are unavailable, historical modeling often depends on traditional drawings, archival documentation, and manual reconstruction. To address the challenges associated with these methods and still achieve accurate, editable, and information-rich models, Rhino.Inside.Revit provides an effective solution by integrating Rhino's advanced modeling capabilities with Revit's BIM environment.

Table 1

Main features of HBIM modelling approachesin 1.3, compared with the solution in this research.

Case	Data Acquisition	Approach		Advantages	Limitations
The Medina of Marrakech	Photogrammetry	BIM authoring tools, eg., Revit, Archicad	Parametric	Rich data Cross-platform compatibility	Dependence on advanced tools
Tusculum Sanctuary	Photogrammetry		Manual	Rich data Future editability	Time-Intensive Model elementjust use for this case
Baptistery of San Giovanni	Laser scanning	Alternative technologies	NURBS	Geometric precision Efficient modeling	Lack of editability
San Pietro di Deca Conventazzo	Photogrammetry + UAV + Laser scanning		Mesh to BIM	High-resolution representation Flexibility	High computational demand Lack of editability
Old-Segeberg Town House	Laser scanning + Photogrammetry		AutoCAD	Flexible modeling Suitable for irregular shapes	Limited BIM integra-tion Additional workflows
Santa Croce Basilica Cloister	Laser scanning + Photogrammetry	Bespoke systems		Tailored solutions, project-specific	Lack of generalizability
This Work	Architectual Drawing	BIM+Alternative technologies	NURBS to HBIM Rhinoceros to Revit by RHINO.INSIDE.REVIT	Flexible modeling BIM information Editability	Lack accuracy without advanced data acquisi-tion techniques,

1.4 HBIM TO VR

HBIM transcends the traditional documentation of physical dimensions in heritage structures by leveraging advanced visualization techniques to enhance understanding, surpassing the limitations of conventional blueprints and basic 3D models. Although visualization is not the primary objective of HBIM, its application results in the creation of intricate 3D models enriched with sophisticated visualization tools, enabling immersive virtual exploration of historic buildings. By integrating extended reality technologies, including Virtual Reality (VR), Mixed Reality (MR), and Augmented Reality (AR), the HBIM framework significantly enhances accessibility to cultural heritage. These cutting-edge technologies not only improve the visualization process but also streamline the acquisition, management, and dissemination of critical heritage information.

The adoption of VR technologies by museums is revolutionizing the visitor experience, offering immersive opportunities to traverse ancient ruins or interact with digital recreations of artifacts. These virtual exhibits foster a profound appreciation for cultural heritage while instilling a sense of responsibility for its preservation. This approach enables experimental analysis and simulations without jeopardizing the physical integrity of historical sites, marking a significant advancement in heritage conservation and education (Penjor et al., 2024).

In recent years, the integration of HBIM and VR has gained significant traction, fostering the development of immersive Virtual Museum (VM) through advanced game engines like Unity and Unreal Engine (Fiorenza et al., 2024). A relevant use case worth to report is The Smithsonian American Art Museum's Beyond the Walls (2019) leverages photogrammetry and laser scanning to create detailed 3D models, offering an immersive VR experience via Unity. Users can explore the museum's east wing, viewing high-fidelity artworks, including paintings, sculptures, and video installations. The experience goes beyond traditional virtual tours, offering innovative interactive elements such as gesture controls and artwork zoom-ins. Notably, approaching the Adams Memorial transports users to a 3D volumetric recreation of Rock Creek Park Cemetery, where they can witness a 360-degree, 6K video of the aurora borealis. Additionally, users encounter a volumetric hologram of artist Alex Prager, who narrates the inspiration behind the 2013 film Face in the Crowd. Distributed on Steam and compatible with multiple VR devices, the project sets a high standard for accessibility and interactive storytelling in virtual museums. The usage of a video allowed visitors to enjoy the virtual visit, fostering user experience and engagement.

The process of integrating CAD models into VR involves creating detailed 3D models using tools like AutoCAD with PointCloud plugins, incorporating geometric and historical data such as construction phases and material properties. These models are then imported into a game engine, such as Unreal Engine, where interactive features like animations and information panels are added through visual programming (Blueprints). While this process enables immersive exploration and dynamic animations showcasing architectural evolution in VR environments like HTC Vive, it is also time-intensive and costly, requiring significant resources for detailed modeling, optimization, and integration (Kersten et al., 2017).

Another case of HBIM integration into VR environments demonstrates advanced visualization methods for heritage conservation, leveraging interactive and immersive technologies. The HBIM model, developed using Autodesk Revit, was optimized in 3ds Max and exported in fbx. format to enable compatibility with VR platforms such as Unity 3D and Unreal Engine. Scripts were implemented to connect BIM data, including technical datasheets and material properties, to specific virtual elements, allowing users to interact with these components using laser controllers in systems like HTC Vive and Oculus Rift. Navigation within the virtual environment utilized collision detection and interactive interfaces, enabling users to explore the space, access detailed information, and annotate or report issues directly within the VR setting (Osello et al., 2018).

Pybus et al. (2019) proposed a workflow for converting HBIM into VR, focusing on Canada's "Parliament Hill." Models were optimized using Rhino 3D and 3DS Max to reduce polycount, refine geometry, and apply high-quality textures. The optimized models were then integrated into Unity 3D, with pre-baked lighting and a VR camera controller ensuring smooth navigation and performance. Users can freely explore the virtual space using headsets like Oculus Rift, toggling between viewpoints and inspecting architectural details. While the current setup supports immersive exploration, future enhancements could include guided narratives to enrich user engagement.

The HBIM-to-VR workflow utilizes enriched IFC files to seamlessly integrate metadata, such as Points of Interest (POIs) and Look-At Objects (LAOs), into an immersive virtual environment. POIs serve as key locations in the model with contextual descriptions, while LAOs link specific elements to multimedia content, including images and videos. External data, such as textures and high-definition models (HDMs), are prepared in tools like Blender and referenced in the IFC file. A Unity-based VR platform automates key processes, including IFC data import, model reconstruction, texture mapping, and interaction features such as teleportation, continuous movement, and UI panels displaying cultural information. Users can explore the virtual space, interact with content, and access real-time audio guidance through Text-to-Speech. Although the workflow automates much of the setup, preparing enriched IFC files and 3D assets requires technical skills in modeling and metadata management, posing challenges for users without programming or 3D design experience (Fiorenza et al., 2024).

Unity Reflect enables seamless integration of BIM model data, including family (component) information, into a real-time 3D environment, allowing users to interactively view detailed geometric data, attributes, and technical specifications directly within the visualized model. This functionality enhances collaboration among design teams and stakeholders by providing real-time access to comprehensive information. However, Unity Reflect has limitations, including its high cost, which may be prohibitive for budget-sensitive projects, and relatively basic interactive capabilities, primarily limited to functions such as rotation, scaling, and element selection. While it supports real-time design synchronization, its optimization for large-scale, complex projects remains insufficient. Furthermore, Unity Reflect has been discontinued, and its features are no longer being updated or actively supported, limiting its future potential and rendering it less suitable for evolving project needs (Unity, 2021).

HBIM-to-VR workflows enable users to explore historic sites virtually, fostering greater public engagement and appreciation for cultural assets. These tools not only enhance visualization and interaction but also provide innovative platforms for education, conservation planning, and heritage storytelling. Despite the technical challenges and resource demands, the potential of HBIM-to-VR to revolutionize heritage management underscores its importance in bridging the gap between traditional conservation practices and modern digital solutions, ensuring cultural heritage is preserved and experienced by future generations.

In conclusion, the integration of HBIM into VR has significantly advanced heritage visualization, yet the transition from models to VR often leads to the loss of critical semantic historical information and parametric data. While various methods have been developed to address this challenge, many are either prohibitively expensive or require advanced technical expertise, making them inaccessible to individuals without programming skills. As shown in Table 2. Currently, there is no universally accessible solution that allows non-technical users to create immersive VR museums enriched with historical and semantic data while supporting semi-automated synchronization of model information.

Table 2

Main features of way transfer BIM information to VR in 1.4, compared with the solution in this research.

		The Smithsonian American Art Museum	Kersten et al., 2017	Osello et al., 2018	Pybus et al., 2019	Fiorenza et al., 2024	Unity, 2021	**This Work**
The way BIM information input		No	CAD to Unreal Engine through Blueprints	Revit to Unity through Script	No	IFC files with metadata to unity	Revit to Unity Reflect drirctly	Revit to Unity through CSV and FBX Files
Cost of making VR experience		Expensive	Expensive	Do not know	Do not know	Do not know	Expensive	Free
Immersive VR		√	√	√	√	√	√	√
External data retrieval	Text descriptions	√	√	√	No	√	√	√
	Images	√	√	√	√	√	√	√
	Videos	√	√	No	No	√	No	√
	Audio descriptions	√	√	√	No	√	No	√
	BIM Information	No	√	√	No	√	√	√
Locomotion system	Teleport areas	√	√	√	√	√	No	√
	Continuous movement	√	√	√	√	√	No	√
User Interface (UI)	UI panels	√	√	√	No	√	√	√
	UI buttons	√	√	√	No	√	No	√

1.5 The Potential Development Trends of Virtual Reality in Museums

The origins of museums can be traced back to the 16th-century "cabinets of natural curiosities," which were intricately connected to the nascent field of archaeology. These early collections, comprising a diverse array of objects, served as symbols of economic status and exclusivity for the social elite, remaining inaccessible to the broader population. Over time, particularly during the Enlightenment and the workers' revolts of the 19th century, access to these collections began to expand, albeit selectively. The emergence of nationalist ideologies further catalyzed the development of grand national museums, which were envisioned as universal repositories showcasing the historical grandeur of states—both in their ancestral civilizations and contemporary imperial ambitions (Pujol, 2004).

The 19th century marked a transformative period for museums. The influence of universal exhibitions inspired curators to democratize access by opening collections to the public and adopting interpretive strategies that rendered objects more comprehensible to non-specialist audiences (Koester, 1993). By the 20th century, museums had evolved beyond their initial educational mandates to embrace their role as spaces of cultural engagement, incorporating elements of entertainment to appeal to a wider audience. This shift reflects the dynamic interplay between museums and their societal contexts, highlighting their ongoing adaptation to cultural, political, and technological changes.

The most significant transformation in the museum field occurred in the 20th century, driven by a range of interconnected factors: the advent of the information society, market-driven influences through competition in the leisure and tourism sectors, increased democratization of access to knowledge, and shifts in educational theory and practice (Hooper-Greenhill, 1998). In this context, the adoption of information and communication technologies (ICT), including the Internet, expert systems, databases, multimedia, and related innovations, has significantly redefined the role of museums. Transitioning from their traditional function as repositories of standardized, object-centered, and authoritative narratives, museums have become dynamic hubs for communication, interactive learning, and information exchange. This evolution reflects their increasing focus on fostering engagement and creating participatory experiences for diverse audiences (Pujol, 2004).

Nowadays we are witnessing the transition from analog to digital, a period widely referred to as Digital Transformation. This era is marked by the increasing integration of intelligent, network-connected machines, impacting not only the productive sectors of society but also reshaping the ways in which humans interact with technology (De Giorgis, 2021). The history of human-machine interaction, efforts have been made to create a relationship between people and technology that mimics real-world experiences. Virtual reality (VR) has emerged as a groundbreaking form of interaction that closely replicates reality, enabling immersive experiences capable of profoundly influencing lives. Unlike traditional video games, VR is distinguished by its high level of immersion and the active involvement of the user's body in engaging with the virtual environment. Interaction goes beyond using a controller or keyboard, allowing users to navigate through space using head movements, eye tracking, or specialized controllers (Campitiello et al., 2022). The term "virtual reality" was first introduced by Jerome Lanier to describe projects undertaken by universities and research institutions. VR refers to an environment constructed by human imagination, though definitions of the concept vary significantly:

- A digital recreation of a real or imagined setting (Heim, 2000)
- A collection of computational devices that facilitate new forms of human-machine interaction (Ellis, 1994)

Certainly, virtual reality is not to be understood as a simple technology, which is increasingly spreading outside academic laboratories, but it is a new mode of knowledge and communication that places the person at the center of one's experience. Since the 2000s, we have seen a decrease in costs and a use aimed at non-expert users which has made this technology democratic. In particular, since 2012 more and more people have tried virtual reality thanks to the marketing of headsets such as PlayStation VR, HTC Vive, Oculus Go and Oculus Quest. Virtual reality systems differ according to the level of immersion, which involves measuring "quantitatively" how much a technology allows you to immerse yourself in a virtual world (Slater et al., 1996), dividing virtual reality into: Immersive virtual reality fully engages the user at a sensory level, utilizing devices like head-mounted displays and position sensors, as seen in systems such as Oculus Quest and PlayStation VR.; Semi-immersive virtual reality involves environments like CAVE (Cave Automatic Virtual Environment), where computer-generated visuals are projected onto room walls, enabling groups to share a collective experience; Non-immersive virtual reality refers to 3D digital environments designed for viewing on 2D displays, such as those of smartphones or computers, providing a less immersive but highly accessible experience (Pallavicini, 2020).

Virtual reality, augmented reality, and mixed reality are often referred to as "synonyms". However, they differ significantly in both technological implementation and practical applications, particularly in the following ways:

- Virtual Reality (VR) provides an immersive experience within a 3D digital environment, enabling users to engage in multisensory interactions through head-mounted displays. Within this virtual space, users can interact with various elements, creating a sense of presence in a parallel world. This environment can either be a product of imaginative design or a precise digital recreation of real-world locations (Campitiello et al., 2022).
- Augmented reality (AR overlays images, text, or 3D models onto the real world to enhance the user's perception of reality with virtual elements. These virtual additions, while not directly manipulable, provide additional information about locations or products, often accessed through mobile apps or AR viewers. Unlike VR, AR maintains contact with the real

world, enriching it with virtual components such as sounds or visual overlays that integrate seamlessly with the surroundings (Campitiello et al., 2022).

- Mixed Reality (MR) combines the real and virtual worlds within a single display, where virtual elements seamlessly integrate with the physical environment. Rather than simply overlapping, these elements interact dynamically with the real world, allowing the user to manipulate them directly (Pallavicini, 2020).

The integration of digital technologies in museums has become inevitable following the rapid technological advancements of the past decade. Digital interactive technologies, which rely on human senses, offer alternative methods to overcome limitations imposed by traditional human ergonomics. They create unique spatial experiences through their innovative approaches. In museums, these technologies enable visitors to engage with the exhibits through various digital interfaces, fundamentally transforming the museum experience. They allow users to customize their interactions, providing flexible and alternative ways of experiencing the space. While traditional static exhibition systems still have a place in museums, many institutions are now incorporating a hybrid exhibition model that blends new technologies. Through the use of VR, artworks that have been removed from their original context for display in a museum can be reintroduced with an immersive experience, reconnecting them to their stories and original setting.

With the development of new technologies such as information technology, artificial intelligence, and virtual reality (VR), as well as the birth and rise of various new platforms and new formats, the cultural communication forms of museums are increasingly showing digital and intelligent characteristics. The impact of the epidemic has also accelerated the pace of digital construction of museums. The rapid development of digital technology is quietly changing the traditional working mode of museums and even reshaping the cultural value of museums in contemporary society. The increasingly intensive application of digital tools to support surveying, modeling and virtual representation has allowed in recent years to refine the integration with traditional techniques, optimizing their processes and consolidating their role in the complex path that leads to the knowledge of a museum.

A first example of VR in real-world museums is the work of Jung et al. (2016) at the Geevor Tin Mine Museum in Cornwall, UK. Using Samsung Gear VR, visitors could virtually descend into the mine shaft, simulating miners' initial work environment. While innovative, this approach had limited interactivity due to the 3 Degrees of Freedom (DOF) of mobile devices and restricted computational capacity, relying heavily on pre-rendered visuals.

Another example is Puig et al. (2020) developed two VR experiences for the Museu d'Arqueologia de Catalunya: a 360° video and a gamified interactive environment, using the HTC Vive's advanced 6 DOF tracking. The tethered system overcame the limitations of 3 DOF devices, enabling richer, room-scale VHEs with complex graphics. Users navigated through walking, teleportation, or smooth locomotion, while hand controllers allowed interaction with virtual objects and interfaces via direct contact or ray casting. Despite its success, the study highlighted the need for user-friendly designs to accommodate novice VR users.

Similarly, The Louvre's "Mona Lisa: Beyond the Glass" project (2019) exemplifies how VR can reimagine art engagement. This experience enabled visitors to virtually enter the world of Leonardo da Vinci's masterpiece, offering high-resolution visuals, interactive elements, and narrated audio guides. The usage of a pre-recorded voice allowed visitors to enjoy the virtual visit, fostering user experience and engagement.

In conclusion, VR applications developed for museum exhibit a wide range of features and functionalities, making it challenging to standardize their development processes. Designing and maintaining these applications require a diverse set of specialized skills. In this context, proposing a simplified HBIM-to-VR workflow becomes essential.

1.6 Considerations

The integration of HBIM and VR is transforming museums by creating immersive, accessible, and engaging experiences that cultural heritage preservation and appreciation. By leveraging VR, museums can offer dynamic virtual spaces where visitors can interact with artifacts, and engage with multimedia narratives. Semi-automated workflows and enriched metadata ensure seamless updates between HBIM and VR environments, reducing manual intervention and enhancing usability. The HBIM workflow typically encompasses three key stages: data acquisition, data processing and modeling, and management.

Multiple modeling methodologies support HBIM, each with distinct advantages and limitations. Conventional BIM tools are effective for parametric modeling but face challenges when handling highly irregular geometries. Alternative technologies offer exceptional precision and flexibility for complex shapes but often produce static representations that lack bidirectional integration with BIM systems. Bespoke systems, while tailored to specific project needs, frequently encounter challenges related to standardization and interoperability. These varied approaches highlight the adaptability of HBIM while underscoring the need for further development to overcome existing limitations.

The integration of HBIM into VR has significantly advanced heritage visualization and cultural preservation, but critical challenges remain in modeling accuracy, data transfer, and accessibility. Complex heritage structures often rely on advanced scanning technologies, and in their absence. Additionally, the transition from HBIM to VR frequently results in the loss of semantic and parametric data, limiting the fidelity of virtual environments. While some workflows enable semi-automated synchronization and metadata integration, they still require technical expertise, making them inaccessible to non-experts. Current VR applications often focus on basic visualization and interactivity, leaving a gap in functionality for creating engaging, immersive virtual museums. Addressing these challenges with universally accessible, automated solutions is essential for broadening the adoption of HBIM-to-VR workflows and enhancing cultural heritage preservation in the digital age.

This research, relying on architectural drawings in the absence of advanced data collection technologies, successfully modeled the complex curved surfaces of the Parliament Hall in Palazzo Carignano. By utilizing Rhino.Inside.Revit, which seamlessly integrates Rhino's advanced surface modeling capabilities with Revit's BIM functionality, the research achieved the creation of detailed 3D models while embedding historical data into a comprehensive HBIM framework.

The transition from HBIM to VR presents significant challenges, including potential data loss and the need for programming expertise. To address these issues, this research proposes a semi-automated workflow that exports historical information from Revit schedules as CSV files and utilizes Power Query in Excel to dynamically update and synchronize the data with Unity. A custom C# script, generated by GPT, processes the data into an interactive VR environment, enabling real-time exploration and engagement. By leveraging AI-generated scripts, this approach lowers the barrier for users with limited programming experience, making the process more accessible while minimizing manual effort.

2. Methodology

The methodology used that starts from BIM (Building Information Modeling) and arrives at VR (Virtual Reality) implies an organized sequence of steps (Figure 1).

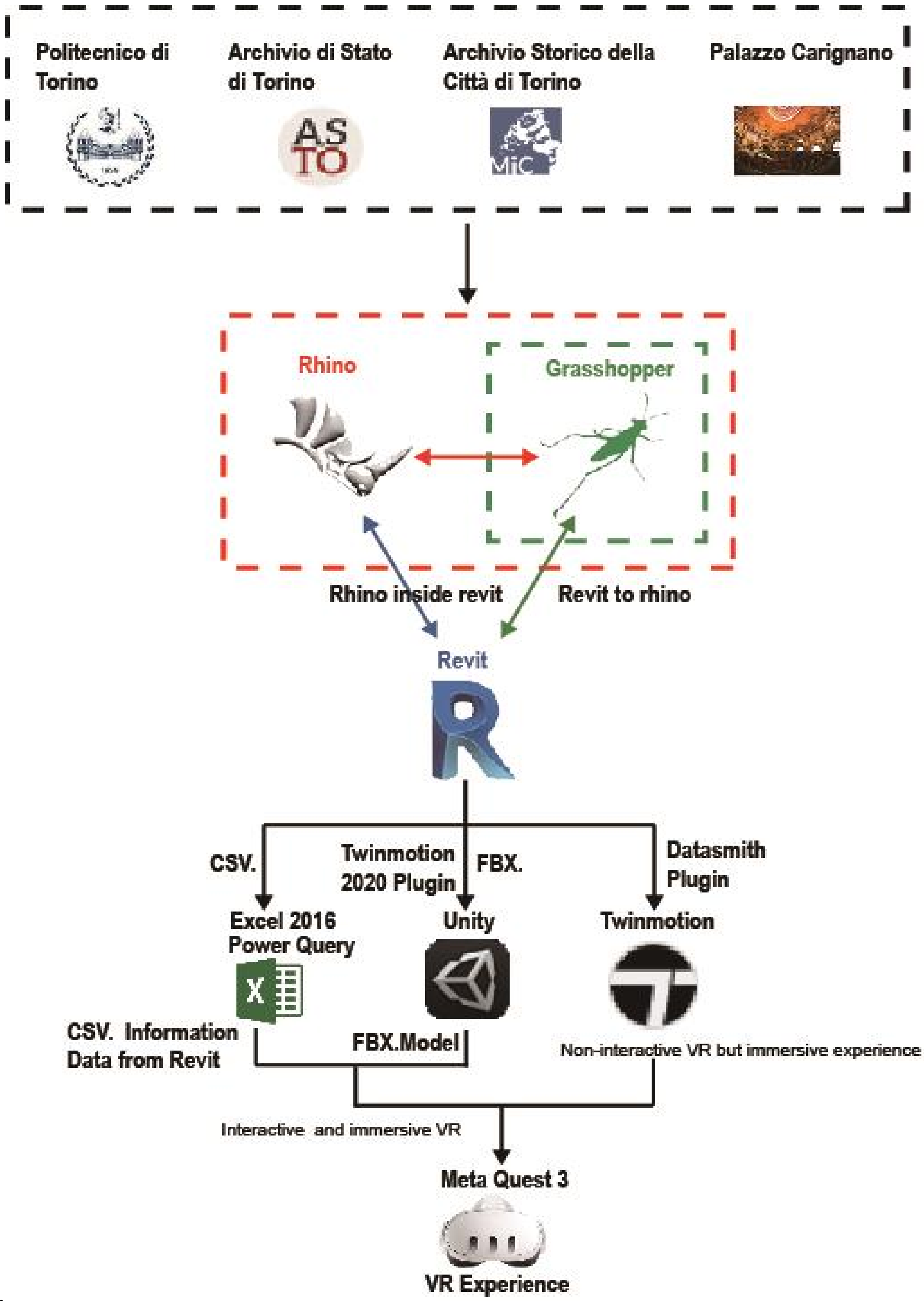


Figure 1. The flowchart from BIM to VR

It is necessary to obtain the necessary data, which may include architectural drawings, technical documents, topographic survey data, historical data and any other relevant information. The accurate collection of this data is fundamental for precise modeling and analysis. In particular, Archivio Storico della Città di Torino and Palazzo Carignano, Unione Culturale Antonicelli were consulted in order to obtain the plans and historical documentation. In addition, field survey of the Parliament Chamber was carried out in order to perform a survey.

Once all the necessary data has been obtained, a BIM software must then be used to translate the collected data into a three-dimensional digital model of the structure. The modeling phase represents a substantial part of this thesis since the parliament hall is an elliptical-shaped room and the numerous details of the room is quite complex as is the creation of its model. Create a 3D model in Rhino, and achieve two-way interaction with the BIM software Revit through Rhino.Inside.Revit. Integrating material, historical and maintenance information obtained from literature and archival research into a BIM model. This HBIM model must represent not only the geometry, but also the historical attributes.

Once the HBIM model is created, it is possible to use advanced visualization technologies, such as Virtual Reality (VR), to immersive explore the model created. Twinmotion and Unity are both widely used software for architectural visualization and virtual reality (VR).

Twinmotion is a powerful and user-friendly visualization tool that enables users to create high-quality VR demonstrations of buildings or scenes with remarkable speed and efficiency. Its intuitive operation and real-time rendering capabilities make it an excellent choice for architects, designers, and professionals who need to present their projects in a visually compelling way. However, the interactivity is limited. Suitable for quickly creating demonstration VR, simple immersive experience, and non-interactive VR roaming. The Datasmith plug-in can quickly synchronize models and provide direct integration with Revit.

Unity is a powerful game engine that supports interactive experience, VR and AR applications, provides high flexibility and scalability, and is suitable for VR projects that require complex interactive logic and high customization. The required element information in Revit is exported into Excel using schedules and then converted to a CSV file. Using a C# script (developed with the assistance of ChatGPT), the model data from Revit is displayed on a panel in Unity. Import Revit models into Unity by exporting FBX files. Interactive design with exhibits in Unity to create an immersive museum experience. Finally, the VR experience is realized through the Meta Quest 3 headset.

2.1 History of the the Parliament Hall in the Palazzo Carignano

Palazzo Carignano (Palass Carignan in Piedmontese) is a historic building located in the heart of Turin, renowned as a masterpiece of Piedmontese Baroque architecture. Alongside Palazzo Reale and Palazzo Madama, it stands as one of the city's most significant historic landmarks and is included in the UNESCO World Heritage site "Savoy Residences." The palace holds immense historical importance, having served as the seat of the Subalpine Parliament (1848-1861) and later as the first Parliament of the Kingdom of Italy (1861-1864), marking its pivotal role in the nation's unification process.

Palazzo Carignano consists of two bodies, one from the seventeenth century and one from the nineteenth century (Figure 2). The seventeenth-century body, the work of Guarino Guarini, with a C-shaped plan once opening onto the gardens, consists of two wings, one towards the north, called "di Mezzanotte" (towards the current via Cesare Battisti), and one towards the south, called "di Mezzogiorno" (towards the current Via Principe Amedeo), and of the facade towards the current Piazza Carignano (Figure 3). The nineteenth-century body is a vast expansion that is grafted Piazza Carlo Alberto with an imposing facade in pseudo-Renaissance eclectic style. Built between 1864 and 1871 based on a design by Domenico Ferri, the extension was intended to house the Italian Chamber (Cerri, 1990).

Figure 2. Palazzo Carignano from different eras

Figure 3. Location of the Palazzo Carignano

It is famous for its beautiful facade (Figure 4). The intricate details and textures will make people curious enough to touch. These details are not just ornamental, but are carefully designed to create a sense of tactile and prosodic effects that are intended to communicate with people. The "concave-convex-concave" facade is distinguished from the surrounding buildings, which is very distinctive, and the palace's own attributes are more obvious. In 1939 the nineteenth-century extension and the first floor of the seventeenth-century body became the permanent seat of the National Museum of the Risorgimento, reopened to the public after a long restoration in 2011.

Today, the palace is home to the Museum of the Risorgimento, which tells the story of the Italian unification movement. The museum features a collection of artifacts, documents, and works of art related to the Risorgimento, as well as exhibits on the history of Turin and the Piedmont region.

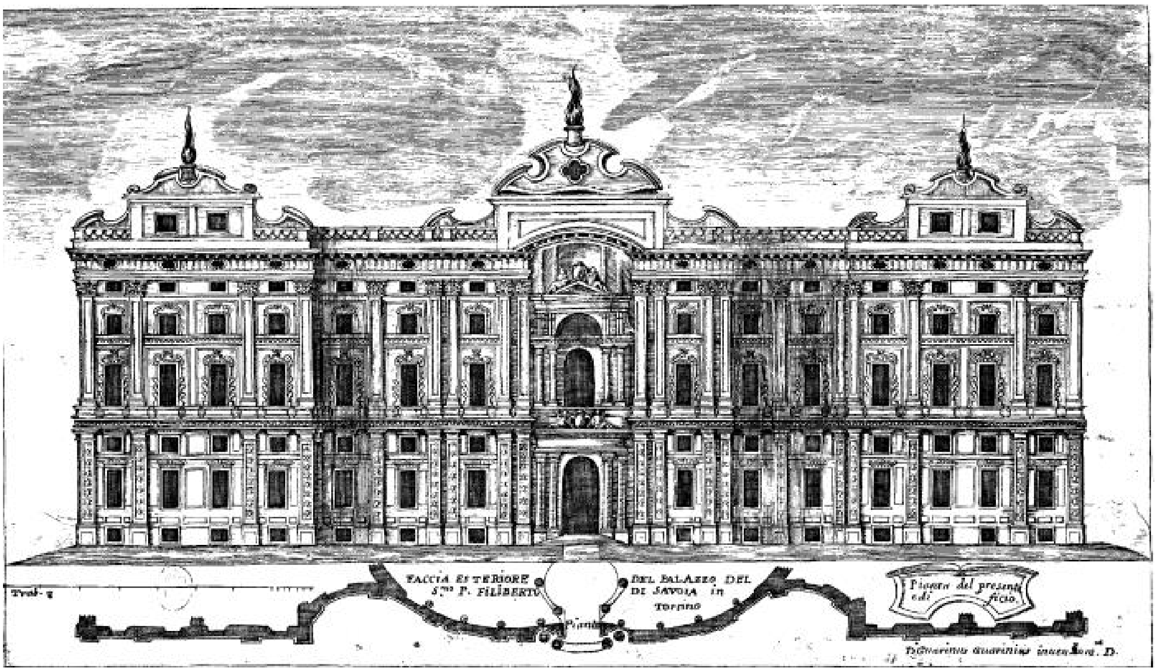


Figure 4. Facade and plan of Palazzo del Santo Filippo in Torino. Imagine from *Faccia esteriore del Palazzo del S.mo P.Filiberto di Savoia in Torin*, e *Pianta del presente edificio*, incisione in rame di Antonio De Pienne su disegno di Guarini, in Dissegni d'architettura civile et ecclesistica ,cit. (BRT, V 38-39).

① The hall was used for public events and ceremonies (1679-1848)

Guarino Guarini began work on Palazzo Carignano in 1679, when he was commissioned by Prince Emanuele Filiberto of Savoy-Carignano to design a new palace for the Carignano family, who were one of the most prominent noble families in Italy at the time. The palace was designed to be a symbol of the family's wealth, power, and prestige, and it was meant to impress visitors and convey the family's status. In addition to serving as a private residence, Palazzo Carignano was also used for public events and ceremonies. The palace's grand staircase (Figure 5) and elegant rooms were designed to accommodate large gatherings and to create a sense of grandeur and drama.

Guarino Guarini (1624-1683) was an Italian architect and theologian who lived during the Baroque period. He is known for his innovative architectural designs, combining traditional elements with the new Baroque. He is good at using complex geometric shapes, the use of light and shadow, and intricate decorative details. Palazzo Carignano, one of his main achievements, can express the characteristics of his design.

In Palazzo Carignano, the main cylindrical center is inserted into the straight residential sides, which contain the building where the two main spaces of the palace are dedicated to public activities: the atrium at ground level between the piazza and the gardens and the main hall on the noble floor. The plan of this cylindrical body is described by an oval with four equilateral centers, very close to an ellipse which has the extensions of the major and minor axes in a ratio of 4:3 (Cerri, 1990). Conceived to provide indirect lighting for the main hall of the building: the Savoy Hall, the lighting was to be obtained through the passage of light from the large windows of the elliptical drum through an existing dome.

The hall (Figure 6) has hosted the royal wedding, and the completion of the interior decoration is closely related to the wedding. An engraving dedicated to the embellishment works carried out in 1750 for a party given in the reception hall on the occasion of the wedding of Vittorio AmedeoIIIand Maria Ferdinanda of Spain. More substantial works, always relating to the decorative arrangement of the hall, were carried out in 1775 for the wedding of Carlo EmanueleIVand Maria Clotilde of France (Cerri, 1990).

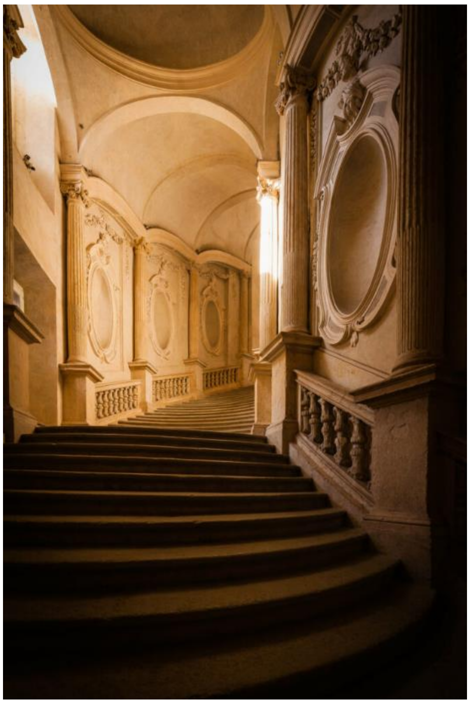


Figure 5. The GUARINI stairs

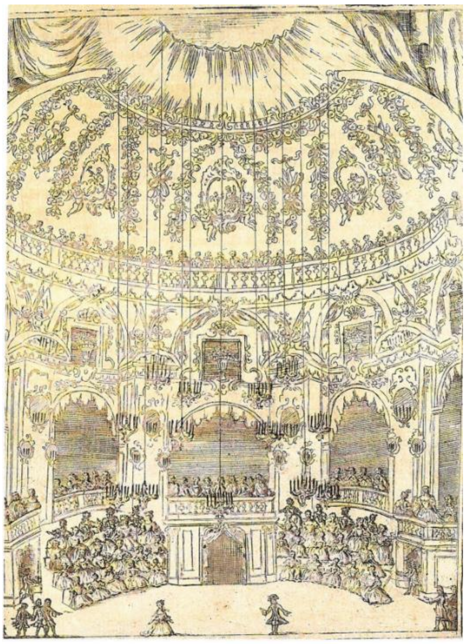


Figure 6. The wedding of Vittorio Amedeo III and Maria. Imagine from Disegno del Salone di S.A.S. il Principe di Carignano, incisione in rame, s.f., 1750

② The hall converted to the Chamber of Deputies of the Subalpine Parliament (1848-1980)

With the French occupation, the Savoy-Carignanos and their court were removed, and the palace was occupied by the Napoleonic government. In 1799 the requisitioned building passed to the State as the seat of the Prefecture and the Po Department. After the Restoration, in May 1814, Carlo Alberto returned to his residence. In 1831, with the accession to the throne of him, the building was handed over to the State, which housed the Council of State and the Post Office. Certainly, the presence of the Council of State, a consultative body, continues to function in parallel with Parliament, together with a series of offices located in rooms adjacent to the large Hall, which can be used for assemblies, also allow the processing of activities connected to the Chamber. The adaptation works of the premises are directed by the engineer Michela in his capacity as State Property Inspector Engineer and last until 1833. The definitive transfer to the State property involves the destination of some parts to public offices and the division into rental apartments, while the area on which it stands becomes the property of the municipality (Cerri, 1990).

In 1848, when the building was destined to house the Chamber of Deputies of the Sub-alpine Parliament, the architect Carlo Sada transformed the ornate ballroom housed within the oval facade.

The administration's complaints grew to outrage from the moment it realized that the payment bill had greatly exceeded the spending ceiling he had foreseen, and that the work had not been completed at all. These works were carried out with the extraordinary speed required by the case, allowing the inauguration of the Subalpine Council to take place on May 8, 1848. But in fact, due to a series of finishing work, they had to be postponed beyond that date; instead of meeting in the hall prepared for them, the delegates met in a room on the ground floor.

He then went on to redecorate the interior, and also took care of all the lobby furniture himself: a series of red velvet high chairs placed in a semicircle in front of the presidential seat, surrounded by the seats of the four secretaries. It is possible to attend the meeting from designated stands: one running in a circular direction in the upper part of the hall, intended for public use and accessible by a small staircase from a very narrow corridor. Below are the stands for the ladies, magistrates, diplomatic corps and journalists.

The constitution that was adopted in 1848 was a landmark achievement for Italy, and it served as a model for the constitutions of other European nations. On May 18, 1848, the 204 deputies of the Sardinian Kingdom took office, the historical vanguard of the first Italian Parliament. Palazzo Carignano played constituent assembly that Kingdom of Sardinia, which was then ruled by King Carlo Alberto. The assembly was made up of representatives from all over the kingdom, and they worked tirelessly to create a constitution that would guarantee basic rights and freedoms for all citizens (Griseri, 1988).

Still due to funding problems, after the Subalpine Parliament (Figure 7), he was removed from office. It wasn't long before worrying movements began to emerge in the structure.

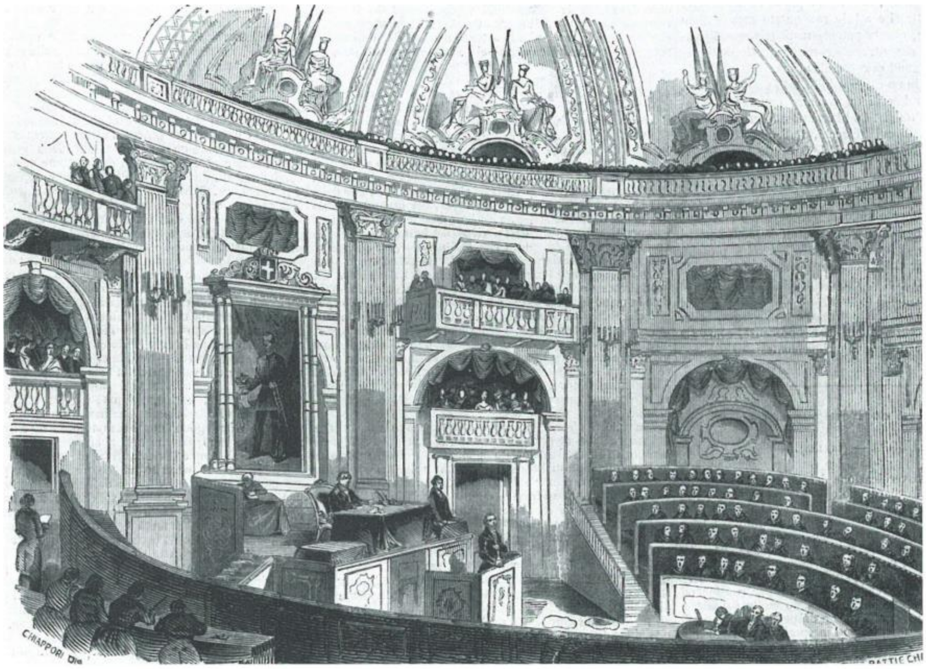


Figure 7. The Subalpine Parliament. Imagine from una delle prime sedute nell"Aula del Parlamento Subalpino (*Il Mondo Illustrato*, 20 maggio, 1848).

③ Added Temporary Council Hall

The instability that had manifested itself since 1853 in the crowning walls of Guarini's hall after the adaptation to the Parliamentary Hall by the architect Carlo Sada was remedied in 1857 with consolidation interventions carried out on a project by the engineer Peyron, The solution of the static problem was not sufficient to solve the problem of the functional insufficiency of the 'Aula, Makeshift solutions were used until 1859, the year in which the massive increase in deputies, first due to the annexation of Lombardy and Emilia and then of Central and Southern Italy, became the reason for the decision to build a special building, in expansion to the existing one. While waiting for the various projects to be drawn up for the new construction and subsequently judged, the Government was proposed to temporarily adapt the Church of San Filippo (Griseri, 1988) for this purpose.

The proposal was superseded by the decision to build “a new temporary building for use by the Chamber of Deputies in the courtyard of Palazzo Carignano”. This task was assigned to engineer Peyron by Camillo Benso di Cavour and formalized by the Minister of the Interior Cassinis who, in the assignment letter of 26 October 1860 specifies: “This building must be made of wood and contain 600 stalls for deputies, as well as public tribunes for no less than 450 people... and although it must only serve temporarily, it must be elegant and decorated in a manner worthy of its intended use” The provisional hall, designed by Peyron and built in just 113 days using a daring iron structure, and was inaugurated on February 18, 1861, with the first sitting of the new Italian Parliament. The hall remained in use until the transfer of the Chamber of Deputies to Florence in 1865, after which it was dismantled.

The hall is designed in Lombard style, a half circle and 24 meters high. It has a single large gallery made up of twenty-one arches. A gray and light green tint, with little gilding, gives freshness and effect to the of light that comes from the rich and elegant skylight that is at the top of the building. Wood, iron and crystal are the elements of the construction (Figure 8).

The appearance of the hall (Cerri, 1990) is documented by various drawings: the plans clearly indicate the distribution layout, adapted to the need to connect the new body to the existing environments and, in particular, to the central part of the building, which unfolds the various horizontal and vertical paths; two independent entrances are obtained in the lateral corners, with the adduction stairs on the upper levels (Figure 9, Figure 10). The sections show the iron structure.

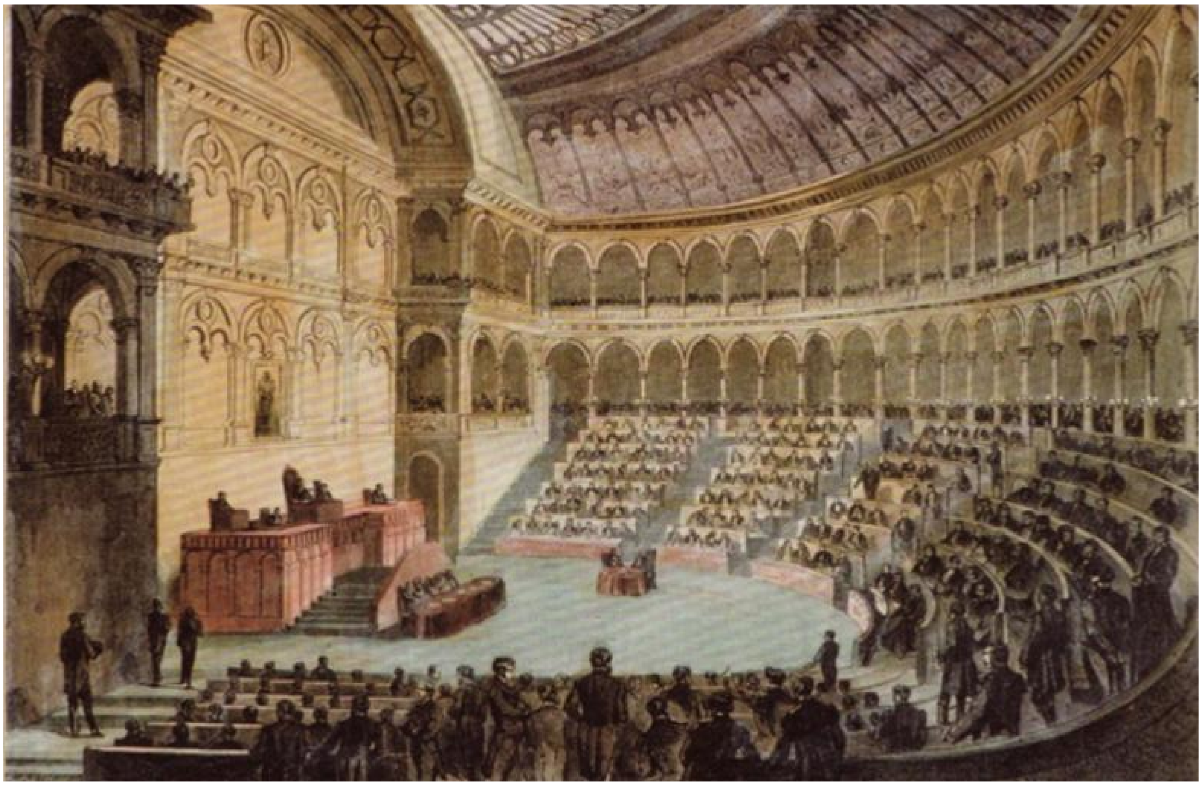


Figure 8. Vittorio Emanuele II and the Count of Cavour are recognized. The public crowding the galleries underlines the spectacular nature of the event. Imagine from Vista dell’interno dell’Aula provvisoria durante la seduta inaugurale, litografia a colori su disegno dal vero di Poirel, s.f., s.d. (Certosa di Casotto, appartamenti reali).

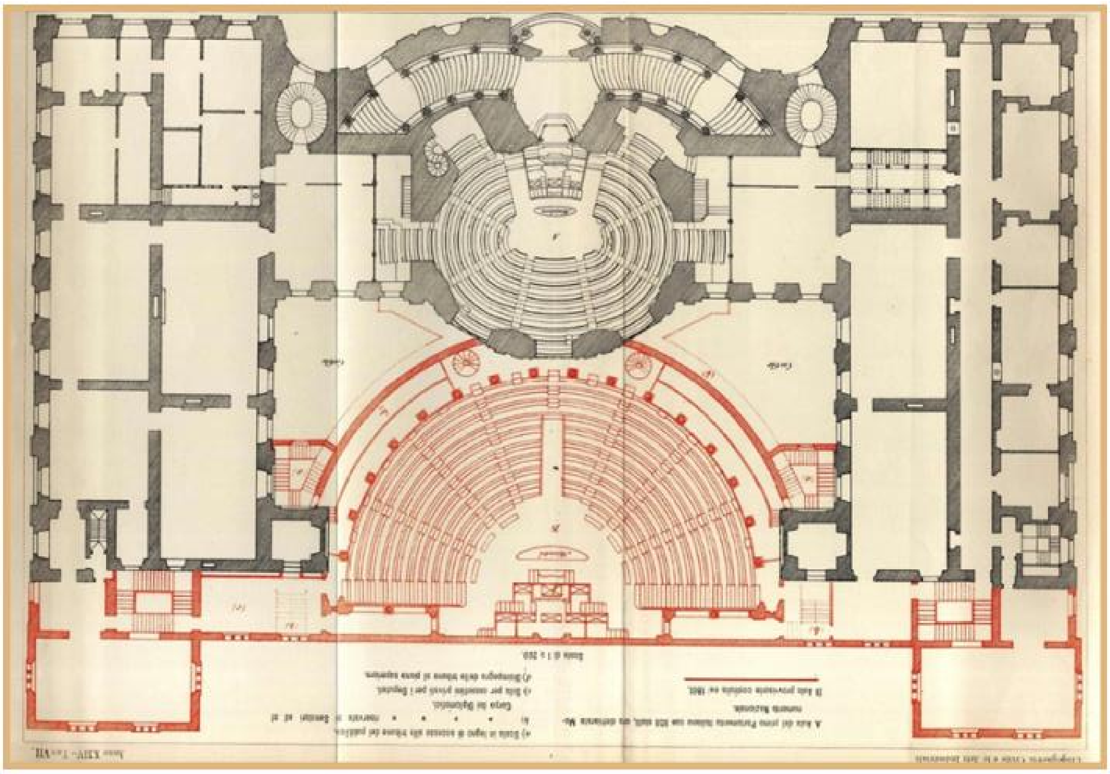


Figure 9. The plan drawing. Imagine from Aula del primo Parlamento italiunocon 358 stalli, ora dichiarata monumento nazionale -Ingegneria Civile 1897-98, Bibl. Facoltà di Architettura.

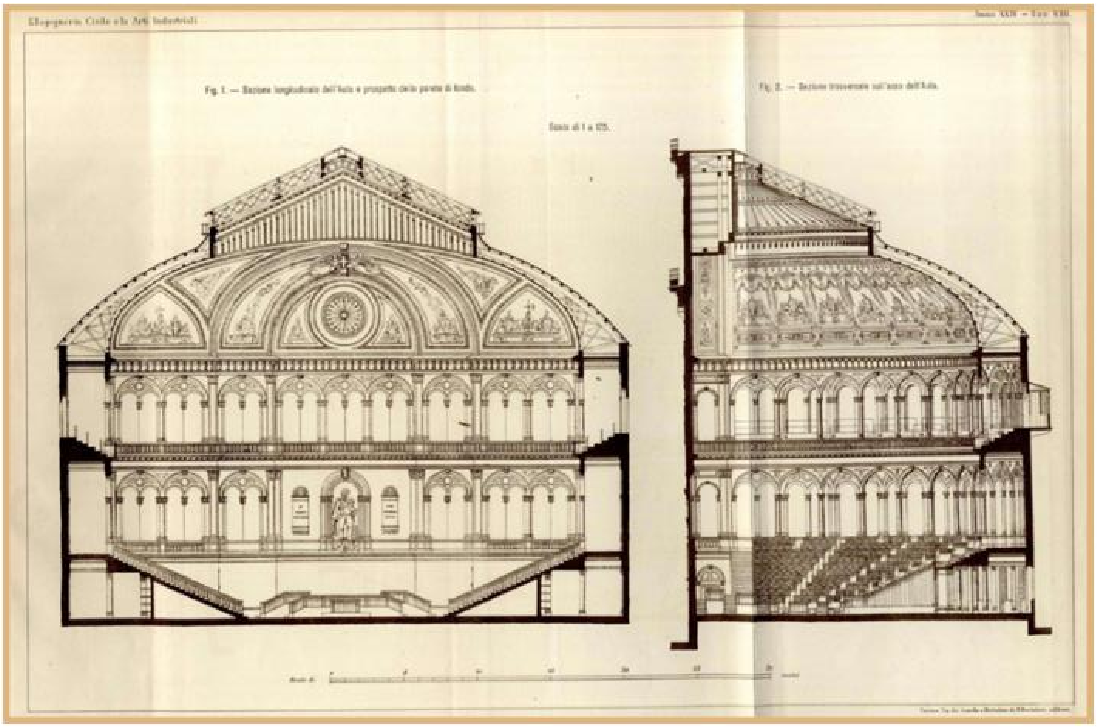


Figure 10. The section drawing. Imagine from AMEDEO PEYRON, *Sezione dell'aula*, 1861 (Archivio privato).

④ Repair the Chamber of Deputies of the Subalpine Parliament (1980-1985)

During the period of 1890-1980, Palazzo Carignano underwent several changes and renovations. In the late 19th century, the building was used as the headquarters of the Italian Senate, and it was during this time that a number of modifications were made to the interior of the building to accommodate its new function.

In the 1960s, the palace underwent a major restoration project that included the renovation of the façade and the installation of modern heating and lighting systems. The interior of the building was also remodeled to provide exhibition spaces and conference rooms.

However, starting from the 1970s, the building faced serious problems related to its roofing. The building was occupied by seven entities and private individuals, each of which transferred responsibility to the others. The state bodies did not have sufficient funds in their budgets to deal with extensive and decisive interventions, and the Civil Engineers limited themselves to executing patches on the facades and roof. Various issues arose, including the damage to the roofs of Palazzo Carignano due to lack of maintenance by the Civil Engineers, the infiltration of water from the ceilings in the premises of the Institute of Geology, and the invasion of cellars by sewage due to the breakage of a drainage pipe. Pieces of the great nineteenth-century painting continue to fall from the ceiling of the hall of the Parliament, and buckets are not enough to collect the water that descends from the rooms. The building facing collapse.

The restoration of the palace has been controversial, and many restoration plans are considered to have not followed the history. Therefore, the roof can only be repaired first to ensure that it does not leak, and then the restoration of the palace is suspended for a period of time. In 1982, Andrea Bruno was appointed as the architect for the restoration.

The restoration project of Palazzo Carignano in Turin was led by the architect in search of an authenticity linked to the control of light set up in the seventeenth century by the architect Guarino Guarini: “Of the vibrant and luminous conclusion conceived by Guarini for the roof of the reception halls of the Savoyard court still have some drawings which confirm the intention of the penetration of light, translated with the constructive means of the perforated vaults surmounted by pavilions with large windows. The expressive intensity that characterizes this work has undergone a drop in tension on the cover of the central body due to the interventions immediately following the architect's death, different from his original thought and concluded with the insertion of a bronze cartouche on the nineteenth-century pediment; this resulted in the loss of an opportunity to appreciate the extraordinary effects deriving from the particular treatment of light.

The control of light is a fundamental theme for understanding Andrea Bruno's (Bosco, 2016) works: natural light understood as a precious asset, which connects the interior with the exterior and above with below, studied in relation to the orientation and geoclimatic position of the architecture. Not only that: light is a concrete element of fundamental design for configuring the interior space; it seems to have the same constructive strength as materials such as reinforced concrete or steel.

Bruno's project dealt with the general restoration of the building, with the arrangement of the brick facings, the windows, and the restoration of the attic ceilings, with the collaboration of struts, chains and tie rods, and the use of sophisticated rehabilitation techniques of wooden parts using resins and fiberglass bars. The architect envisaged a functional redistribution of the spaces with the creation of two stairwells, new paths, emergency exits, systems.

In addition, the dilapidated roof was replaced, and the arrangement under the internal courtyard of a conference room with six hundred seats with an underlying environment for equipment and systems, built after the necessary tests, underpinnings and the consolidation of the foundations (Figure 11).

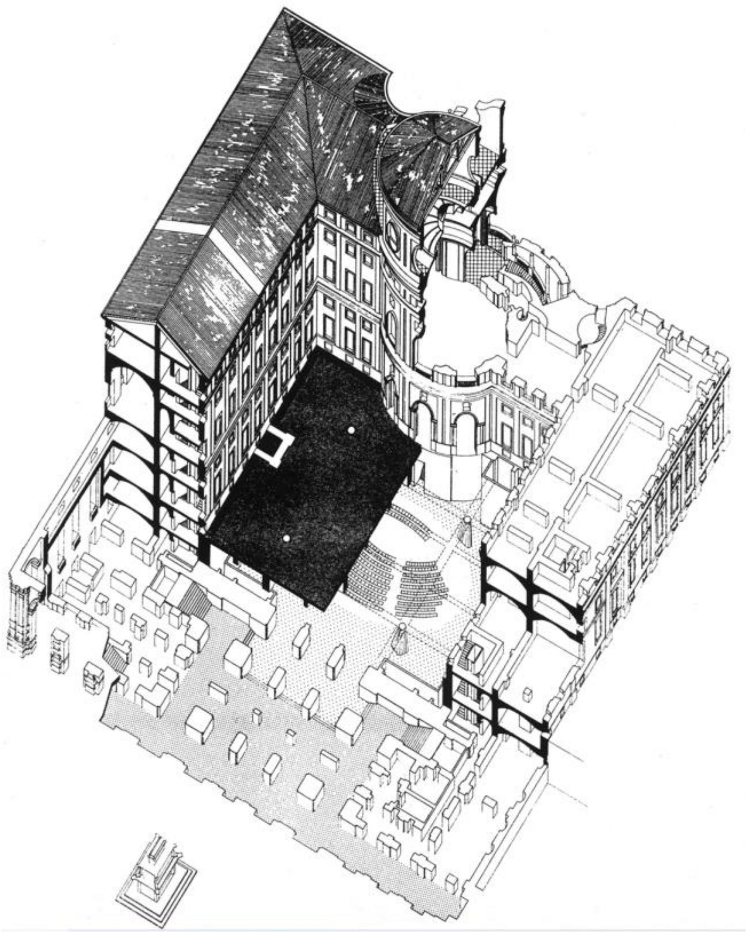


Figure 11. The axonometric section. Imagine from Palazzo Carignano: spaccato assonometrico. Il progetto di Andrea Bruno ha previsto ilrestauro generale dell"edificio compreso il rifacimento delle coperture, 1inserimento di nuovicorpi scala e la costituzione di una sala ipogea per conferenze, in conformità alla funzione musea-le cui l'edifcio è adibito.

In Palazzo Carignano, the control of light conceived specifically as a means to rediscover the original authenticity of the work. The seventeenth-century project by Guarini, which envisaged indirect lighting of the main hall of the building. Illumination was to be obtained by passing light from the large windows of the elliptical drum through a glass dome below. Andrea Bruno's project sought this condition of light lost due to later alterations which had led to the creation of a pediment dedicated to V. EmanueleII. Bruno chose to remove the flaps leaning against the elliptical dome, creating an annular terrace around the altar and thus reopening the large axial windows to light, the new roof was made of laminated wood with vertical steel connecting rods, and with skylights at the attachments of the nineteenth-century wing, maintaining in situ testimonial elements of the pre-existing construction technique (Figure 12-Figure 16).

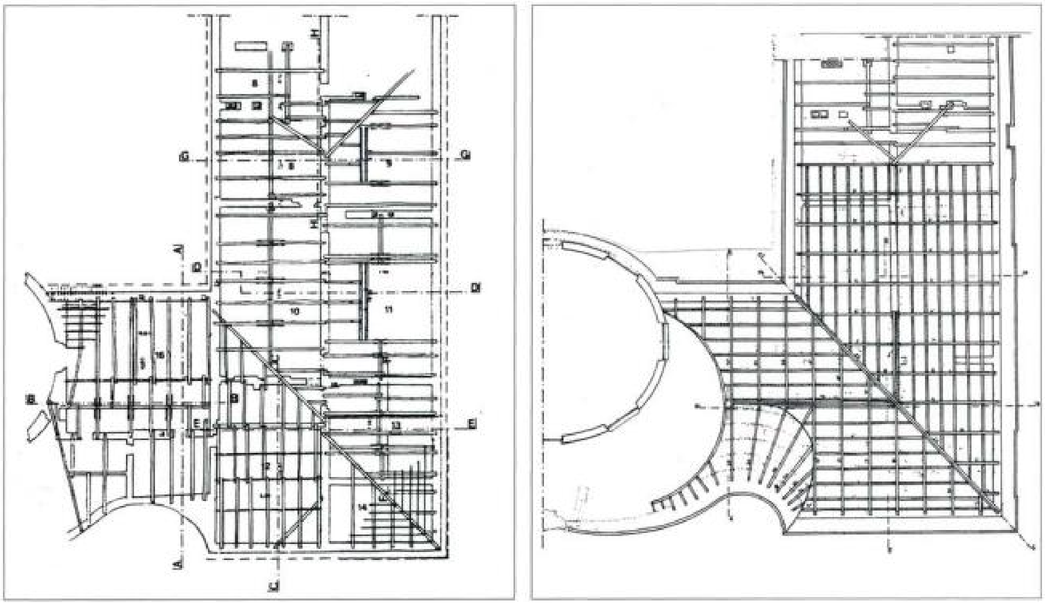


Figure 12. The plan of the dilapidated roof structure and project plan of the new roof structure in laminated wood. Imagine from Palazzo Carignano: pianta di rilievo della stnuttura di copertura fatiscente e pianta diprogetto della nuova struttura di copertura in legno lamellare.

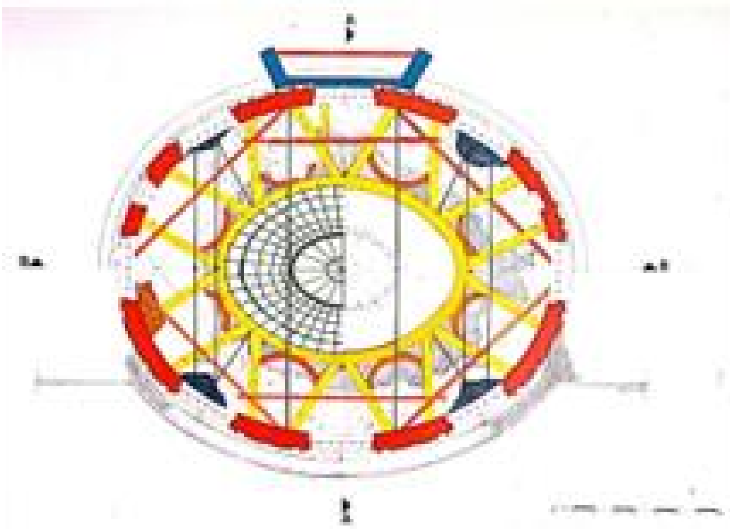


Figure 13. Plan of the pavilion. Imagine from le nervature della volta intorno al lucernario e le catene ligneee metalliche (rilievo di G. Gritella).

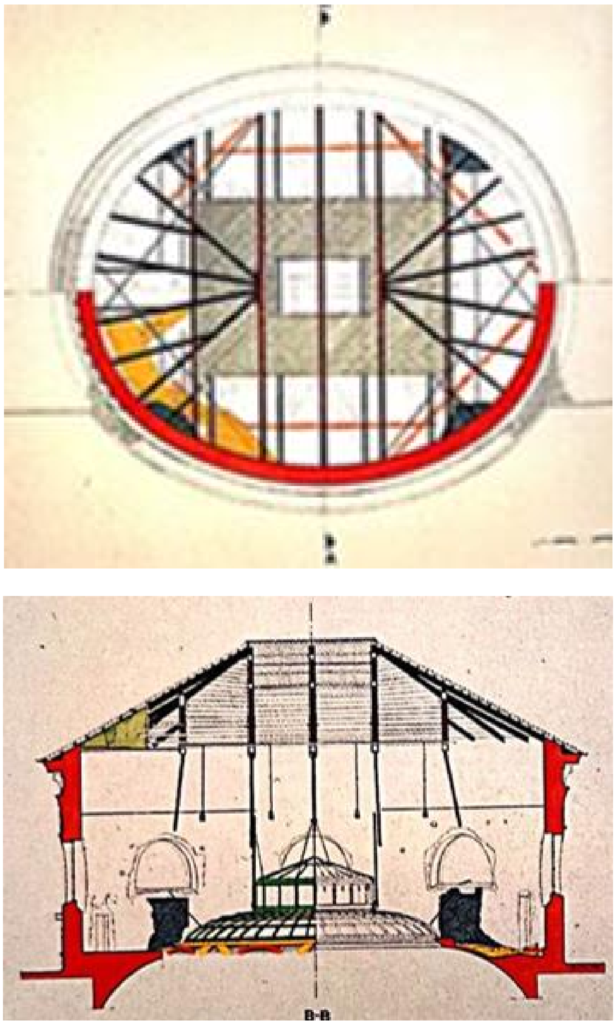


Figure 14. Longitudinal section of the pavilion. Imagine from sezione longitudinale del padiglione e pianta con l''indicazione della struttura portante del te (rilievi di G. Gritella).

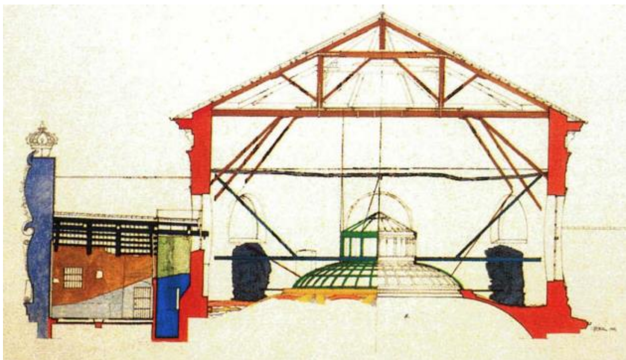


Figure 15. Section of the pavilion. Imagine from sezione del padiglione ellittico. A sinistra il frontone di Ceppi; all'interno le zone scure corrispondonoai resti degli arconi della *seconda volta* di Guarini (rilievo di G. Gritella).

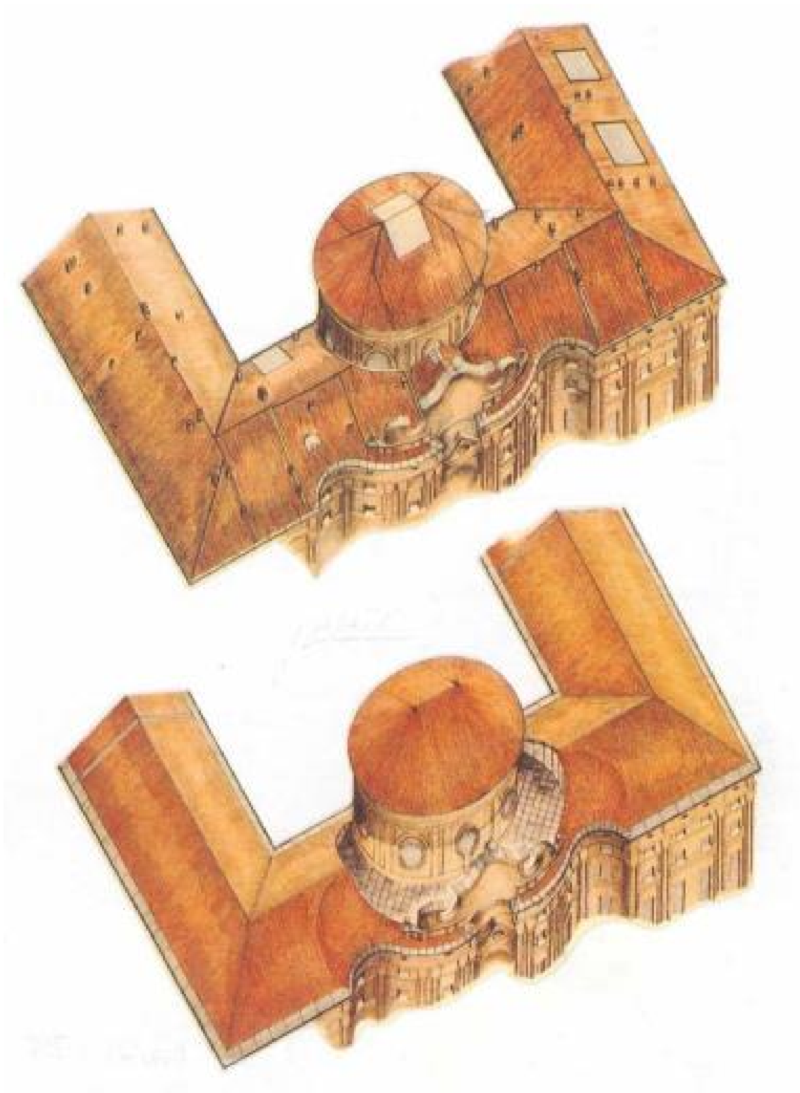


Figure 16. Axonometric views of the existing roof and the new roof. Imagine from Palazzo Carignano: assonometrie delln copertura prcesistente e delln nuova copertunIl progetto di Bruno ha ricereato la condizione di illuminazione originaria della saln delParlamento Subalpino: sono state rimosse le falde addossate in rimanegginmenti posteriori allacupola ellittica realizzando un terrazzo anulare e riaprendo cosi alln luce i finestroni ovali.

The skylight within the Subalpine Parliament Hall pavilion, before the restoration, revealed significant insights into the building's structural integrity. The removal of the mantle exposed the load-bearing structure of the pavilion roof (Figure 17). This process provided a clearer view of the roof's primary structural framework (Figure 18). Images captured the building's condition before the intervention (Figure 19). The pavilion after the renovation of the roof. The lateral flaps, offset from the emerging volume, leave it free to develop. The roof of the pavilion after the works (Figure 20).

Figure 17. The roof before restoration. Imagine from Il lucernario interno al padiglione, sull'Aula del Parlamento Subalpino, prima del restauro.

Figure 18. The framework of the pavilion's roof. Imagine from la rimozione del manto lascia vedere lorditura portante del tetto del padiglione.

Figure 19. The building before the intervention.Imagine from Il palazzo prima dell'intervento.

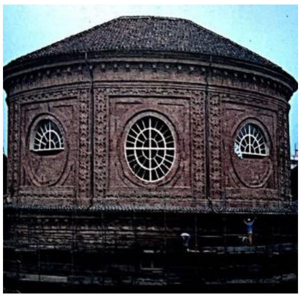


Figure 20. The pavilion after the roof restoration. Imagine from Il padiglione dopo il risanamento della copertura. Le falde laterali, scostate dal volume emergenne lasciano libero lo sviluppo.

2.2 The Flowchart of the 3D Model

The flowchart used that starts from data acquisition and arrives at HBIM Model implies an organized sequence of steps (Figure 21).

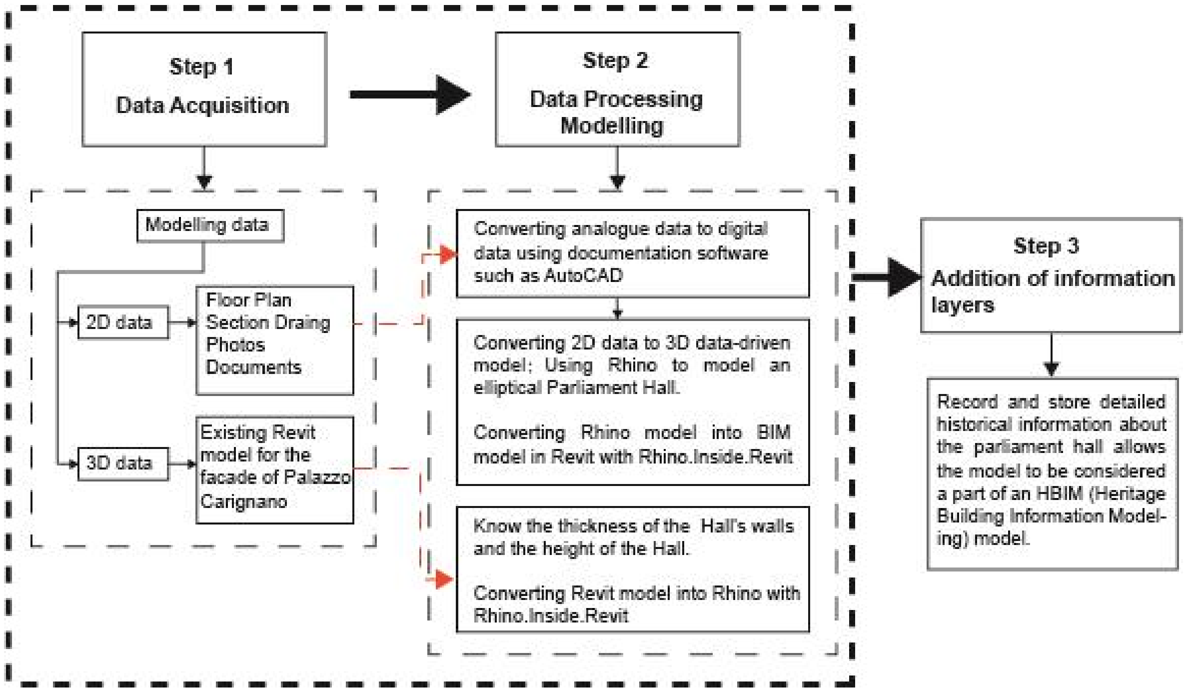


Figure 21. The flowchart of building the 3D model

The process begins with data acquisition. Based on the current floor plan, section, and the existing Revit model of the Palazzo Carignano to build 3D model. Technical drawings from the Archivio Storico della Città di Torino and Palazzo Carignano, Unione Culturale Antonicelli. The existing Revit model is from Drawing to the Future lab in Polytechnic of Turin.

Next, a 3D model of the Hall is created. The Parliament Hall is an elliptical room, or one with an organic geometric shape, which can be challenging to model precisely in Revit. Rhinoceros excels at creating complex free form shapes, and its powerful surface and NURBS (Non-Uniform Rational B-Splines) modeling tools make it ideal for accurately shaping and refining elliptical or other non-standard shapes. Revit, as an industry-standard BIM software, supports integrated construction documents, material schedules, and data-rich models. Modeling the elliptical room in Rhino and then transferring it into Revit using

Rhino.Inside.Revit leverages Revit's documentation, structural analysis, and project management capabilities to manage the elliptical room within a broader architectural model.

The process of transferring models from Revit to Rhino is streamlined with the Rhino.Inside.Revit plugin, which integrates Rhino and Grasshopper directly within the Revit environment. This approach enables architects and designers to take advantage of Rhino's advanced modeling and Grasshopper's parametric capabilities without leaving Revit, enhancing workflows for design, visualization, and computational analysis.

Finally, information layers are added to enrich the model with additional details. Record and store detailed historical information about the parliament hall allows the model to be considered a part of an HBIM model. The information is mainly from two books: *Il parlamento subalpino in Palazzo Carignano: strutture e restauro, Palazzo Carignano* and *Tre secoli di idee, progetti e realizzazioni*.

2.3 Data Acquisition

A thorough review of historical documents, architectural drawings, photographs, and other archival materials provides the foundational information necessary to accurately recreate structures from the past. These resources help to ensure the model's historical accuracy and provide insights into the architectural styles, construction techniques, and cultural context of the period.

Through the consultation of bibliographic sources such as *Il parlamento subalpino in Palazzo Carignano: strutture e restauro* and *Palazzo Carignano*, *Tre secoli di idee, progetti e realizzazioni*, it was possible to trace various information, both regarding the plan and section of the hall. Thanks to the Archivio Storico della Città di Torino and Palazzo Carignano, Unione Culturale Antonicelli, it was possible to trace the documentary sources that allowed the reconstruction of the events that occurred during the construction and the period immediately following. Technical drawings from the Archive, documentary and bibliographic analysis of the Parliament Chamber before modeling are presented below.

Technical Drawing 1

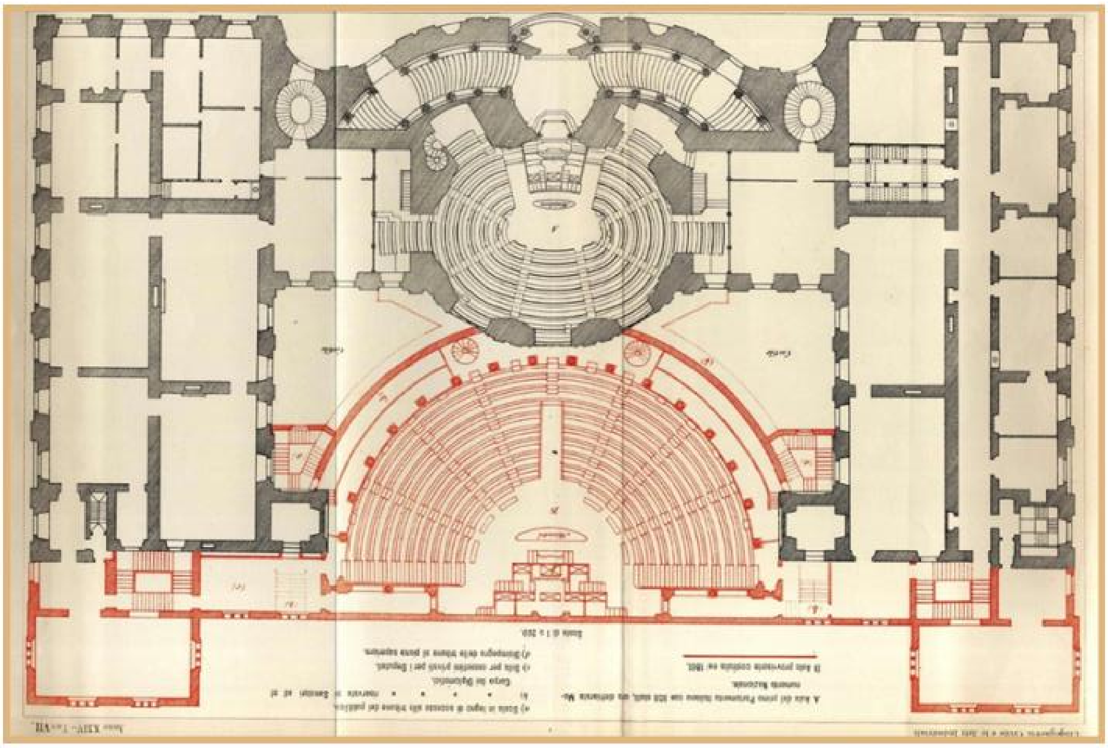


Figure 22. The plan drawing. Imagine from Aula del primo Parlamento italiunocon 358 stalli, ora dichiarata monumento nazionale -Ingegneria Civile 1897-98, Bibl. Facoltà di Architettura.

Title: Temporary Hall of the Italian Parliament in Turin in Palazzo Carignano (Plate I) – Scale 1:200

Author: Amedeo Peyron

Publisher: Camilla e Bertolero typography – lithography by N.Bertolero, Turin

Published in: Civil engineering and industrial arts: monthly technical periodical for the development and improvement of practical science and national industries, XXIV, 9, 1898

Description: This technical drawing (Figure 22) represents Palazzo Carignano in two areas, depicting in black the hall of the first Italian Parliament, declared a National Monument, and in red the temporary hall built in 1861. The drawing is in scale 1:200, showing the layout of the stairs and the windows of the parliamentary facade.

Technical Drawing 2

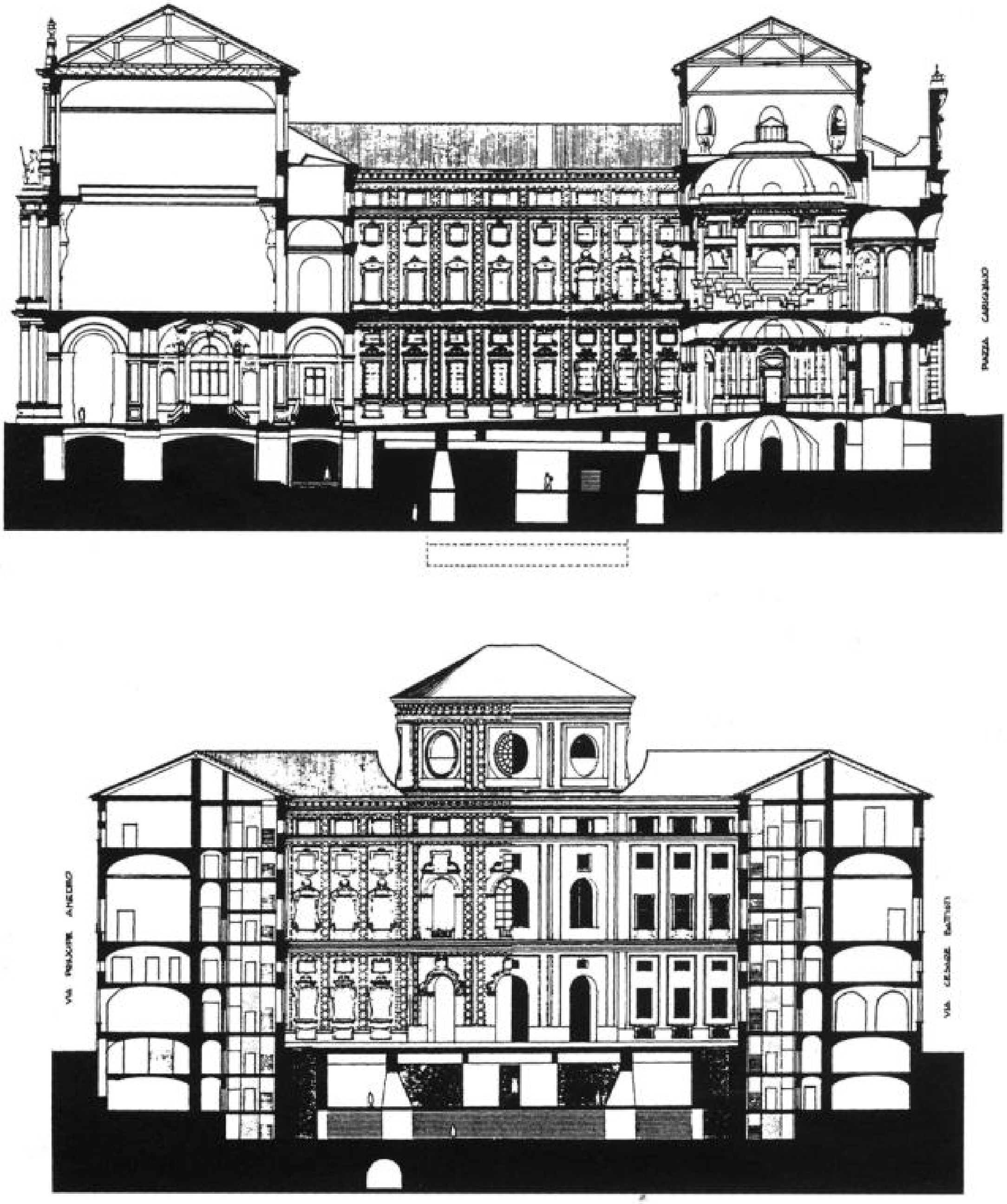


Figure 23. Cross-section and longitudinal section. Imagine from Palazzo Carignano: sezione trasversale e sezione longitudinale. L'edificio è composto da un'ala a “C" seicentesca creata da Guarino Guarini e da um'altra a essa contrapposta ottocentesca, che vanno a creare una corte quadrata.

Title: Palazzo Carignano: cross-section and longitudinal section

Author: A.Bruno, A.I.Studio

Publisher: Maggioli Editore

Published Date: April 15, 2016

Published in: Andrea Bruno Tecniche esecutive e dettagli progettuali Execution techniques and design detai

Description: These two sections (Figure 23), one longitudinal and one cross-section, only two relatively informative cross-sectional drawings have been found so far, even if the quality of the drawing itself does not allow for excellent reading. Through the cross-section, we can get information about the exterior of the Parliament, such as the location and style of the windows. Through the longitudinal section, we can get information about the interior of the Parliament, such as the height of the columns, dome, and stairs. These sections were fundamental for the initial CAD redesign and allowed us to build the3D model of the parliament.

Technical Drawing 3

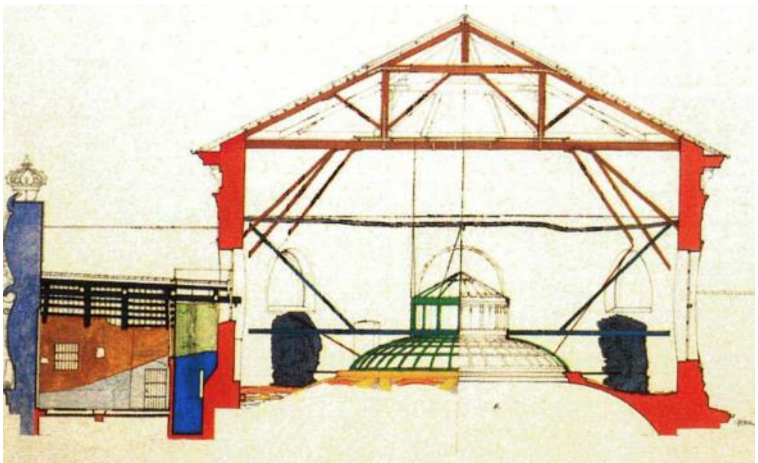


Figure 24. Section of the pavilion. Imagine from sezione del padiglione ellittico. A sinistra il frontone di Ceppi; all'interno le zone scure corrispondonoai resti degli arconi della *seconda volta* di Guarini (rilievo di G. Gritella).

Title: Palazzo Carignano: survey of the wooden roofing carpentry. Cross-section of the elliptical drum and the underlying glass dome

Author: A.Bruno, A.I.Studio

Publisher: Maggioli Editore

Published Date: April 15, 2016

Published in: Andrea Bruno Tecniche esecutive e dettagli progettuali Execution techniques and design detai

Description: Through the cross-section (Figure 24), we can get information about the position and shape of the glass dome. The glass dome is located above the middle of the building. The glass material of the dome allows natural light to enter the interior of the building, which is conducive to natural lighting during the day.

Technical Drawing 4

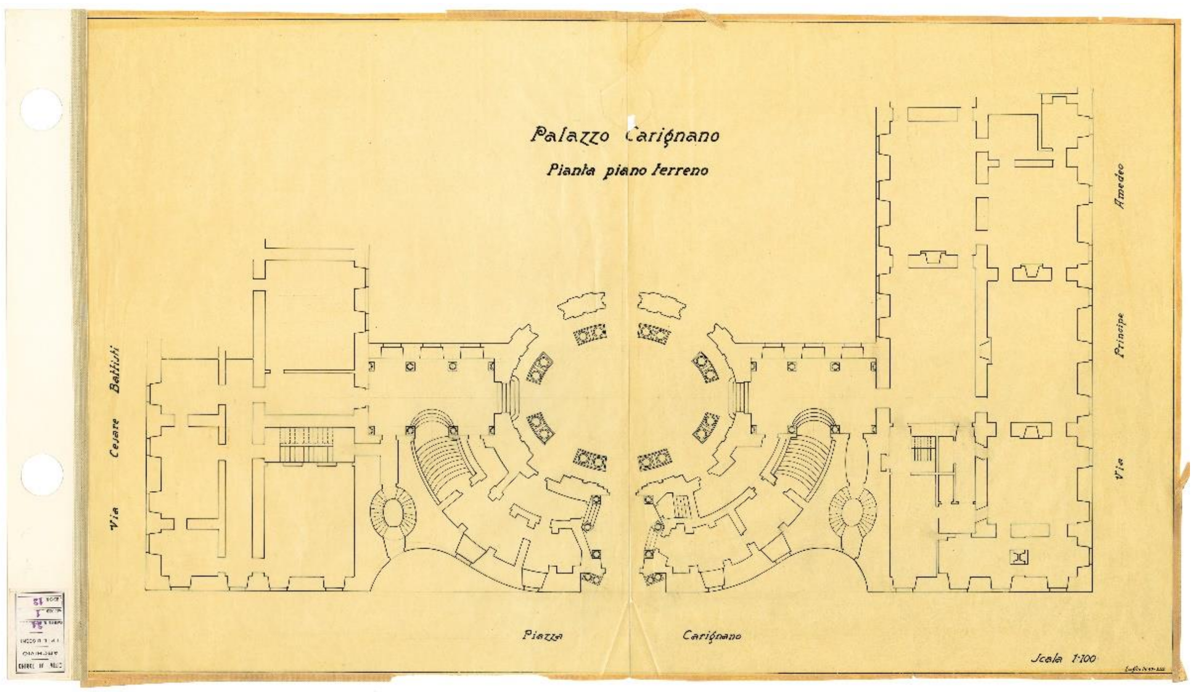


Figure 25. Floor plan 1:100. Imagine from Archivio Storico della Città di Torino

Title: Palazzo Carignano - Ground floor plan - Scale 1:100

Author: /

Publisher: Printed copy

Location: Archivio Storico della Città di Torino

Description: From an initial search on bibliographical material, this is a 1:100 floor plan

(Figure 25) of the Palazzo Carignano, with the wording on the location as "Archivio Storico della Città di Torino". The quality of the drawings is very good and useful elliptical space information can be gathered.

Technical Drawing 5

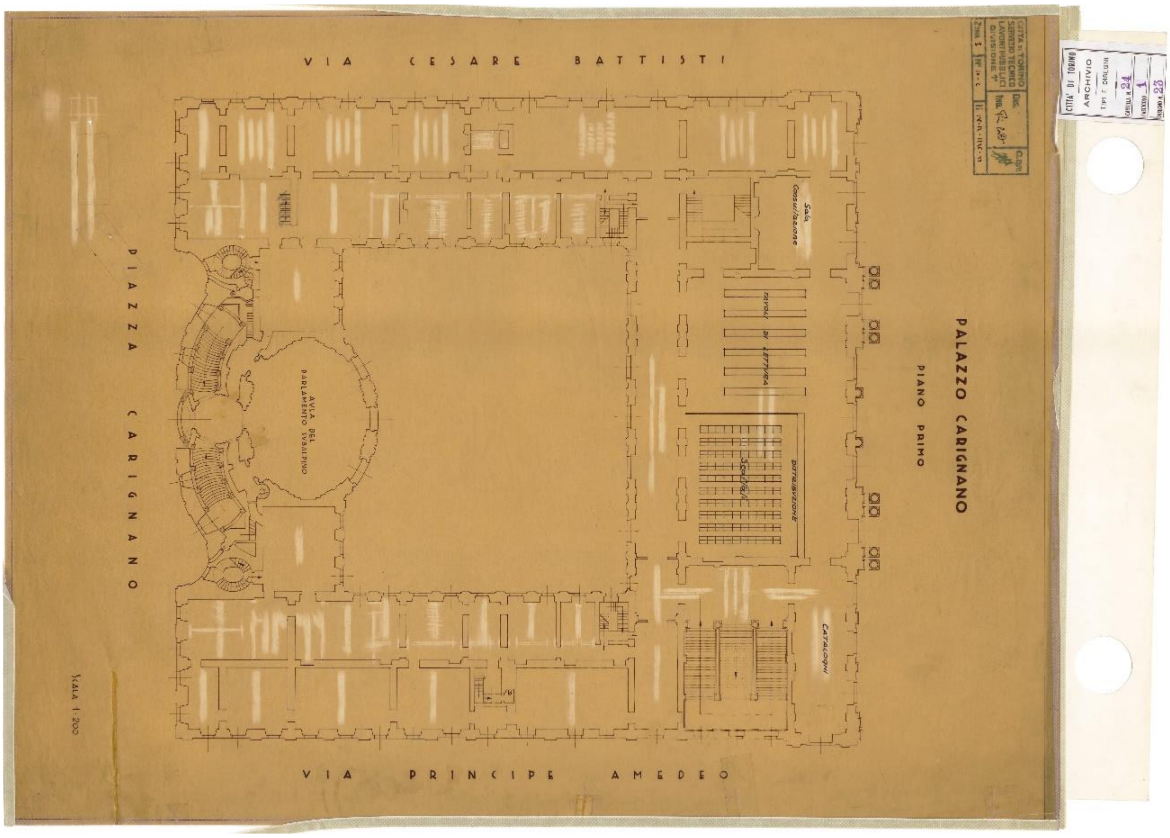


Figure 26. Floor plan 1:200. Imagine from Archivio Storico della Città di Torino

Title: Palazzo Carignano - Ground floor plan - Scale 1:200

Author: /

Publisher: Printed copy

Location: Archivio Storico della Città di Torino

Description: From an initial search on bibliographical material, this is a 1:200 floor plan (Figure 26) of the Palazzo Carignano, with the wording on the location as "Archivio Storico della Città di Torino". The quality of the drawings is very good and useful spatial dimension information can be gathered.

Technical Drawing 6

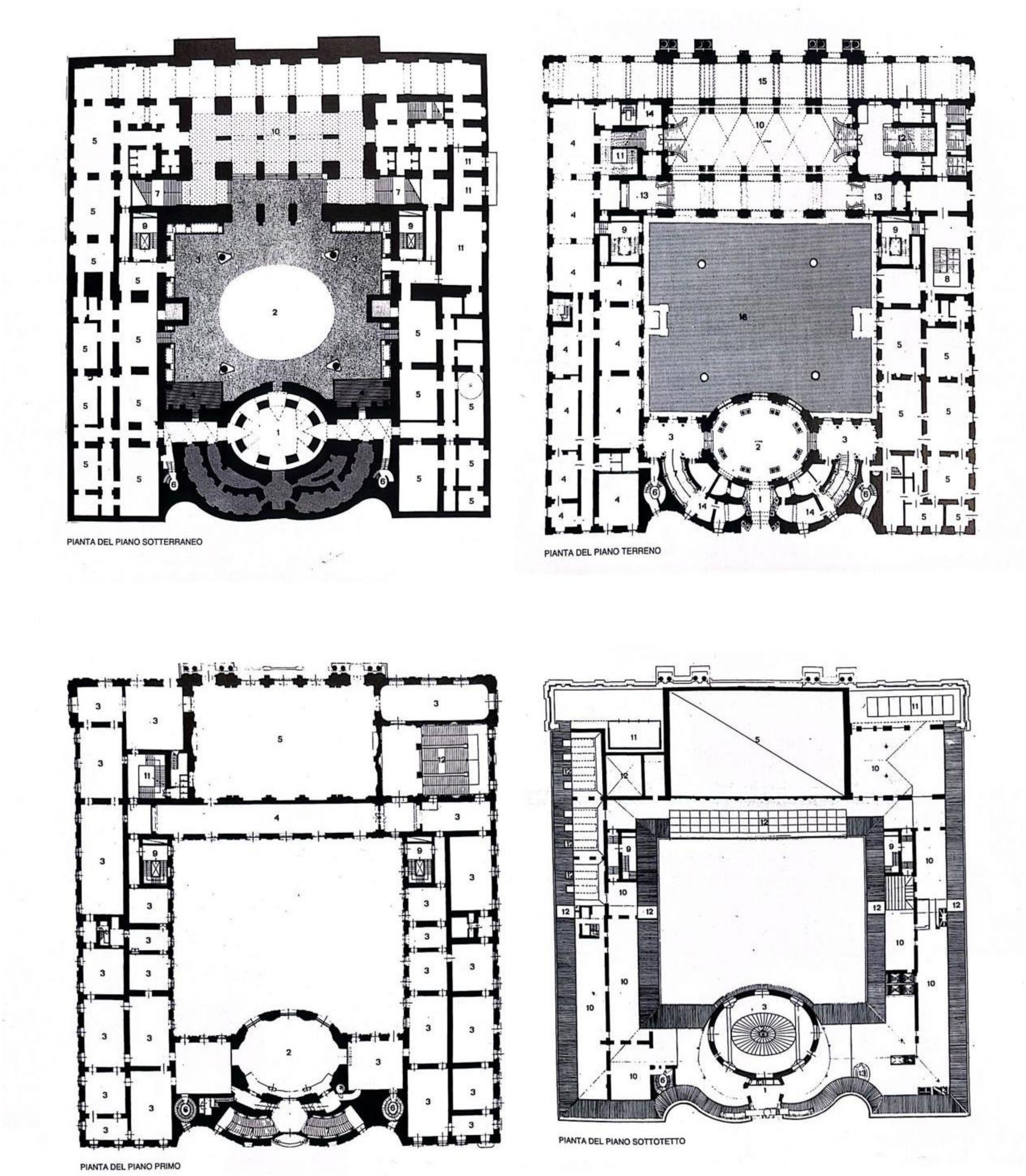


Figure 27. Plans at different levels. Imagine from Progetto 1985 (A, Bruno, A. I. Studio). Piante ai diversi livelli.Il salone sotterraneo al cortile è coperto da un solettone retto da quattro pilastri; un'intercapedine ispezionabile lo isok dalle fondazioni del palazzo.

Title: Project 1985, Plans at different levels

Author: A.Bruno, A.I.Studio

Publisher: Printed copy

Published in: M. G. Cerri, Palazzo Carignano: Tre secoli di idee, progetti e realizzazioni, Torino, Allemandi, 1990, p.242 p.243

Description: These plans (Figure 27) show different heights of the parliament hall, particularly the shape and structure of the ceiling within the hall.

Technical Drawing 7

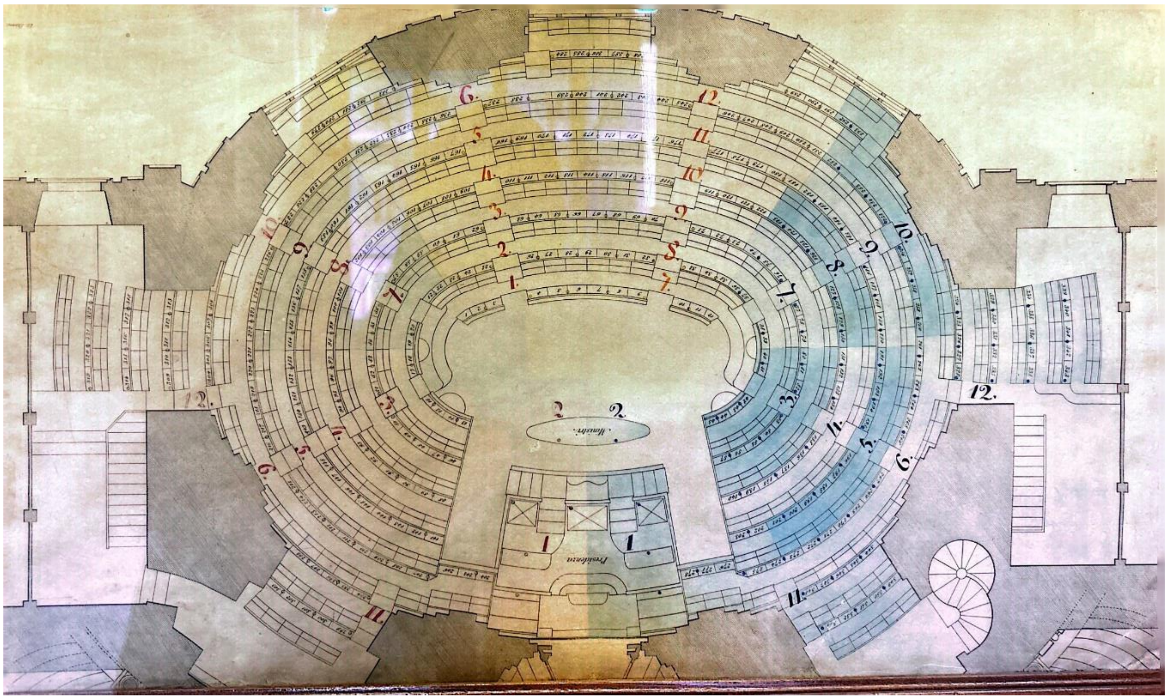


Figure 28. Imagine from Palazzo Carignano, Unione Culturale Antonicelli

Title: Parliament Plan in Palazzo Carignano

Author: /

Published Date: /

Location: Palazzo Carignano, Unione Culturale Antonicelli

Placement: Framed document displayed on the wall along the museum corridors

Description: The plan (Figure 28) of the parliament hall, hung on the wall in the corridors of Palazzo Carignano, is currently the most detailed floor plan available for the parliament hall. It provides extensive details on the architectural layout and seating arrangement. The plan shows the seating layout and the position of windows, which are essential for 3D modeling.

2.4 Data Processing Modelling

Modeling mainly uses Rhino and Revit software. Rhino.Inside.Revit plugin embeds Rhino and Grasshopper into Revit, enables bidirectional data exchange between Revit and Rhino to ensure interoperability. Grasshopper is Rhino's parametric design environment, providing a visual scripting interface for algorithmic modeling, data management, and workflow automation. Three steps to build the model：

Step 1: Import the Revit model into Rhino through Rhino.Inside.Revit to ensure the Parliament Hall remains in the same position in both Rhino and Revit.

Step 2: In Rhino, unroll the elliptical outer wall. The UnrollSurface command flattens (or develops) a surface or polysurface with curvature in one direction to a planar surface; Use FlowAlongSurface to “flow” the model from a planar surface onto a curved surface, while maintaining its proportions.

Step 3: Rhino.Inside.Revit enables seamless geometry transfer Rhino to Revit, preserving Rhino’s modeling precision and benefiting from Revit’s BIM environment.

To implement step 1, Rhino and Revit must ensure unit consistency. The existing Revit model of the Palazzo Carignano shows (Figure 29): the parliament has an elliptical floor plan of 2160 cm x 1600 cm, with walls 170 cm thick. The template in Revit is set to centimeters, so the template in Rhino should also be in centimeter. The steps to import the model into Rhino are as follows:

- Select required Revit elements to export

  Select elements: Walls, Floors, Roofs, Stairs, Generic Models（In Revit model, the roof of parliament is defined as Generic Models)

- Extract geometry, and other necessary information for each Revit element (Figure 30)
- Bake the geometry and information into Rhino (Figure 31)

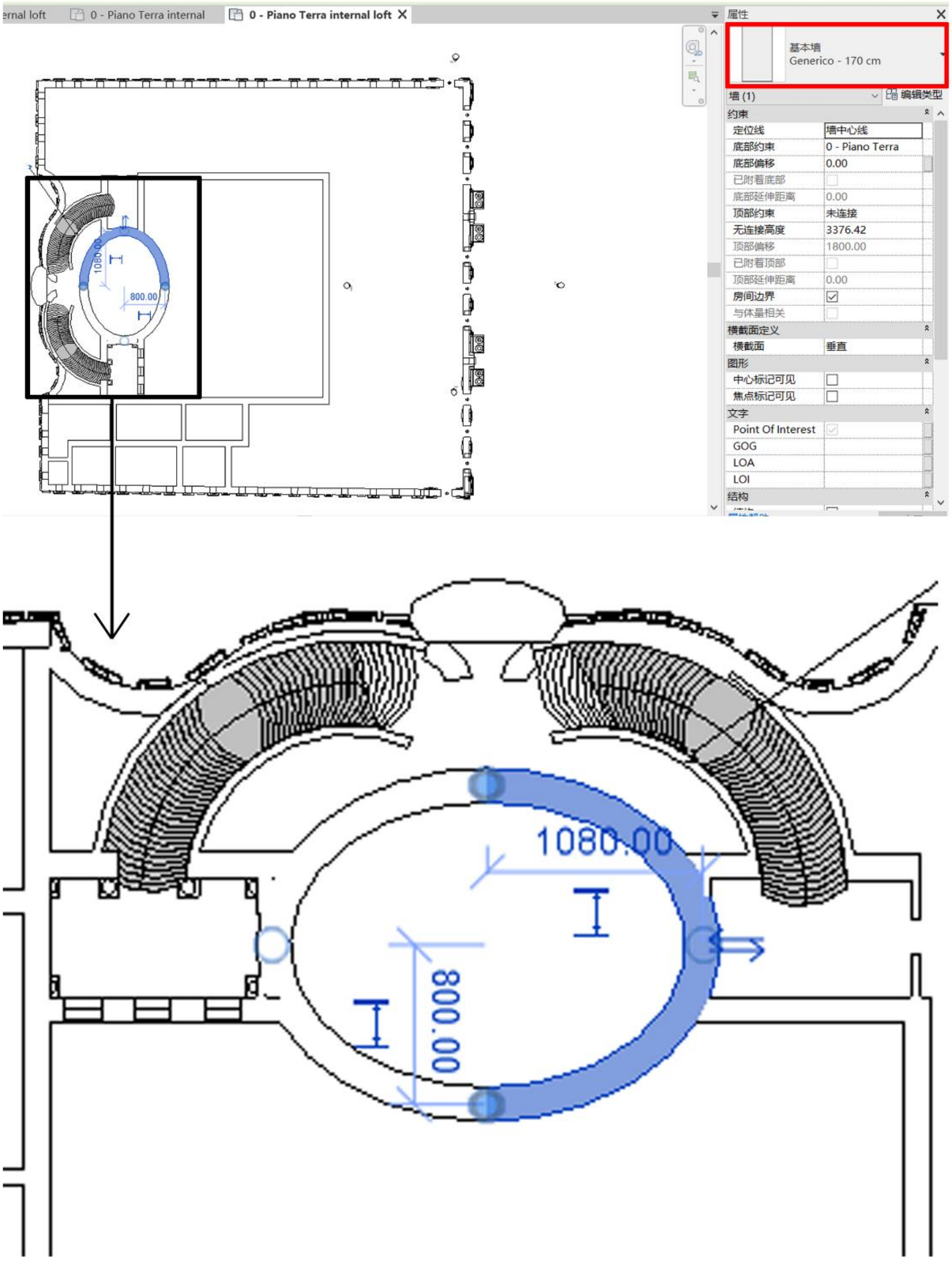


Figure 29. The floor plan dimensions of the parliament in Revit

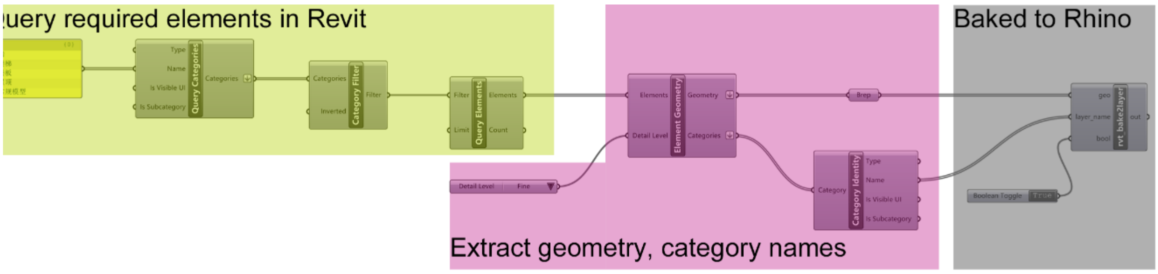


Figure 30. The grasshopper components to import the model from Revit into Rhino

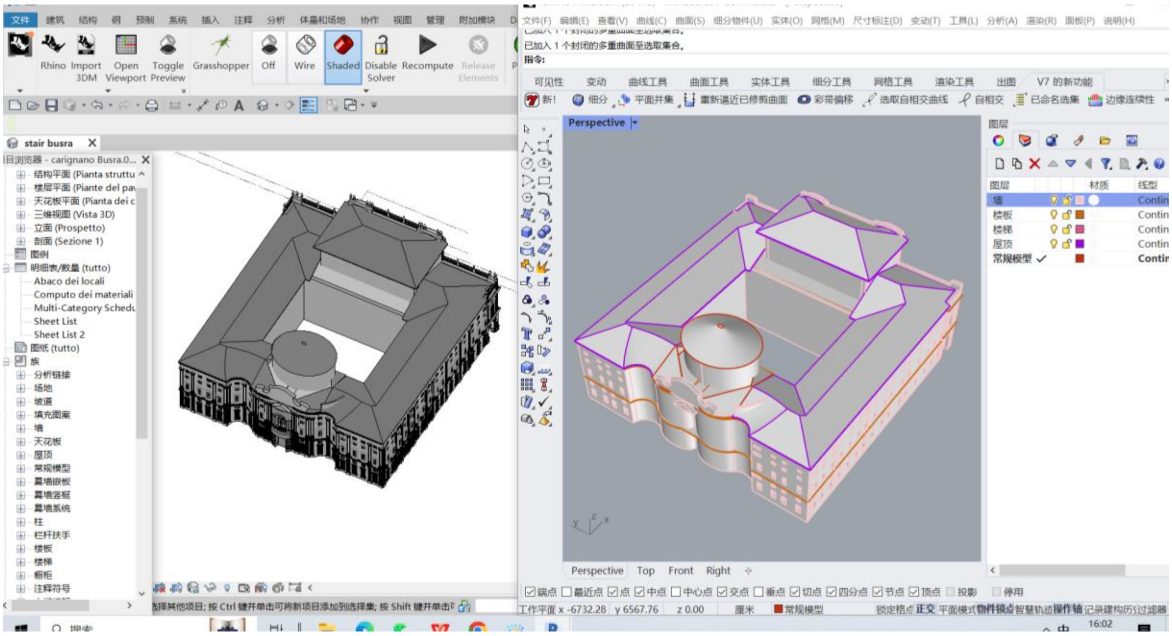


Figure 31. Model in Revit and Rhino

Step 2 is to create a surface model in Rhino. The unroll command in Rhino can convert complex surface modeling to planar modeling. According to the data currently collected by the Parliament Hall, only the plan and section drawings can be used for modeling. Therefore, Rhino is selected to build the 3D model. Tracing electronic versions of drawings into CAD drawings is the foundation of modeling (Figure 32, Figure 33).

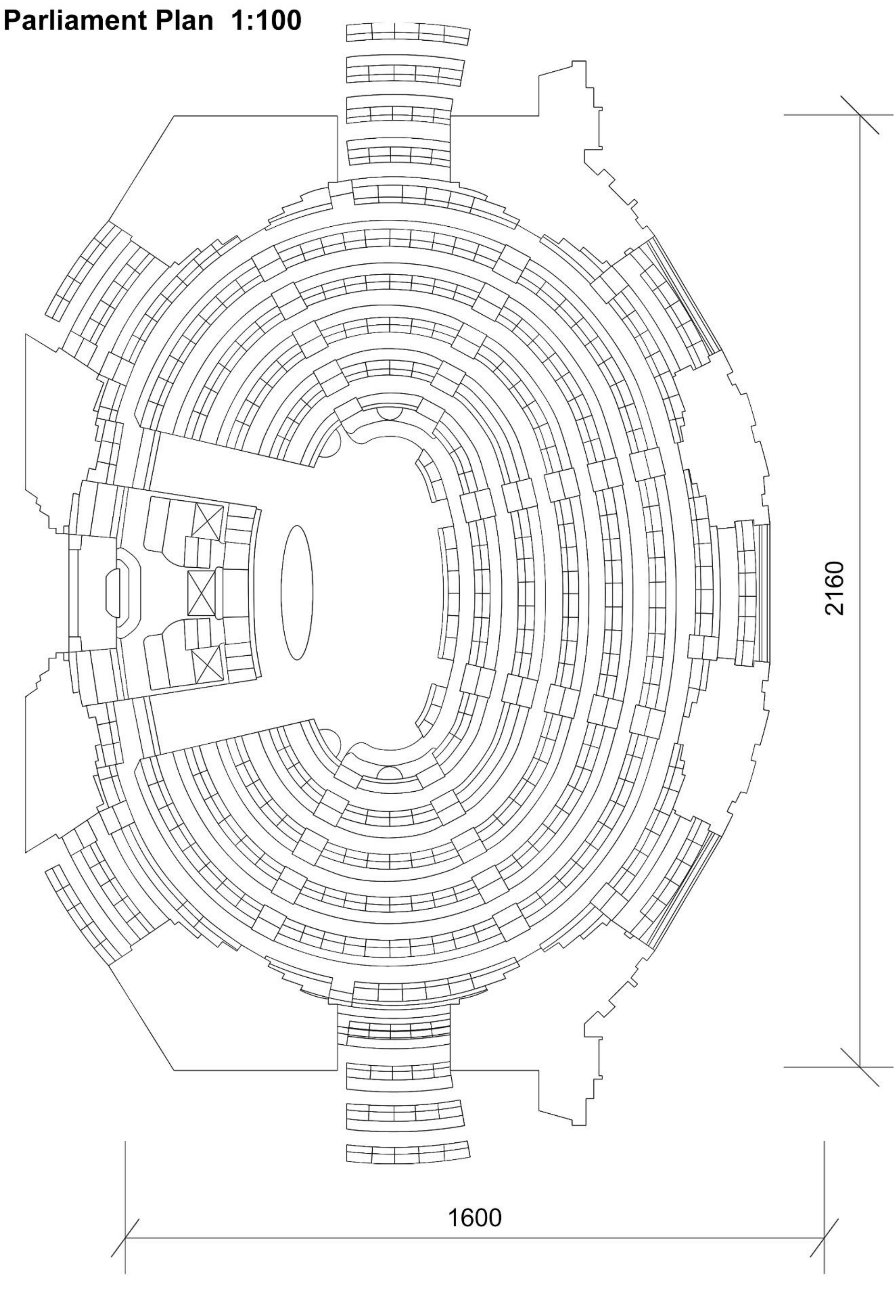


Figure 32. The parliament hall plan 1:100

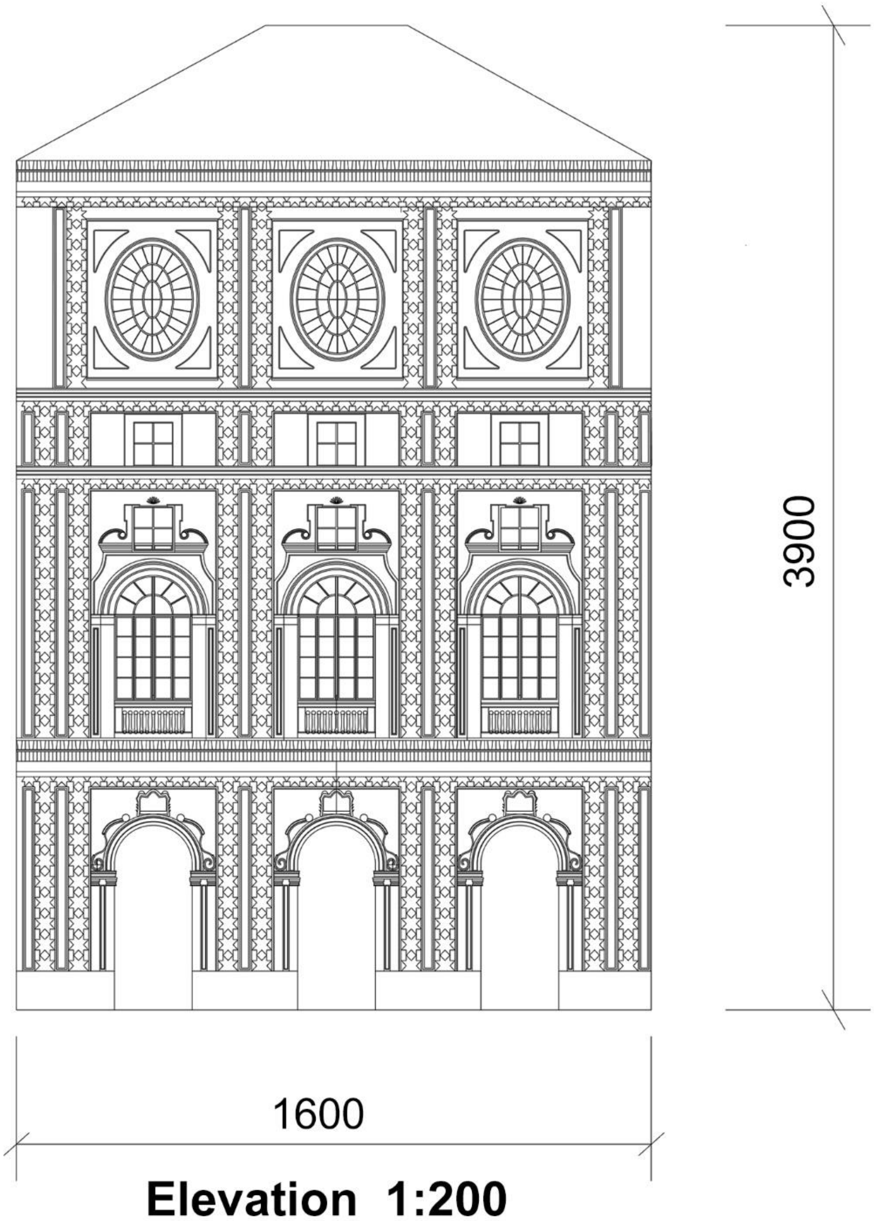


Figure 33. Elevation 1:200

Use UnrollSrf in Rhino to convert complex surface modeling to planar modeling: In Rhino, create a surface based on the wall's centerline, then use the UnrollSrf command to unroll the surface. The unrolled surface marks in red (Figure 34). The elements that make up the parliament hall are unique. Based on the elevation, the section view not only determines the height of the floor, dome, and windows of the parliament hall, but also the details of the decoration (Figure 35). When using UnrollSrf in Rhino, keep the following points in mind:

- Surface Type: UnrollSrf works best with single surfaces or polysurfaces that have curvature in only one direction. Complex curved surfaces, like double-curved or highly twisted shapes, may not unroll accurately.
- Surface Integrity: Make sure the surface has no gaps or irregularities, as these can lead to distortions in the unrolled result.
- Orientation and Scale: Verify that the unrolled surface retains the correct proportions and alignment with the original. You may need to adjust or scale the output slightly to ensure it matches your design need.
- Result Verification: Always check the unrolled result to ensure that it's flat and aligns correctly with your intended design dimensions.

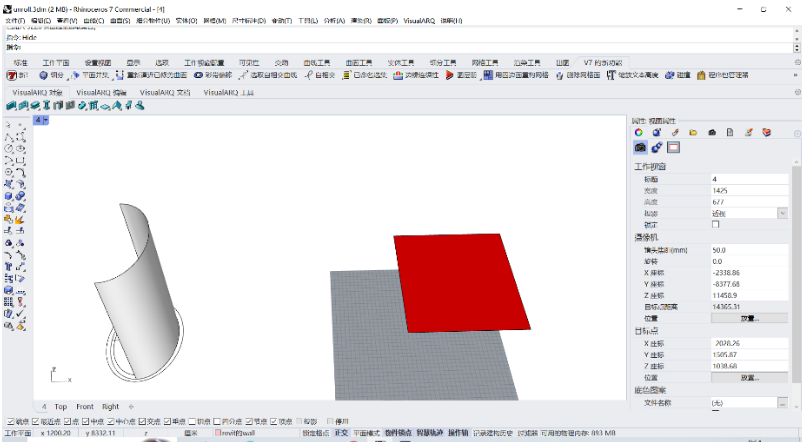


Figure 34. Unroll surface

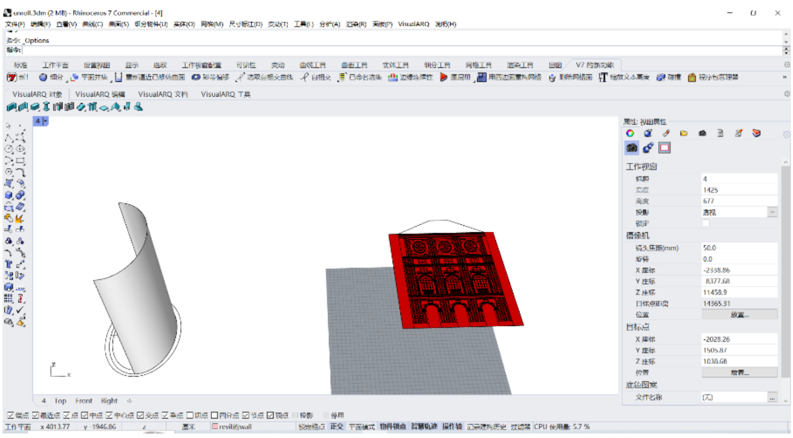


Figure 35. Details of the facade in the Unroll surface

Build a 3D facade model (Figure 36) and flow it to the surface (Figure 37). When using flow in Rhino, keep the following points in mind:

- Base and Target Surface Compatibility: Ensure the base and target surfaces have similar structures and are roughly the same size and proportion. Significant differences in shape or proportion can lead to distortions.
- Orientation: Pay close attention to the orientation of both surfaces. Make sure the base surface and target surface are aligned properly so that the geometry flows in the intended direction. Use the Dir command to adjust surface directions if needed.
- Surface Matching: It's helpful if both surfaces are UV-matched, meaning the direction and structure of the surfaces' UV coordinates align. This ensures smoother transformations without unexpected twists.
- Scale Factor: Choose the correct scale option (either "Rigid" or "Stretch"). Rigid preserves the original proportions of the geometry, while Stretch scales it to fit the target surface.
- Complex Shapes: FlowAlongSrf works best on geometry with moderate complexity. Highly intricate models may lose detail or suffer from distortion. For these cases, simplify or subdivide the geometry before flowing it onto the target surface.
- Testing: Always test the command on a copy of your geometry first to verify the result. This allows you to adjust settings without altering the original model.

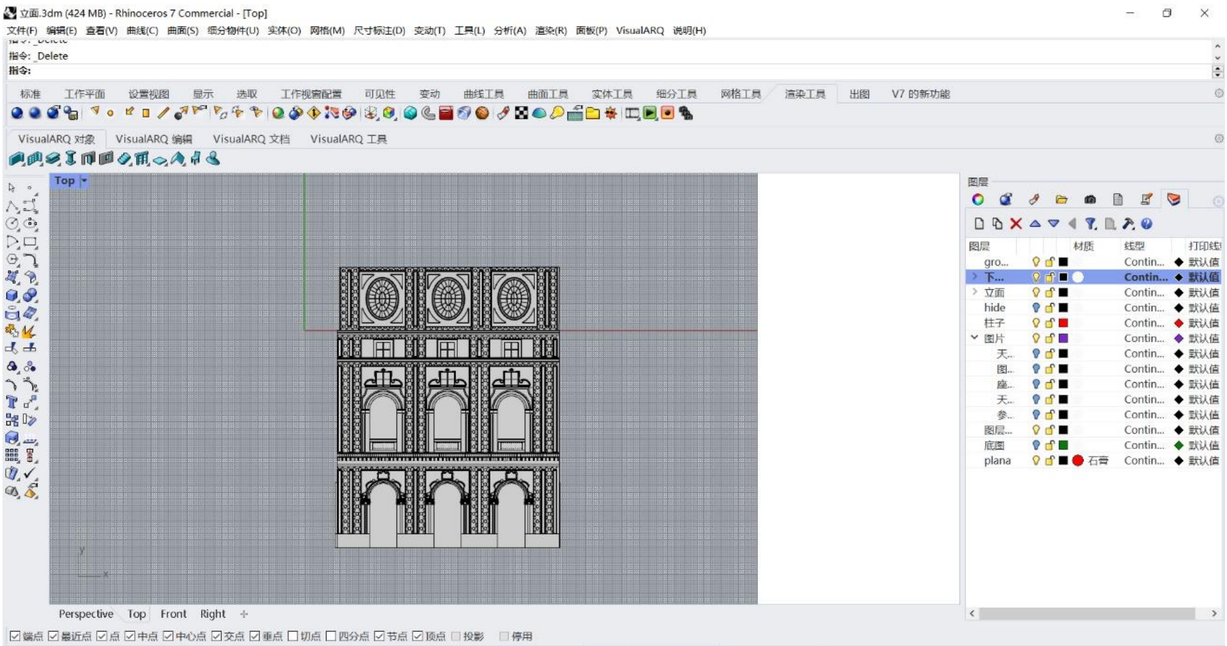


Figure 36. 3D facade model

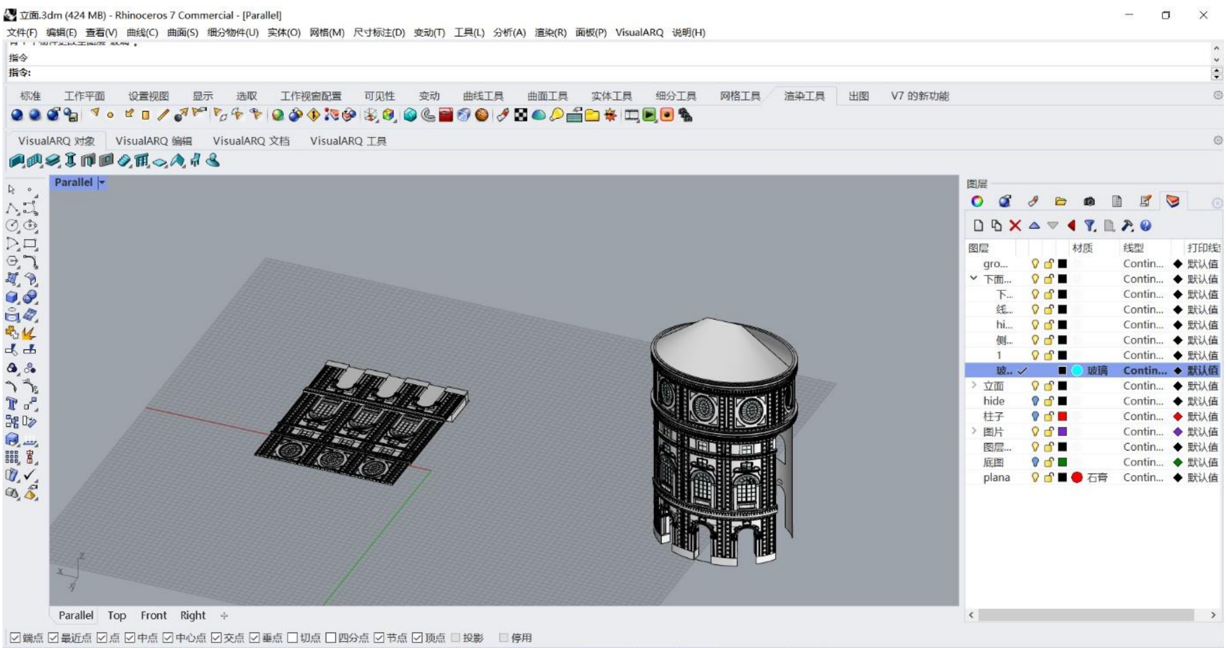


Figure 37. FlowAlongSurface

Step 3 is to transfer Rhino to Revit using Rhino.Inside.Revit. In Revit the architectural model represents the physical structure of the building, and is created through the use of categories, instances and families.

Categories are the highest level of organization in Revit and are predefined and uneditable. They are divided into Model Categories (e.g., walls, floors, doors, windows) and

Annotation Categories (e.g., dimensions, tags, text). Categories determine the general behavior and appearance of elements in Revit.

To provide more specific definitions for elements and their characteristics, the hierarchy introduces the next level: Families**.** Similar to how all elements are grouped by Category, each element also belongs to a specific Family. A Family consists of similar items that share a common appearance and behavior, such as the "Basic Wall" family, "Double Door" family. Unlike the broader scope of Categories, Families offer a more detailed structure, organizing elements into finer divisions. There are three main types of Families:

- **System Families**: These families are predefined in Revit. You don't load them from external files into the project, nor do you save them to a location outside the project.
- **Loadable Families**: These families are created in external RFA files and imported or loaded into the project.
- **In-Place Families**: In-place elements are unique elements you create when you need a component that is specific to the current project.

Families are further divided into Types and Instances. A Type is a specific version of a Family with defined parameters (e.g., a "Single Door - 90cm x 210cm" type within a door family). An Instance is an individual placement of a Type in the model, which can be customized without affecting other instances.

The modeling of the Parliament Hall uses two methods working with Rhino.Inside.Revit :

① **Using Rhino Geometry to Generate Native Revit Elements:** Rhino.Inside.Revit allows you to transform Rhino geometry directly into native Revit elements, like walls, floors, and other model components. Advantages of native elements include:

- Great integration in the project BIM schema including maximum graphic control, dynamic built-in parameter values and all access to all common project standard BIM parameters as any native elements would have.

- Elements can be edited even when Rhino.Inside.Revit is not available. The elements may have dimensions attached to them. The elements may be used to host other elements.
- Many Revit users downstream may not realize these elements were created with Rhino.Inside.Revit.

② **Developing Loadable Families with Subcategories:** This approach is often used in Rhino.Inside.Revit for creating Revit elements based on custom Rhino geometry. By using Rhino to design standalone components or items that will be built independently (e.g.custom windows, doors, or furniture), you can then import them as Loadable Families with Subcategories in Revit. Advantages of wrapping Rhino geometry inside Loadable Families include:

- Repeated objects can be inserted multiple times allowing forms to be scheduled and counted correctly.
- Forms in loadable families can be edited by Revit if needed.
- Forms placed inside Family/Types can be placed in subcategories for further graphics control and scheduling.

For the parliament 3D model, the wall, floor and window use Rhino Geometry to Generate Native Revit Elements

(1) Add Wall (Curve): This component is used to generate walls in Revit based on the curves provided (Figure 38, Figure 39).

Curve: Defines the curve used to create the wall.

Type: Specifies the wall type.

Level: Defines the level or story for the wall placement.

Height: Sets the wall height.

LocationLine: Controls the location of the wall line relative to the curve.

Flipped: Determines if the wall orientation is flipped.

AllowJoins: Indicates whether the wall can join with other walls.

StructuralUsage: Sets the structural usage of the wall (if applicable)

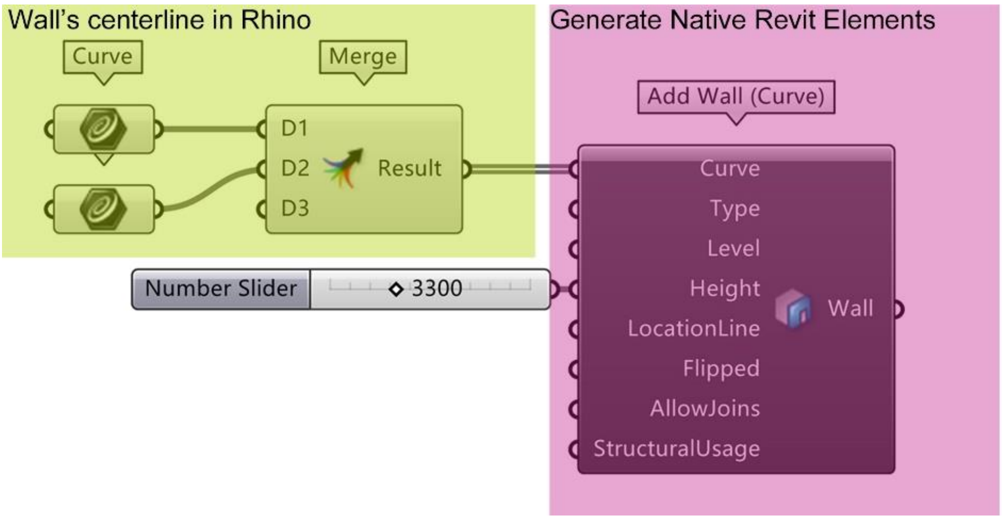


Figure 38. The grasshopper components to generate walls in Revit

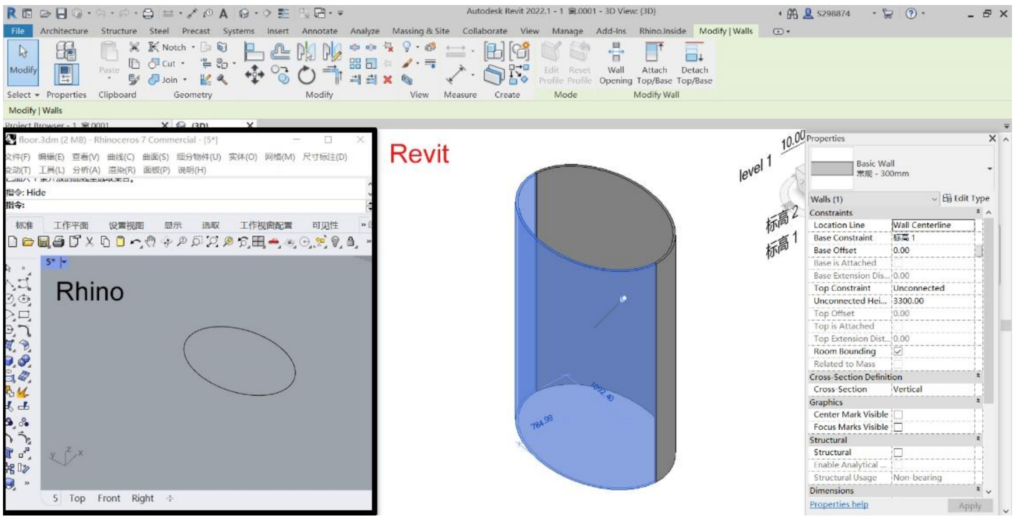


Figure 39. Generate native Revit element: Wall

(2) Add Floor: This component generates a floor element in Revit, using the input curve and level data to create the floor within the Revit model (Figure 40, Figure 41).

Curve: Represents the curve that defines the edge of the floor in Rhino.

Elevation (Number Slider): A slider to adjust the elevation value, set at 1000 here, which affects the placement height.

Add Level: Used to create a new level in Revit with specific elevation and name parameters.

Move To Plane: Aligns or relocates geometry to a defined plane.

Toggle: A boolean toggle switch, which might control the execution of the floor creation process.

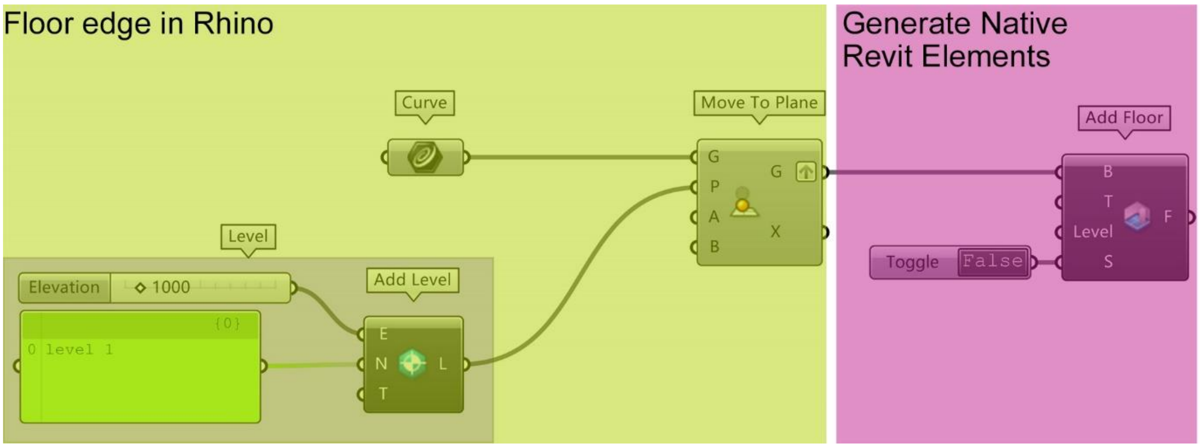


Figure 40. The grasshopper components to generate floor in Revit

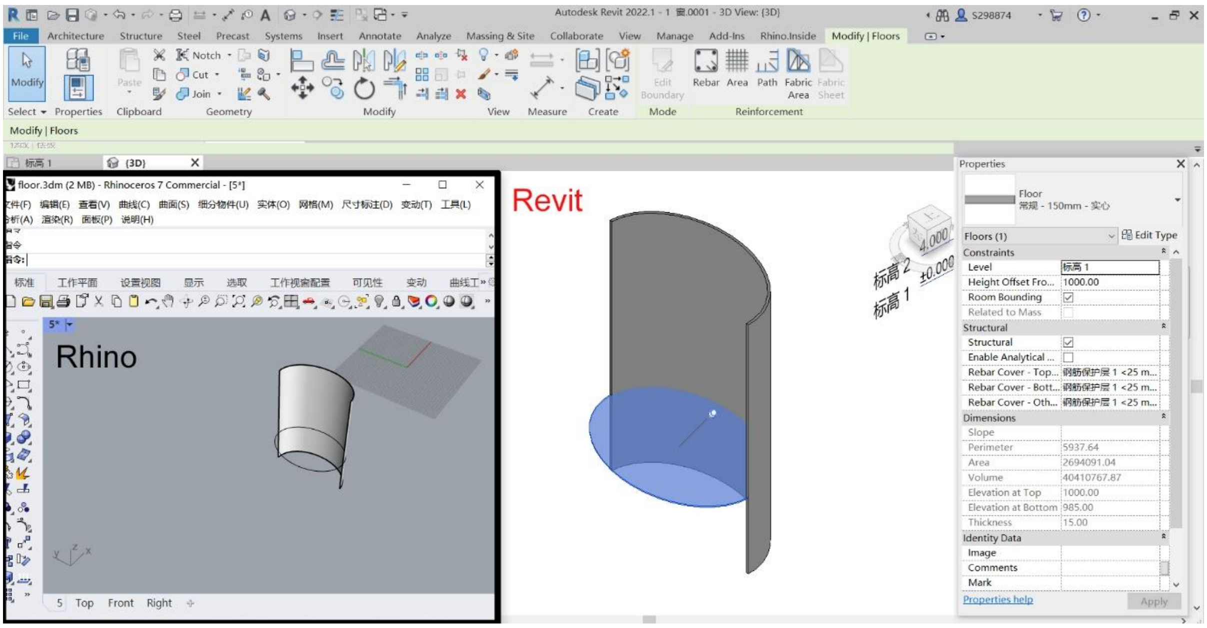


Figure 41. Generate native Revit element: Floor

(3) Add Window

As a historical museum, the windows have unique characteristics. Based on the floor plan and field research, a window family (RFA file) was created:

- Open the Family Editor: In Revit, select "New Family" and choose an appropriate family template, the "Metric Window".
- Draw the Geometry: Use tools like Extrusion, Revolve, and Sweep in the Family Editor to draw the specific shape of the window.
- Add Constraints and Dimensional Parameters: By adding dimensions and parameters (such as height, width, and depth), the window family can have adjustable dimensions in the model to fit different window sizes or design needs.
- Set Material: Define material parameters for the window family to ensure that it matches the windows in the Council Hall.

Load the Family into the Project: After finishing the window family, click "Load into Project" to import it into the project model (Figure 42).

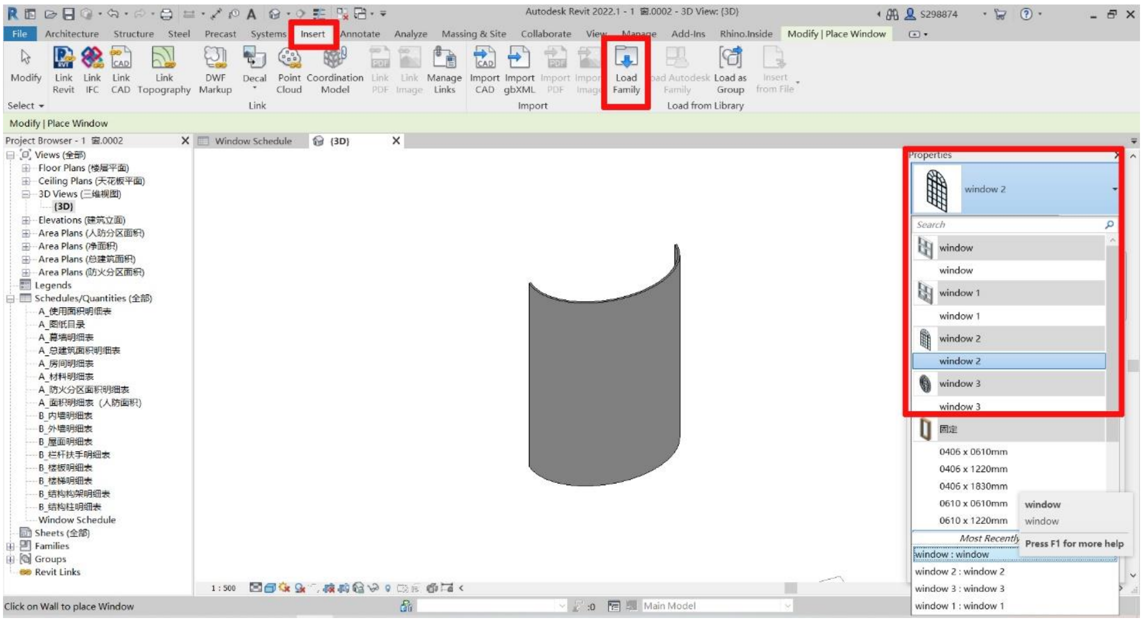


Figure 42. Load the window family into the project

Add Component (Location): a component used to add Revit elements at specified locations, allowing the insertion of designated Revit families (such as windows, doors, etc.). It enables precise control over window placement, especially when windows need to be arranged on non-flat surfaces. This component helps ensure the correct position and orientation of the windows. First, the Add Component (Location) requires a location parameter to specify location. This parameter is typically a point or a plane (such as the normal plane of a wall), which defines the insertion point of the window in the model (Figure 43); The family selection is by importing a Revit window family file (RFA file), you can load the window component into the Add Component (Location). This ensures that the type and dimensions of the window added to Revit meet design requirements (Figure 44).

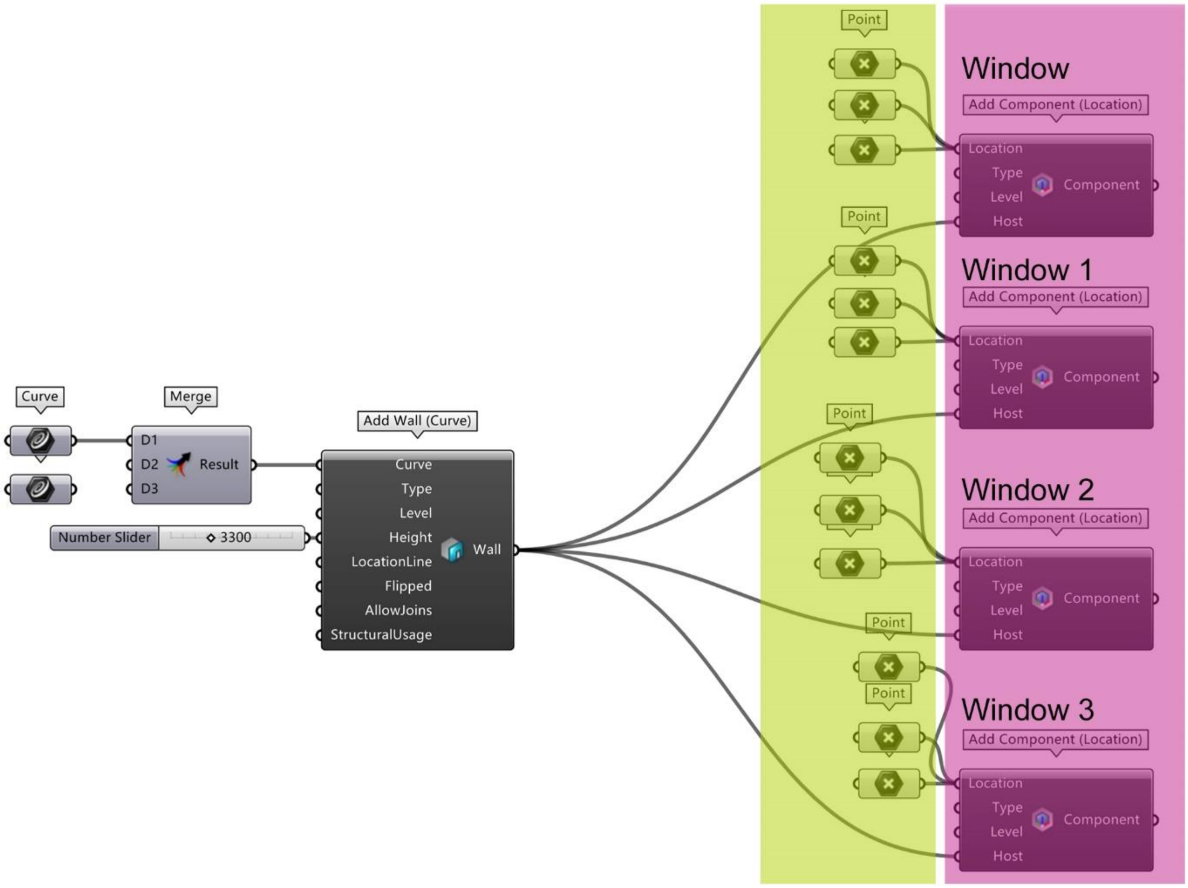


Figure 43. The grasshopper components to generate windows in Revit

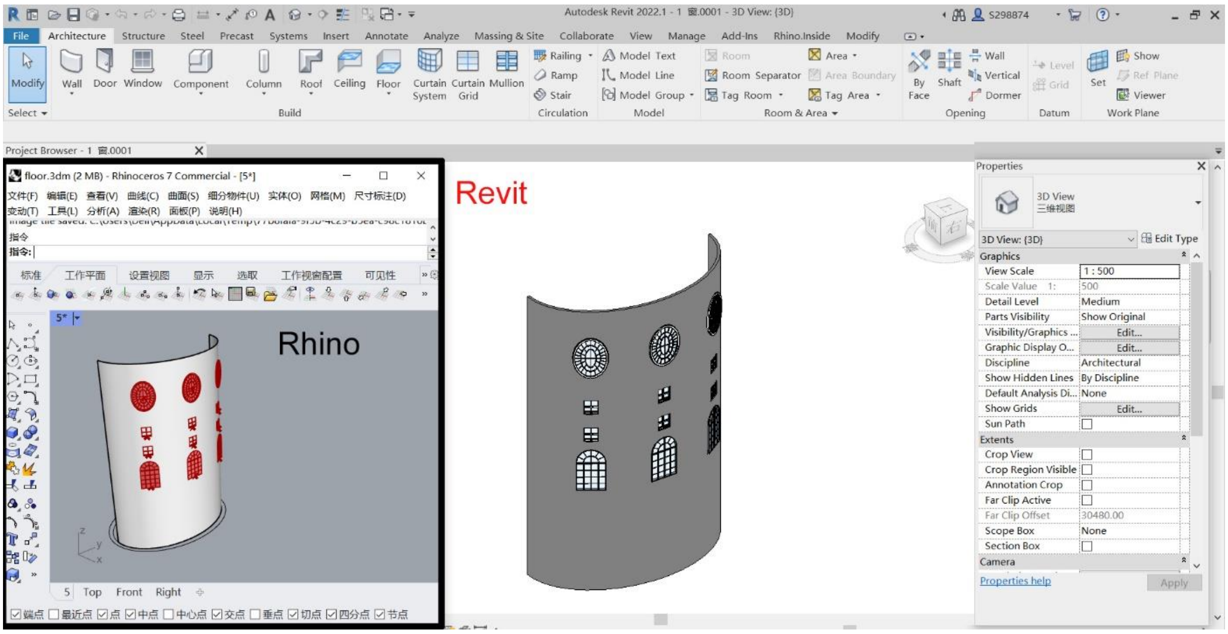


Figure 44. Generate native Revit element: Windows

For the parliament 3D model, the columns, furniture, stairs, decorations develop Loadable Families with Subcategories. Using Subcategory in Rhino.Inside.Revit is because the Categories in Revit are system-defined and cannot be customized or edited. Therefore, to have more precise control over the properties of imported geometry (such as line style, color, material, etc.), it is often necessary to use subcategories.

(1) **Add Column**: In Revit, the "Column" is a system-defined element. It is part of Revit's built-in categories and cannot be customized or modified in terms of its fundamental properties or structure. To locate the column family file in Revit for use as a template in the "Add New Component" process, follow these steps:

- Locate the Revit Family Files: Revit families, including columns, are typically stored in the default family template folder. The way to find the path (Figure 45).

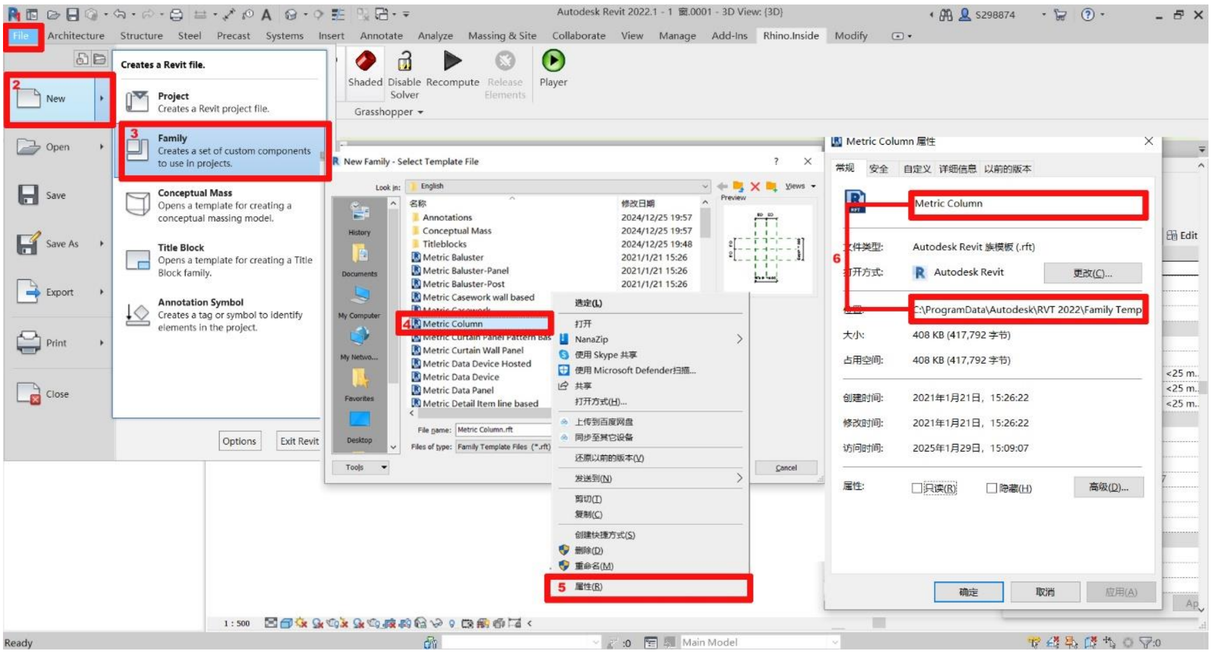


Figure 45. Find Family Template

- Use the Family in Rhino.Inside.Revit: Once located the family, use it as a template to add new components within Rhino.Inside.Revit by referencing the family file path when using the Add Component component in Grasshopper (Figure 46, Figure 47).

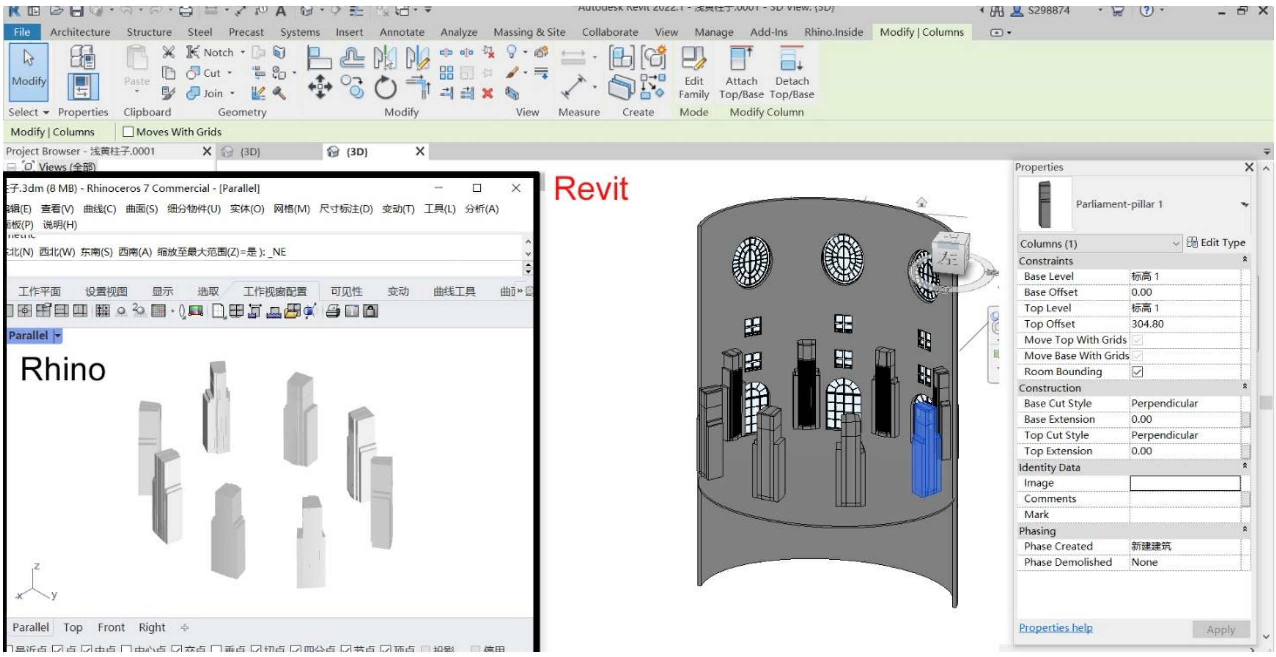


Figure 46. Develop loadable families with subcategories: Column

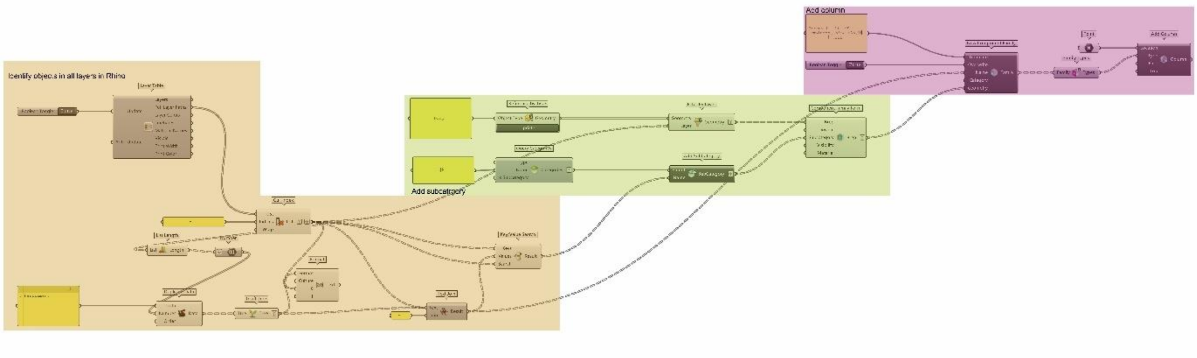


Figure 47. The grasshopper components to develop Subcategories: Column

(2) Add Furniture (Figure 48, Figure 49)

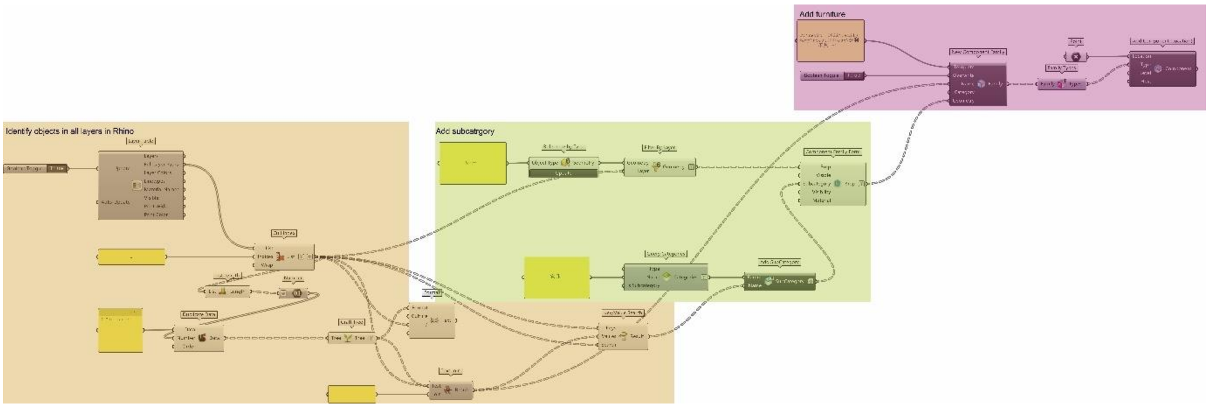


Figure 48. The grasshopper components to develop Subcategories: Furniture

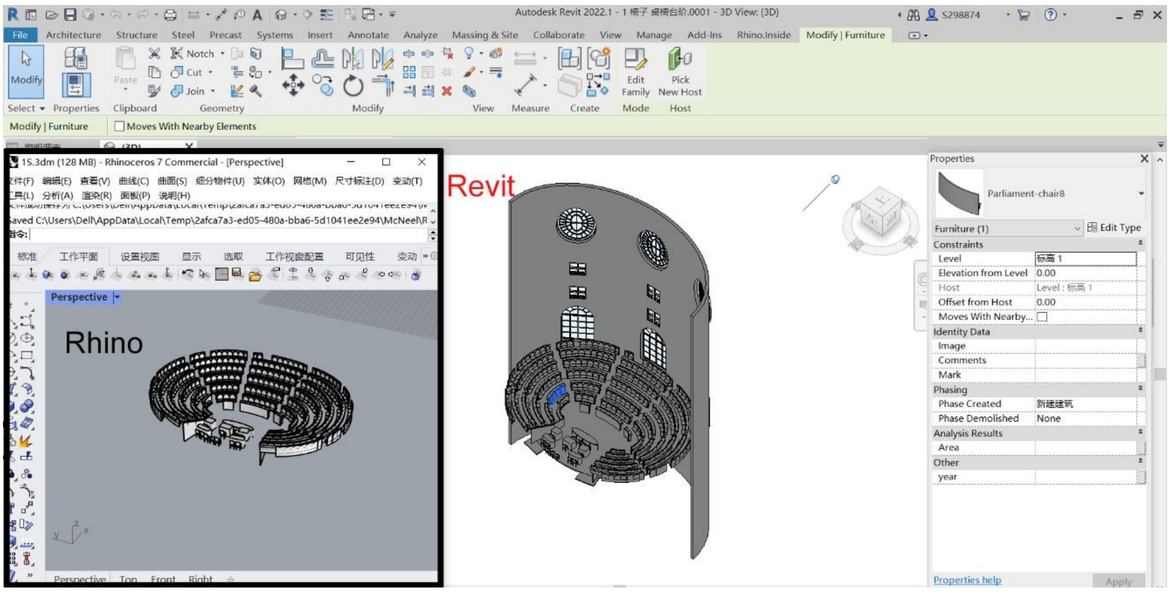


Figure 49. Develop loadable families with subcategories: Furniture

(3) Add Generic Models

The parliament hall features numerous decorative elements, both on the exterior facade and within the interior. The template for decorative elements is selected as Generic Models (Figure 50, Figure 51).

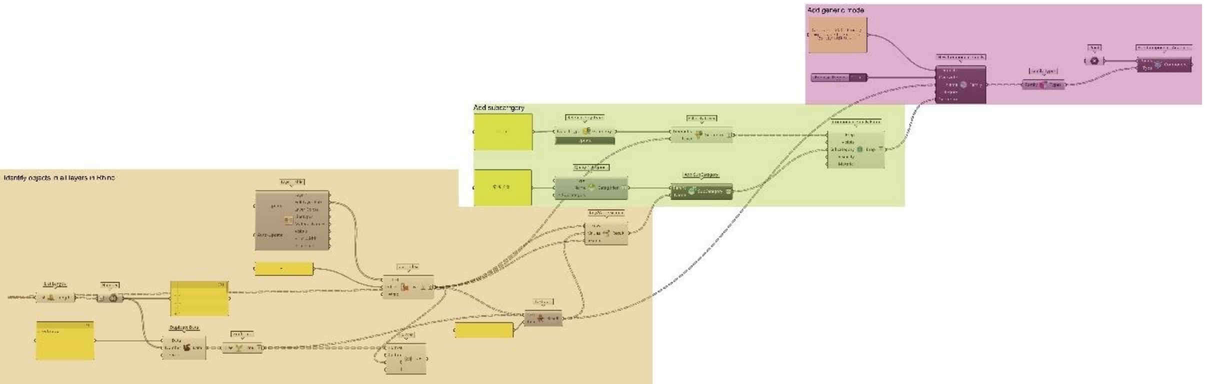


Figure 50. Develop loadable families with subcategories: Generic Models for decoration

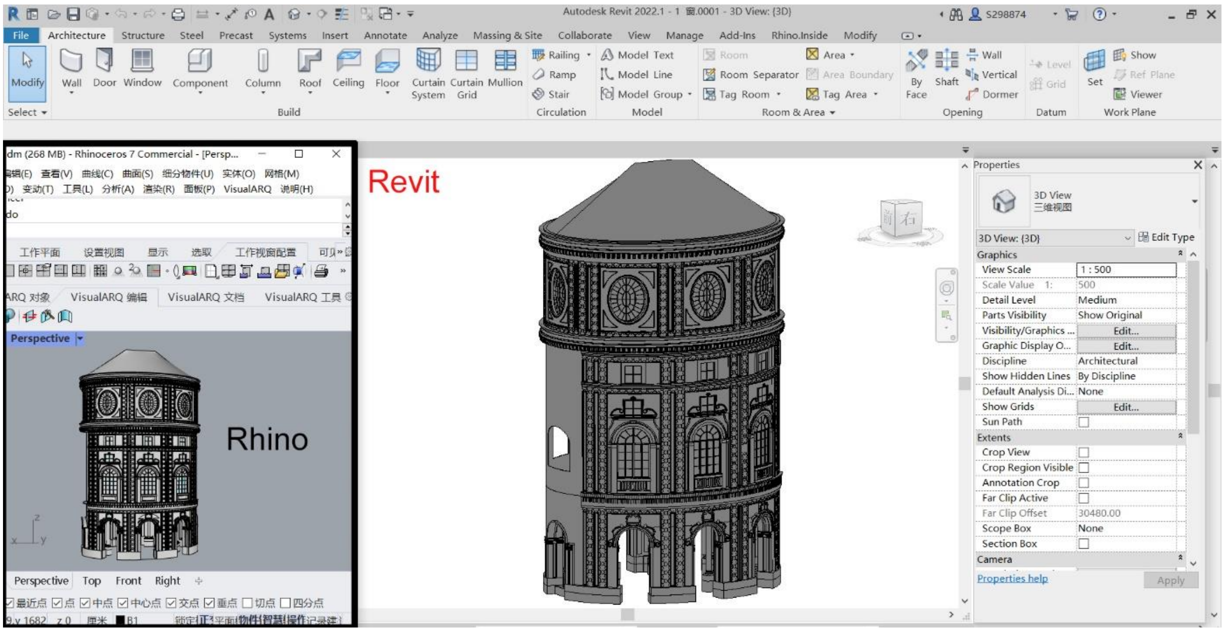


Figure 51. Develop loadable families with subcategories: Generic Models for decoration

2.5 Addition of Information Layers

HBIM is a specialized application of BIM that focuses on the conservation, management, and documentation of heritage and historic buildings. Unlike conventional BIM, which is typically used for new construction, HBIM integrates historical research, preservation data, and specialized modeling techniques to document and digitally reconstruct historic structures.

HBIM is used to record and store detailed historical information about heritage buildings, often capturing their current state, including damages, materials, and unique architectural features. The historical information for the parliament hall is mainly from two books: *Il parlamento subalpino in Palazzo Carignano: strutture e restauro, Palazzo Carignano* and *Tre secoli di idee, progetti e realizzazioni*.

To incorporate historical information into a schedule in Revit, begin by navigating to the Manage tab and selecting Project Parameters. In the Project Parameters window, click Add to create a new parameter. Assign an appropriate name (e.g., "Author," "Installation Time," or "Description") and set the discipline to "Common." Choose the parameter type as either "Text" for descriptive information or "Number" for numerical data, depending on the type of information being added. Organize the parameter under a relevant group, such as "Text" or "Other," and specify the applicable categories, such as "Generic Models" or other relevant object types. Once the parameter is created, navigate to the desired schedule under Schedules/Quantities in the Project Browser. Add the newly created parameter to the schedule's fields and input the corresponding historical information, including text-based descriptions or numerical data, ensuring detailed and structured documentation within the Revit model.

For example, through a literature review, historical information about the portrait of King Vittorio Emanuele II hanging on the wall (Figure 52) can be documented. The historical information, such as the author, installation time, and a concise description of the king's life—highlighting his pivotal role in unifying Italy—can be systematically integrated into the Revit schedule (Figure 53). This process enriches the HBIM model with cultural and historical context, enhancing its value for heritage documentation. Additionally, it supports VR integration workflows, enabling immersive exploration and deeper engagement with the cultural narrative.

Figure 52. The portrait of King Vittorio Emanuele II hanging on the wall

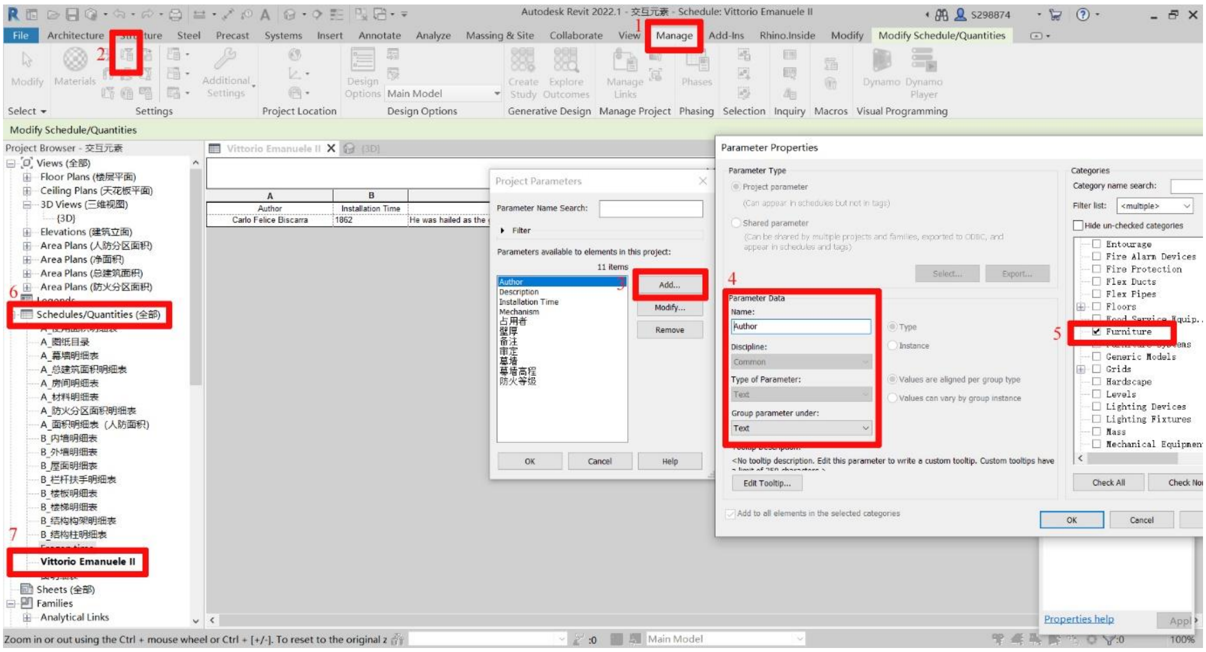


Figure 53. Revit schedule

The modeling phase concluded with the creation of a detailed 3D representation of the Parliament Hall in Palazzo Carignano, achieved solely through existing technical drawings in the absence of advanced scanning technologies. Rhino was employed for its advanced surface modeling capabilities to address the complex curved geometry of the hall, while Revit served as the primary platform for integrating structural and historical data. Utilizing Rhino.Inside.Revit, the workflow seamlessly combined Rhino’s precision in surface modeling with Revit’s robust BIM functionality, enabling the incorporation of critical historical information, directly into the model's schedules.

The next phase involves visualizing this enriched information within an interactive and immersive environment. By exporting the HBIM model data to VR platforms, the workflow aims to allow users to explore the historical and architectural significance of the hall in real-time.

2.6 Twinmotion

Unity and Twinmotion are both widely used for architectural visualization and virtual reality (VR), but they differ significantly in functionality and application, particularly in VR development. Twinmotion is user-friendly and allows for quick and easy VR experiences. With intuitive controls and real-time rendering, users can efficiently create VR presentations of architectural designs or scenes. However, its interactivity is limited, making it suitable for producing straightforward, showcase-style VR projects, such as architectural walkthroughs. Unity is more complex but offers complete customization of UI, interaction logic, and scenes. As a powerful game engine, it supports game development, interactive experiences, VR, and AR applications. Unity provides high flexibility and scalability, making it ideal for VR projects requiring advanced interaction logic and extensive customization. It is often used in scenarios requiring procedural development, such as immersive education, VR gaming, or highly interactive architectural experiences.

The Datasmith plug-in in Twinmotion enables rapid synchronization of models and seamless integration with Revit (Figure 54, Figure 55). After importing the model into Twinmotion and applying materials, it can be connected to a Meta Quest 3 device for a VR experience (Figure 56, Figure 57). However, while this setup allows for immersive visualization, it does not support interactive design features or the integration of historical information from the model into the VR environment.

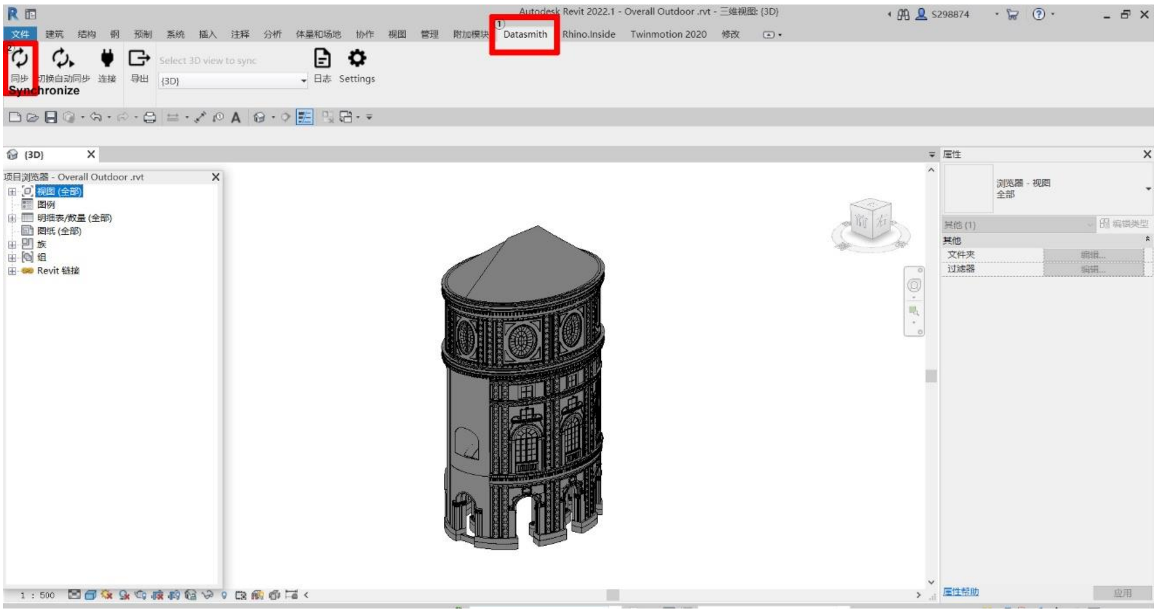


Figure 54. Datasmith Plug-in Revit

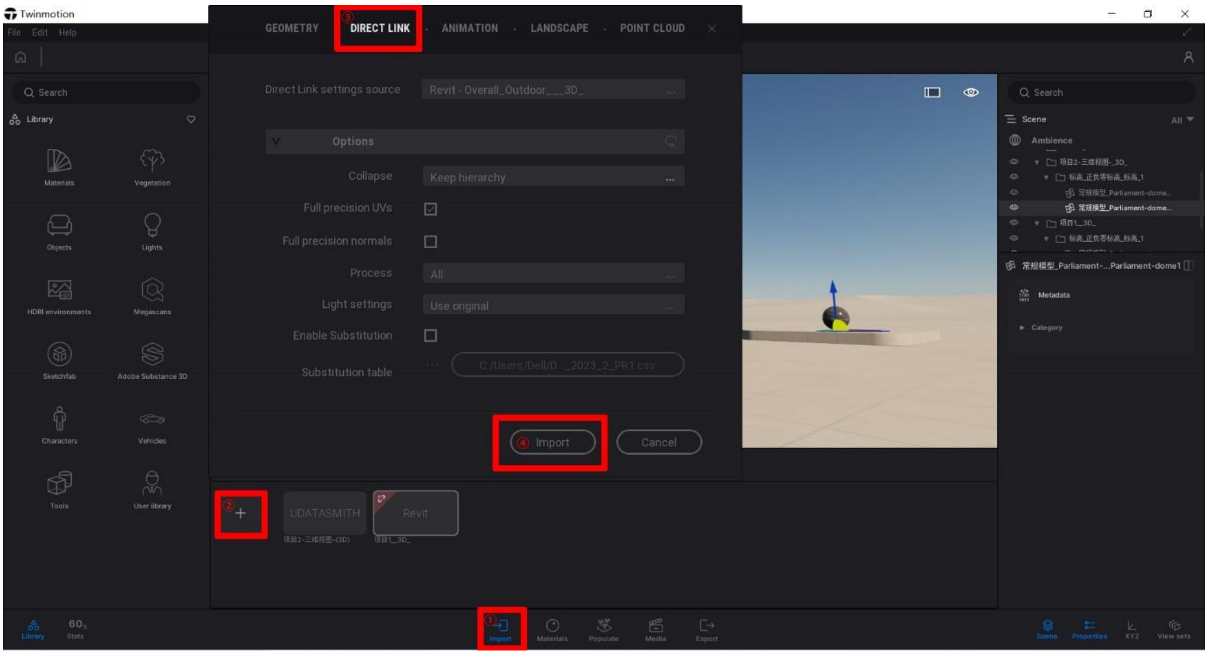


Figure 55. Import to Twinmotion

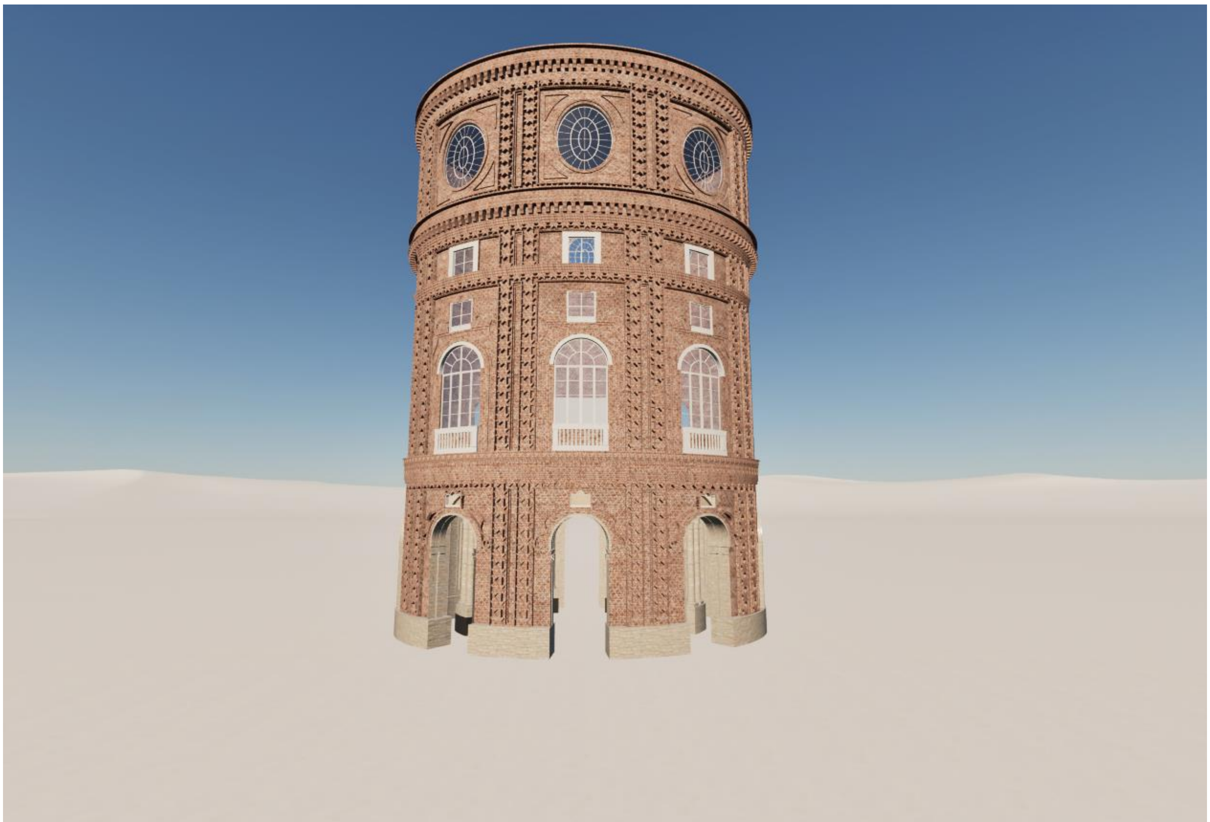


Figure 56. The facade of the parliament hall in Twinmotion

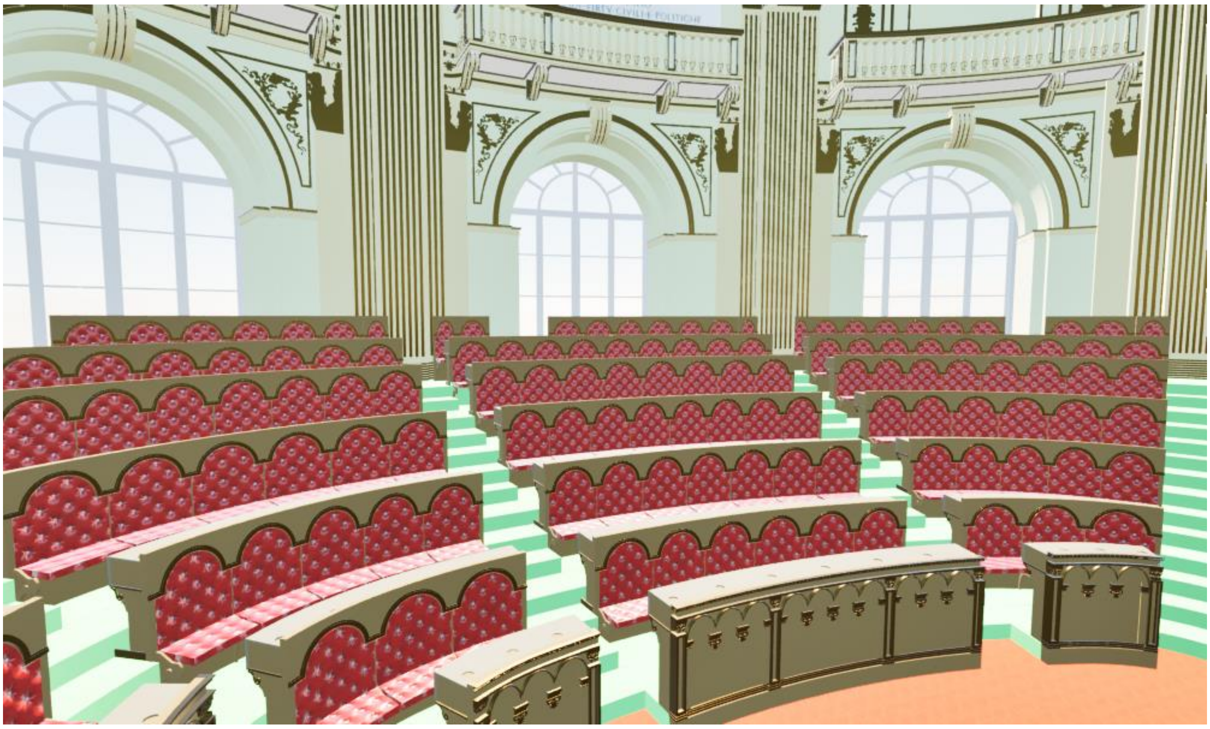


Figure 57. Interior of the parliament hall in Twinmotion

2.7 Unity

The flowchart of information transfer from HBIM to VR (Figure 58). By leveraging Power Query and C# scripting, the workflow facilitated dynamic updates to the Revit model, ensuring that any information modifications were automatically synchronized with the VR environment.

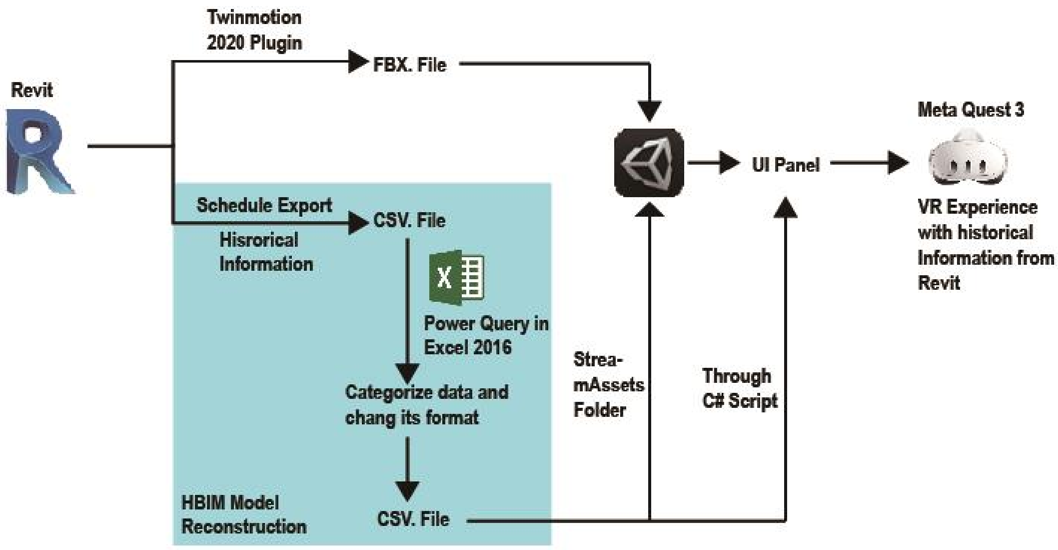


Figure 58. The flowchart of information transfer from HBIM to VR

Using the Twinmotion 2020 plugin, exporting a Revit model as an FBX file becomes an efficient and streamlined process. After ensuring the plugin is installed and accessible in the Add-Ins tab of Revit, open the desired project and navigate to the Twinmotion 2020 Export tool (Figure 59). Select Export to FBX, and in the export dialog, assign a descriptive file name, choose a save location, and configure export settings, such as preserving object hierarchy or including all model elements, depending on the project requirements. Once configured, click Export to generate the FBX file, which will be saved to the specified directory. The exported file can then be imported into unity. This approach facilitates the seamless integration of Revit models into advanced visualization workflows, making it a valuable tool for architectural and heritage documentation.

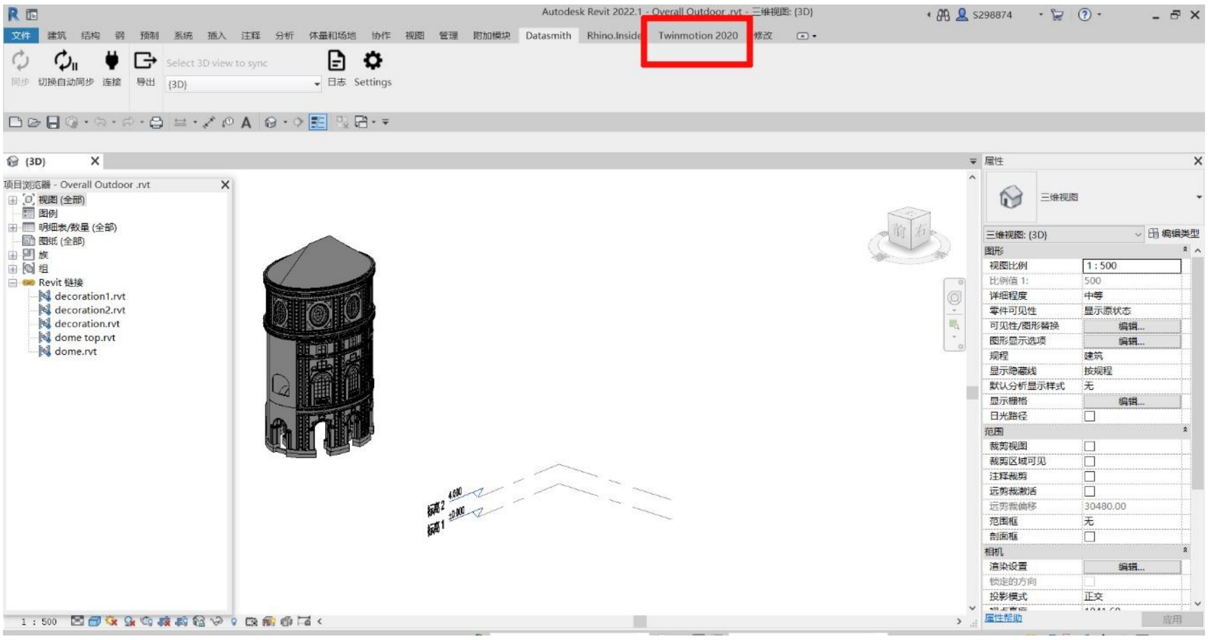


Figure 59. Twinmotion 2020 plugin

After importing the model into Unity, setting up a locomotion area is essential to confine user movement within the Parliament Hall, as the study focuses solely on this single room. This can be achieved by defining the room boundaries using colliders. These colliders act as barriers, preventing users from navigating beyond the designated area. To ensure smooth and intuitive navigation within the space, this study utilizes Unity's XR Interaction Toolkit, which enables continuous movement. This approach allows users to explore the room naturally while ensuring they remain confined to the Parliament Hall. By carefully setting boundaries and implementing controlled movement, the VR experience remains immersive and focused on the designated space.

To display Revit information in a VR environment, historical data must first be exported as a CSV file using Revit's schedule feature. For instance, to export the schedule for the portrait of Vittorio Emanuele II, navigate to the File menu, select Export, then choose Reports and click on Schedules. In the export dialog, select the relevant schedule (Figure 60) and save it as a CSV file (Figure 61). This file will contain all the necessary fields and their corresponding data, making it ready for seamless integration into the VR environment.

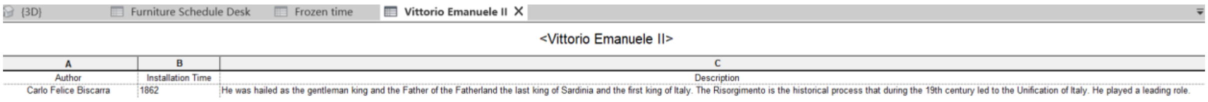


Figure 60. The schedule

To display the contents of a CSV file in Unity using a UI Panel, the CSV file is first placed in the StreamingAssets folder to ensure compatibility across platforms. A UI Panel is then created within the Unity Canvas to serve as a container for the parsed CSV data, with a Text component added to the panel for displaying the content. The visibility of the panel is controlled by buttons, allowing users to toggle its display interactively. A custom C# script (generated with GPT) reads the CSV file dynamically at runtime, the script parses the CSV data line by line, splits each row into fields, and formats the information for presentation in the Text component. However, displaying CSV file contents directly on a UI Panel in Unity fails to present the information in a readable or meaningful format (Figure 62).

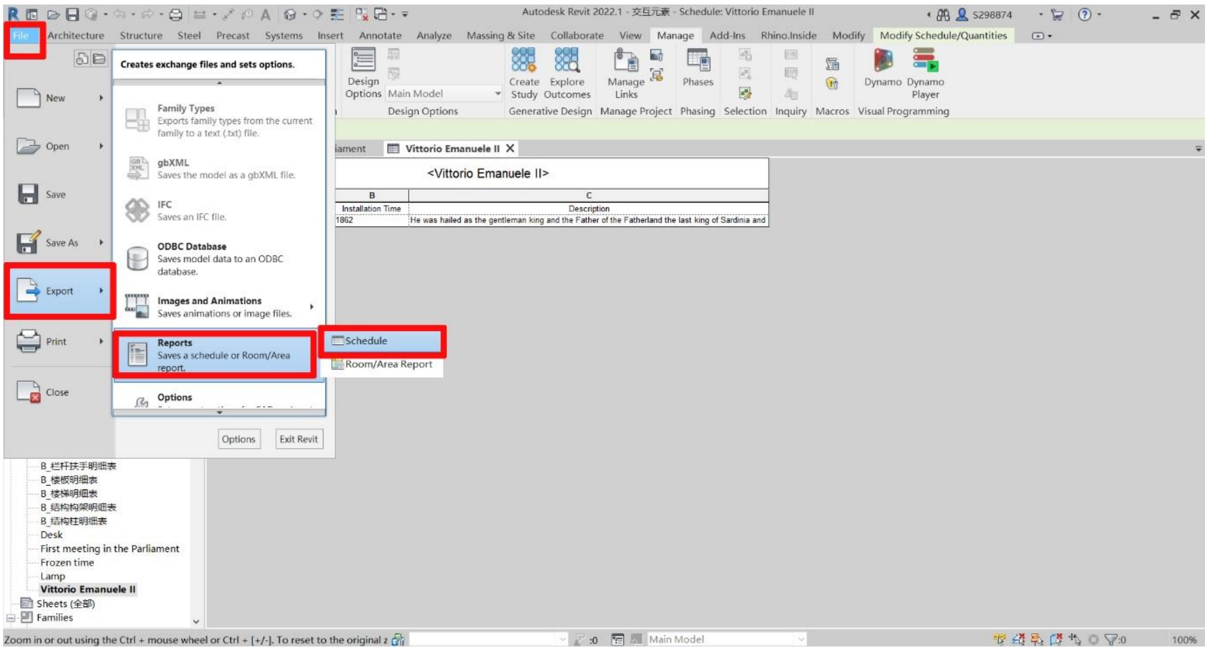
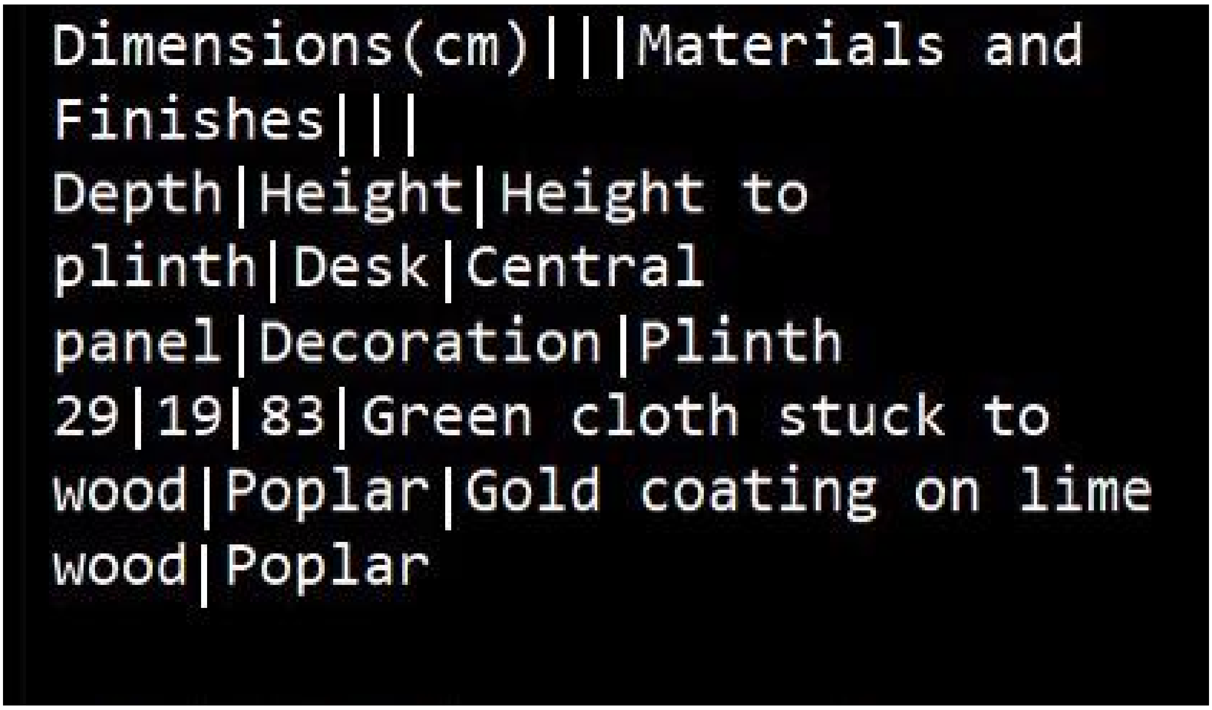


Figure 61. CSV file

To make the exported CSV file from Revit more readable for Unity's UI Panel, Power Query in Excel can be used to reformat the data into a user-friendly structure. Power Query allows you to clean, transform, and organize the raw data into a table format that is easier to



```
Dimensions(cm)|||Materials and
Finishes|||
Depth|Height|Height to
plinth|Desk|Central
panel|Decoration|Plinth
29|19|83|Green cloth stuck to
wood|Poplar|Gold coating on lime
wood|Poplar
```

Figure 62. Unreadable format

parse and display. Additionally, Power Query can automatically update the data whenever the source CSV file changes, ensuring the information remains up to date. In Power Query, go to Data Source Settings and enable Refresh on File Open to automatically update the data whenever the source file changes. Once the CSV file is properly formatted for readability, it can be imported into Unity to correctly display the data. Place the updated CSV file in Unity's StreamingAssets folder, ensuring easy access during runtime.

To display data from six CSV files in Unity, the files are first placed in the *StreamingAssets* folder, ensuring each is properly formatted and uniquely named for accurate identification. A custom C# script, which can be generated with the assistance of GPT, is employed to dynamically load and parse the CSV files at runtime. This script assigns each file to its corresponding UI Panel and Text component, processes the content, and displays it within Unity's UI environment. The setup involves creating six UI Panels, each equipped with a Text component, and linking them to the script in Unity's Inspector, alongside their respective CSV file names (Figure 63). Toggle buttons are integrated for each panel (Figure 64), allowing users to interactively control the visibility of the information presented.

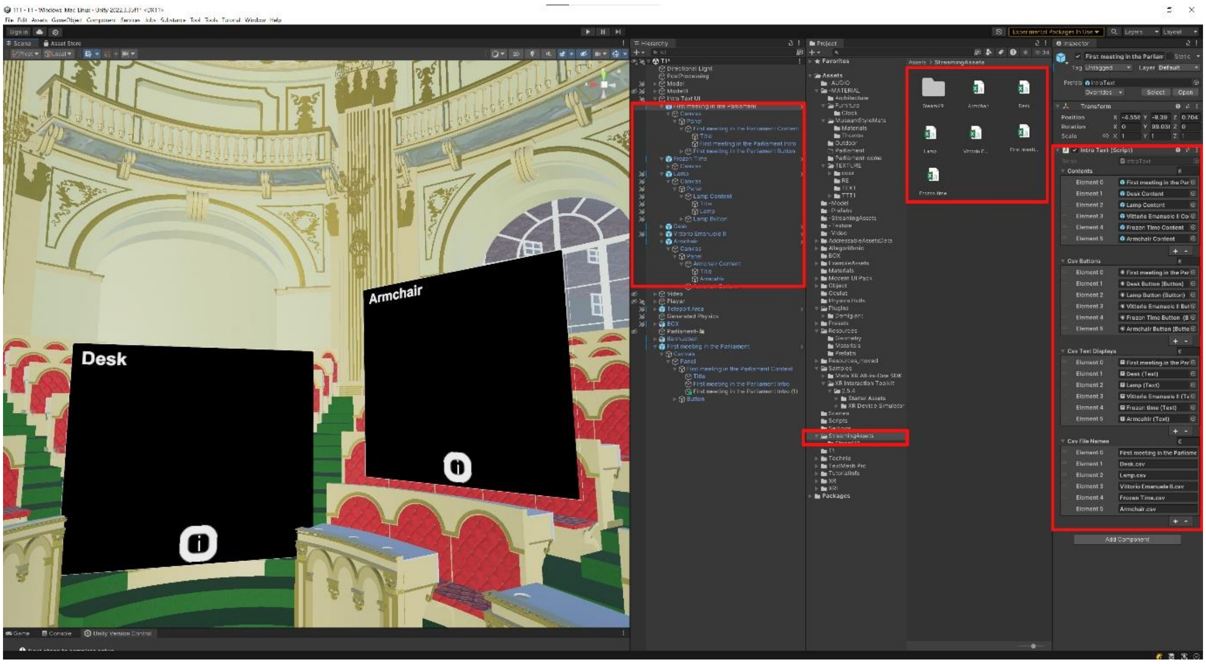


Figure 63. CSV file names

Figure 64. Readable format

Furthermore, the six datasets are preformatted for readability using Power Query. This ensures that any updates made in Revit are automatically synchronized with the formatted CSV files, eliminating the need for manual updates. Power Query's dynamic functionality enables seamless propagation of modifications or additional data from the Revit model to Unity. This integration ensures data accuracy and consistency across the Revit-to-Unity workflow.

This automated pipeline not only enhances the efficiency of the process but also ensures that the VR environment consistently displays up-to-date, well-structured, and easily readable information. By leveraging this approach, the VR experience is enriched with accurate and interactive data visualization, fostering greater engagement and usability for users while streamlining the workflow for developers.

To enhance the immersive experience, an audio introduction serves as the Parliament Hall's welcoming message, providing visitors with a brief overview of its historical significance and setting the tone for exploration. Additionally, a video sourced from YouTube (National Geographic, 2015) has been integrated into the exhibit, offering a visual narrative of Vittorio Emanuele II's legacy.

To align with the exhibit’s focus and maintain user engagement, the video has been carefully edited to feature only the most relevant segments. Visitors can interact with the exhibit to access both the audio introduction and the edited video, creating a layered and informative presentation of Vittorio Emanuele II's story. This approach enhances the storytelling experience while ensuring the content remains accessible and engaging.

3. Result

The research successfully modeled the curved geometries of the Parliament Hall in Palazzo Carignano without relying on advanced scanning technologies such as point cloud data or laser scanning. By utilizing Rhino.Inside.Revit, the workflow seamlessly integrated Rhino's advanced surface modeling capabilities with Revit's BIM functionality. This approach enabled the creation of detailed 3D models enriched with historical and material data, demonstrating the feasibility of producing accurate HBIM models even in resource-limited contexts.

The transition from HBIM to VR, often hindered by data loss and technical barriers, was effectively addressed through a semi-automated workflow designed to enhance accessibility for users with limited programming expertise. This workflow leveraged Power Query in Excel to dynamically update Revit data and synchronize it with Unity, ensuring seamless data transfer while preserving model fidelity. To further simplify the process, custom C# scripts were generated using GPT-based tools, allowing non-programmers to implement interactive features in Unity, such as real-time data visualization and engagement with cultural narratives. By combining AI-generated scripts with Unity's intuitive interface, users with basic knowledge of the platform were able to import models, set up scenes, and integrate interactivity, significantly reducing the complexity of VR creation. While this workflow lowers the barrier to entry, a foundational understanding of Unity remains essential for effectively utilizing the proposed approach.

3.1 Model

The Parliament Hall was modeled in Rhino and seamlessly integrated into Revit using Rhino.Inside.Revit (Figure 65, Figure 66). This workflow leverages Rhino's advanced surface modeling capabilities and combines them with Revit's parametric and data-rich environment, enabling the accurate representation of the hall's complex curved and decorative architectural elements. The model was developed based on technical drawings, demonstrating how detailed geometries can be recreated even in the absence of advanced scanning technologies. The model remains editable within Revit, providing flexibility for further refinements and updates.

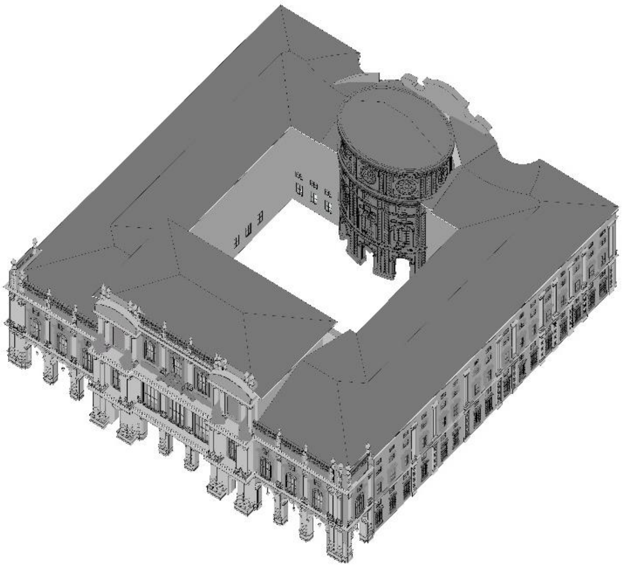


Figure 65. The facade of Parliament

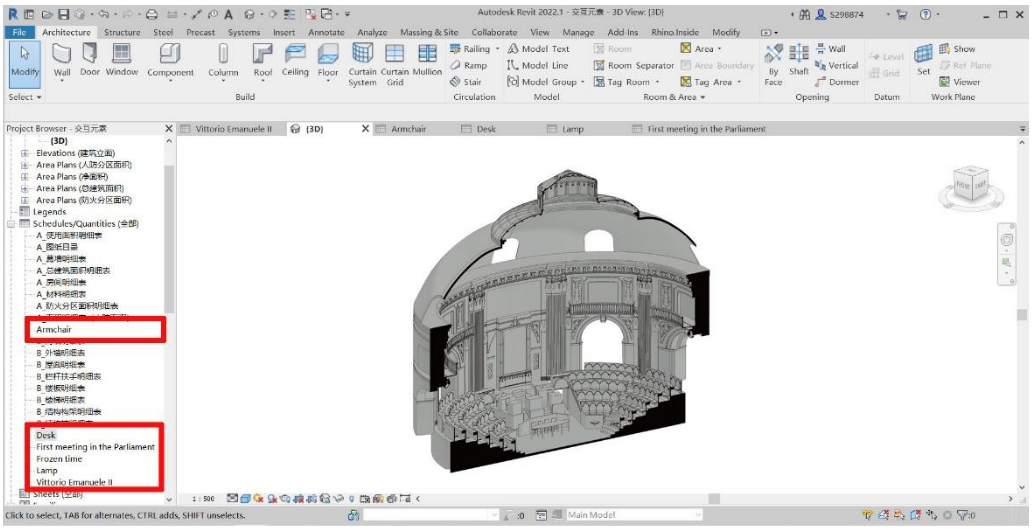


Figure 66. The Parliament Hall

Historical and material information, meticulously gathered through extensive literature review, was systematically integrated into the corresponding Revit model elements. To enhance data visualization, Revit schedules were utilized to effectively organize and display this integrated information. These schedules provide a structured representation of the historical data associated with specific elements within the model (Figure 67-Figure 72). This approach enriches the model with valuable contextual insights, streamlines heritage documentation, and lays a solid foundation for advanced applications such as VR integration and interactive exploration.

Armchair

<Armchair>

A	B	C	D	E	F	G
Dimensions(cm)			Materials and Finishes			
Depth	Height	Height to plinth	Desk	Central panel	Decoration	Plinth
29	19	83	Green cloth stuck to wood	Poplar	Gold coating on lime wood	Poplar

Figure 67. Armchair schedule

Desk

<Desk>

A	B	C	D	E	F	G
Dimensions(cm)			Materials and Finishes			
Depth	Height	Height to plinth	Desk	Central panel	Decoration	Plinth
29	19	83	Green cloth stuck to wood	Poplar	Gold coating on lime wood	Poplar

Figure 68. Desk schedule

First meeting in the Parliament

<First meeting in the Parliament>

A
Description
On March 4,1848, the Statuto Albertine was promulgated. Through the king's clear intention and concession, his absolute sovereignty transitioned to a constitutional monarchy. Thus, the Kingdom of Sardinia moved from an absolute regime to an era wh

Figure 69. First meeting in the Parliament Schedule

Lamp

<Lamp>

A
Description
The wall lamps are probably from 1860. This hypothesis is supported by the stylistic characteristics of the objects, with the cast iron arm-supporting masks applied to the wall, reminiscent of the decorative motifs of the Do

Figure 70. Lamp Schedule

Frozen time

<Frozen time>

A	B
Mechanism	Description
Clock with the mark	eeting was held here. It lasted half an hour, during which the royal decree dissolving the seventh legislature was read. After that, the room was closed.

The time on the wall is on December 28,1860, when the last last meeting was held here. It lasted half an hour, during which the royal decree dissolving the seventh legislature was read. After that, the room was closed.

Figure 71. Clock Schedule

{3D} Furniture Schedule Desk Frozen time Vittorio Emanuele II

<Vittorio Emanuele II>

A	B	C
Author	Installation Time	Description
Carlo Felice Biscarra	1862	He was hailed as the gentleman king and the Father of the Fatherland the last king of Sardinia and the first king of Italy. The Risorgimento is the historical process that during the 19th century led to the Unification of Italy. He played a leading role.

Figure 72. The portrait of Vittorio Emanuele II Schedule

3.2 Virtual Reality

In virtual reality (VR), museum interactivity refers to the way visitors interact with the virtual museum environment, exhibits, and other visitors. Compared with traditional offline museums, VR museums provide a richer and more immersive experience, allowing visitors to explore and learn in new ways. Some exhibits are designed to be interactive. For example, visitors can click, drag, or rotate virtual exhibits to view more information or trigger additional animation effects. This interactive method is more attractive than traditional exhibit labels. The following is an introduction to the interactive design of the parliament hall.

① **Guide language**

In virtual reality (VR) experiences, guide language serves as a critical bridge, enabling users to transition smoothly from the real world into the virtual environment while minimizing confusion or frustration. A well-structured and concise guide act as a foundation for users to quickly grasp the essential operations, interact effectively with virtual elements, and navigate the immersive space with ease. This not only enhances user experience but also deepens immersion by reducing barriers to engagement, allowing users to focus entirely on the virtual world. When thoughtfully designed, guide language can also spark curiosity and foster a sense of discovery, drawing users further into the VR experience through clear, purposeful, and engaging messaging.

In the context of historical and cultural virtual exhibitions, the role of guide language becomes even more significant. Beyond providing practical instructions, it acts as a storyteller, creating an emotional and intellectual connection between the user and the exhibition content. By incorporating culturally rich and historically meaningful narratives, the guide language transforms the experience from passive observation to active participation. Interactive prompts, thematic cues, and interpretive descriptions enrich the user's understanding of the exhibition's significance, helping them engage with artifacts, architectural details, or historical moments on a deeper level.

The following guide language was developed for the virtual tour of the Chamber of Deputies of the Subalpine Parliament: Welcome to the virtual tour of The Chamber of Deputies of the Subalpine Parliament. Please press the A button on the left-hand controller or the X button on the right-hand controller to display the panel. The panel shows the controller's usage, the room's history, and allows you to adjust different museum styles. Click on the markers to view detailed information about the exhibits.

This guide language integrates clear operational directives, an engaging introduction, and interactive prompts, providing users with an intuitive and immersive experience. By emphasizing interactivity and educational engagement, it enhances the overall value of the virtual tour, ensuring accessibility and relevance for a diverse user base.

② UI Panel

Expanding on the guide language, the UI panel in the virtual reality experience serves three primary functions: providing guidance on controller usage (Figure 73), offering a curated summary of the room's history, and enabling the customization of museum styles to enhance user engagement.

The room's history (Figure 74) presents a concise yet comprehensive overview of key documents and significant historical events related to the Chamber of Deputies. This feature highlights the hall's crucial role in shaping historical narratives, offering users a richer understanding of its cultural heritage.

The VR experience also allows users to explore scenarios beyond the limitations of traditional displays. Through the Settings function (Figure 75), users can adjust various parameters to tailor their virtual exploration. By modifying sliders for color temperature, shade, exposure, and saturation, users can experience alternate visual representations of the parliament hall (Figure 76). Furthermore, the style settings feature provides two distinct predefined styles

(Figure 77), enhancing the interpretive depth of the experience. For convenience, a RESET option restores the hall to its original state, ensuring users can easily return to the authentic representation of this historic site.

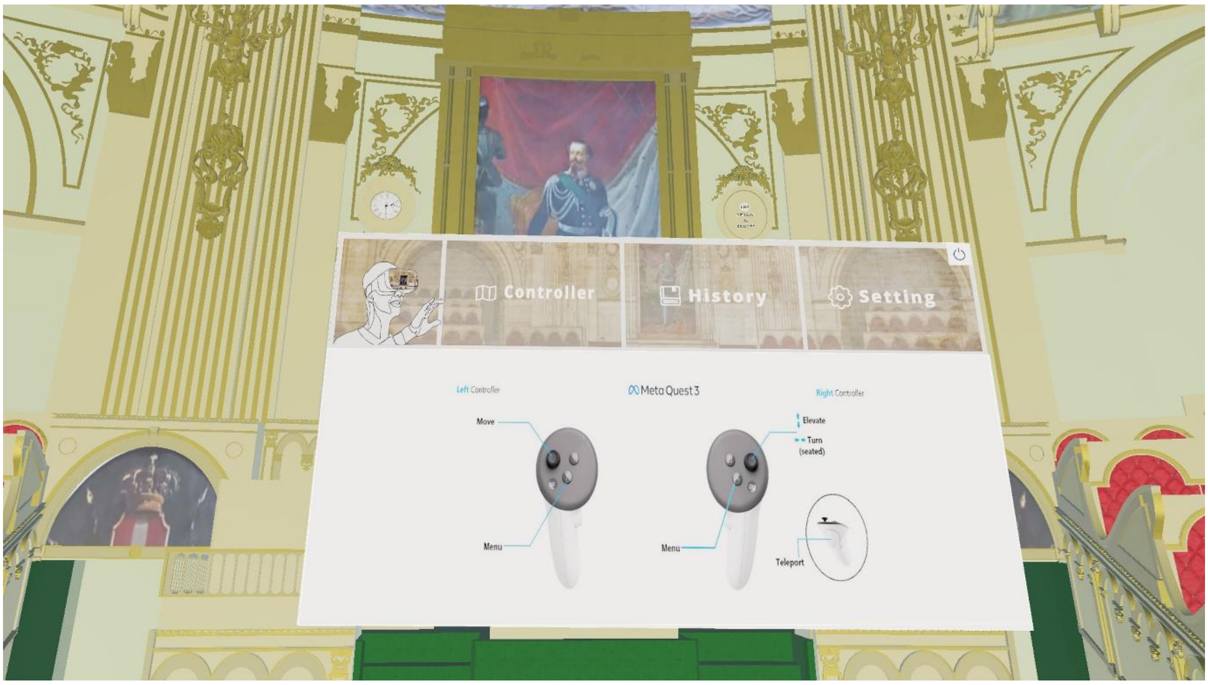


Figure 73. Controller

Figure 74. History

Figure 75. Setting

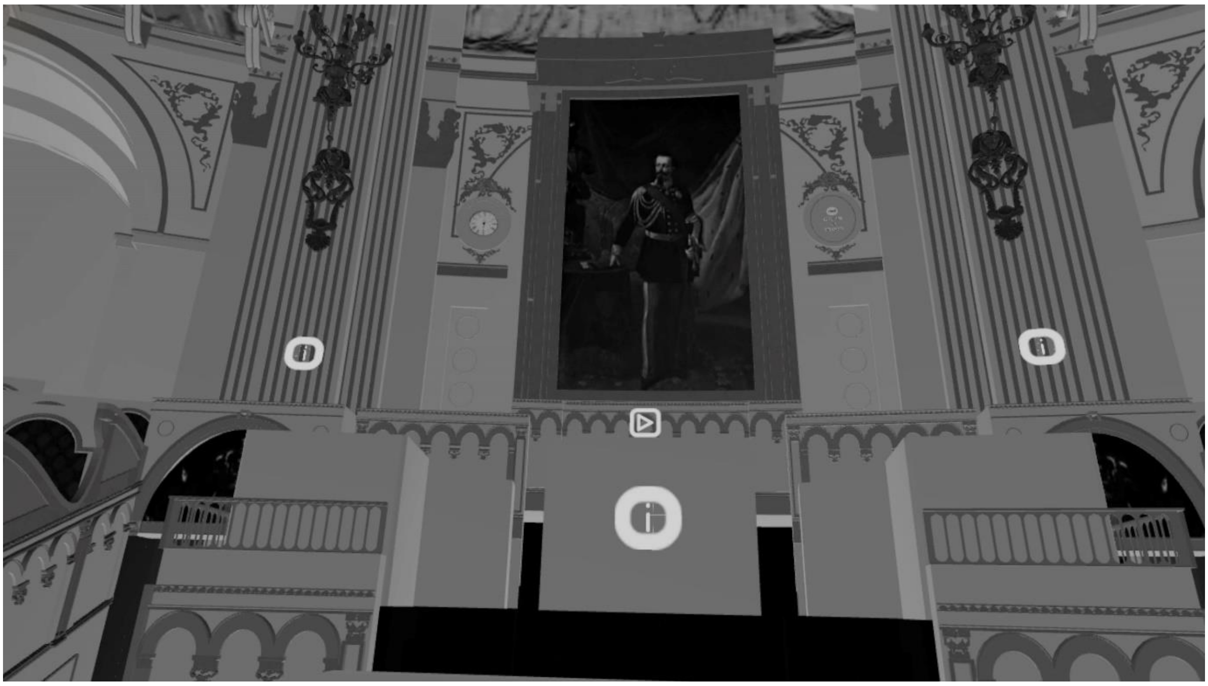


Figure 76. Adjust Slider

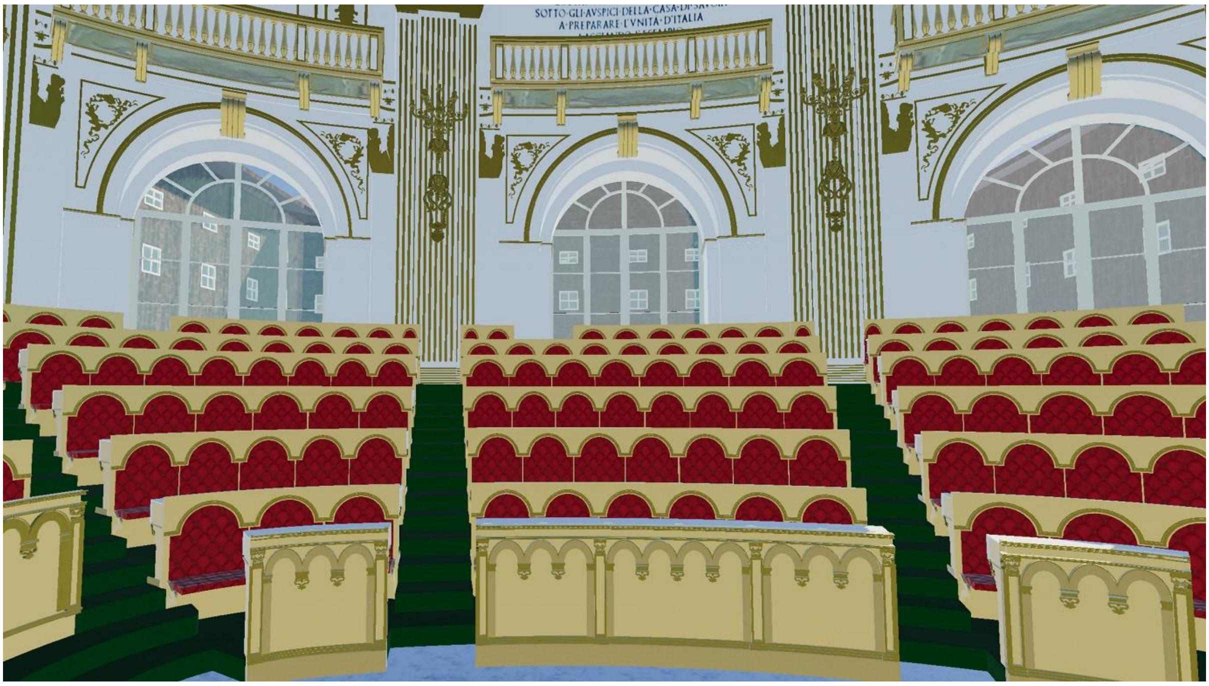


Figure 77. Another style

③ UI Panel with Historical Information (Information Export from Revit)

In the virtual parliament hall, users can interact with various objects to reveal their historical significance, visualized through HBIM-to-VR workflow with historical information seamlessly exported from Revit. By using the laser pointer to click a button (represented by a triangular play symbol), an information panel is activated. This panel provides detailed insights into key elements, such as Armchair (Figure 78), Desk (Figure 79), The First Subalpine Parliament (Figure 80), Frozen Time (Figure 81), Lamp (Figure 82) and Vittorio Emanuele II (Figure 83).

Figure 78. Armchair

Figure 79. Desk

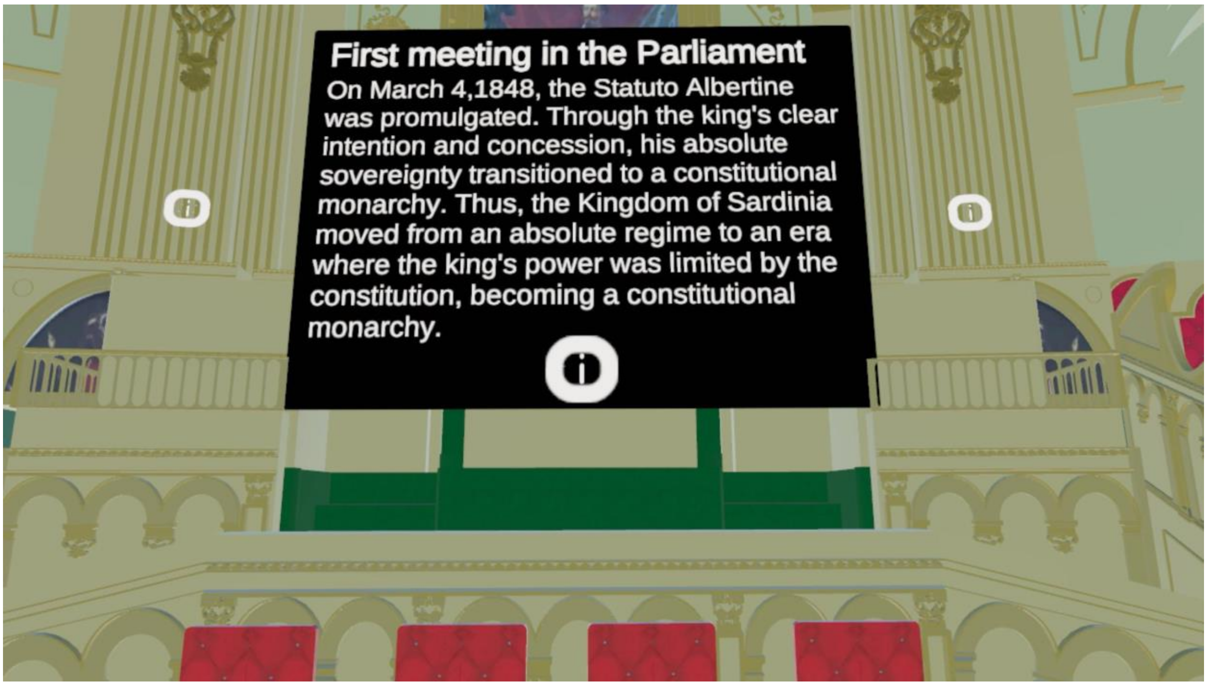


Figure 80. The First Subalpine Parliament

Figure 81. Frozen time

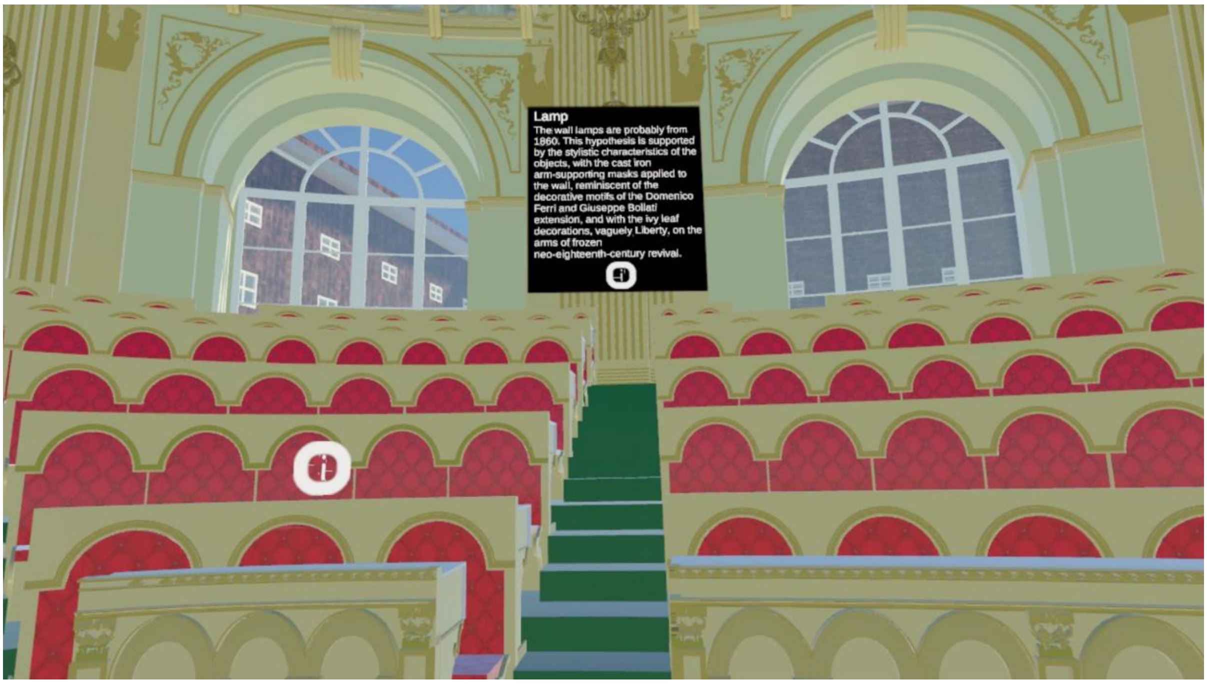


Figure 82. Lamp

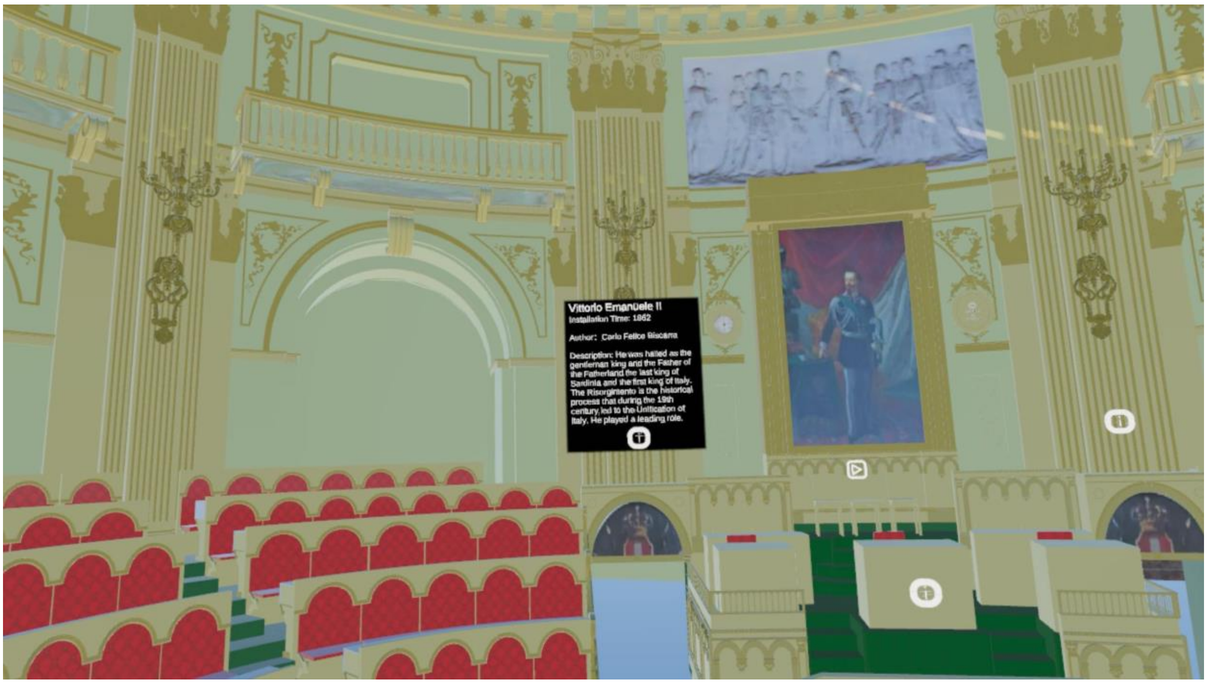


Figure 83. Vittorio Emanuele II

④ Video

Incorporating videos into the VR experience enriches the storytelling by combining visual, auditory, and interactive elements, making historical narratives more vivid and memorable. It allows users to connect emotionally with historical figures and events, fostering a more comprehensive and immersive learning experience. This dynamic approach transforms passive observation into active engagement, enhancing the educational impact of the VR environment.

Beneath the portrait of Vittorio Emanuele II, an additional play button allows users to trigger a video (Figure 84, Figure 85) using the laser pointer. This video provides an engaging and dynamic medium to delve into the life and achievements of Vittorio Emanuele II, the first King of a unified Italy. Through the video, users gain a deeper understanding of his pivotal role in the unification process and his enduring legacy in Italian history.

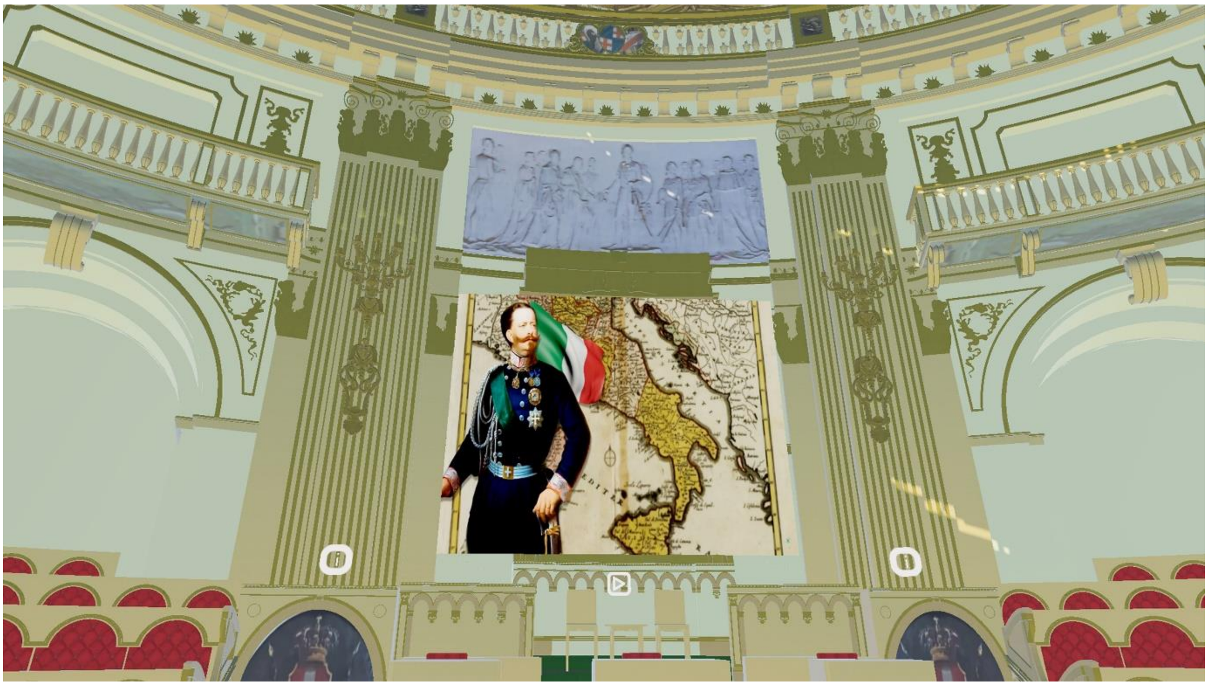


Figure 84. Beginning of the video

Figure 85. Video to introduce Vittorio Emanuele II

4. Conclusion

This research presents an effective solution for integrating HBIM and VR technologies to preserve and showcase cultural heritage, and proposes a solution for modeling and data transfer. By leveraging Rhino.Inside.Revit, a detailed HBIM model of a curved historical space was d successfully eveloped without the need for advanced scanning technologies. Historical and material information was meticulously integrated into Revit, and a semi-automated workflow was implemented to seamlessly transfer this data into Unity for immersive visualization. Utilizing Power Query and C# script, the workflow enabled dynamic updates to the Revit model, ensuring that changes were automatically reflected in the VR environment. Notably, this approach offers a user-friendly solution for individuals with limited programming expertise, making it both practical and accessible for cultural heritage professionals. By reducing technical barriers, the proposed workflow enhances the potential of HBIM and VR technologies, facilitating efficient documentation, visualization, and dissemination of heritage information while supporting broader accessibility and engagement.

Future research and development should prioritize the integration of advanced data acquisition technologies, such as laser scanning and photogrammetry, to enhance the accuracy and efficiency of HBIM workflows. These tools enable the precise capture of geometric details for complex heritage structures, minimizing reliance on manual modeling and significantly improving model fidelity. Furthermore, the development of user-friendly automation tools and AI-driven solutions could streamline the HBIM-to-VR pipeline, making it more accessible to a wider audience, including non-technical users. Advancements in VR interactivity, such as the inclusion of guided narratives or adaptive storytelling, have the potential to enrich the immersive experience, fostering deeper public engagement with cultural heritage sites. By embracing these innovations, the integration of HBIM and VR will continue to evolve into a robust methodology for preserving and showcasing the architectural heritage of the world.

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