

Article

Historical Heritage Maintenance via Scan-to-BIM Approaches: A Case Study of the Lisbon Agricultural Exhibition Pavilion

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Abstract: Building Information Modeling (BIM) has emerged as a revolutionary tool in the domain of architectural conservation and documentation. When combined with terrestrial 3D laser scanning, it presents a powerful method to capture and represent the intricate details and nuances of historic structures. Such buildings, with their unique architectural lineage, often exude a geometric complexity unparalleled by standard designs. Consequently, the transition from scan data to a BIM framework, or the scan-to-BIM process, becomes intricate and time-intensive. Beyond the challenge of digital translation, the true essence of these historic buildings lies not only in their geometric form but also in understanding and preserving their design logic, formal composition rules, and primitive geometry. It then becomes imperative that the resulting model maintains fidelity in terms of proportion, shape, symmetry, and spatial rationale. Considering these challenges and potentials, this article delves into the process of digitalizing and BIM modeling of the Lisbon Agricultural Exhibition Pavilion located in Portugal. Our study proceeds in a tripartite structure: initiating with an in-depth terrestrial 3D laser scanning of the pavilion, followed by a comprehensive registration, processing, and alignment of the acquired scans, and culminating in a detailed BIM model using the industry-standard Revit 2020 software.

Keywords: scan-to-BIM; 3D laser scanning; point cloud; HBIM; heritage; LiDAR



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1. Introduction

Technological advancements have had an impact on the architecture, engineering, and construction industry with the introduction of Building Information Modeling (BIM) 3D laser scanning and photogrammetry. BIM, based on 3D models, has brought about changes in how information is managed within the construction sector. It has influenced aspects such as information management, visualization techniques, and facility maintenance [1,2], and the industry has witnessed significant advances due to the rapid development of information technology, leading to the adoption and use of BIM technologies in the design of infrastructure projects [3–6]. The use of laser scanning technology has made it possible to accurately capture data from existing environments contributing to the digitization and visualization stages of BIM [7]. Moreover, 3D laser scanning, combined with aerial digital photogrammetry has proven to be highly effective in creating precise models of cultural heritage sites and buildings. This combination showcases its potential for documentation and preservation purposes within the AEC industry [8–10].

In order to incorporate a building into a Building Information Modeling (BIM) framework it is crucial to take a reverse engineering approach, which involves creating a model of the existing structure [11]. However accurately representing the building using measurement techniques can be quite challenging, especially when dealing with complex structures. As a result, there has been an increasing use of surveying methods, like 3D laser scanning and digital photogrammetry, in the industry. These methods offer improved precision and efficiency when capturing details [12].

The integration of BIM with technologies like Light Detection And Ranging (LiDAR) and digital photogrammetry, also known as scan-to-BIM, is a process that involves the conversion of point cloud data obtained from reality capture devices into a 3D model using BIM software and has brought about significant improvements in the digital reconstruction of existing buildings [13]. This process has gained significant attention due to its potential applications in various fields, particularly in cultural heritage preservation and construction projects. The scan-to-BIM process typically involves several major steps, including data acquisition, point cloud processing, 3D modeling, and information mapping [14]. The benefits of scan-to-BIM include improved management of building information throughout its life cycle, enhanced visualization, and the potential for accurate preservation and documentation of cultural heritage sites [15–18]. This process enables the creation of 3D models that enhance the accuracy of building sections and elevations while simplifying error detection [5]. However, transitioning to this method is not without its challenges. The costs associated with adopting platforms, the need for training, as well as the nature of the projects undertaken can hinder complete adoption. Additionally, current methods still involve an amount of modeling work that can be time-consuming and imprecise [5,6,19]. In a recent survey among professionals specializing in architectural surveying with 3D laser scanning and photogrammetry, 40% of the respondents reported using BIM software in more than 50% of their reality capture projects. This percentage decreases to 29% when the projects involve old or historic buildings [5].

The use of Historic Building Information Modeling (HBIM) has emerged as an approach for conserving and documenting heritage buildings. This method, based on BIM, allows for the creation of 3D models that capture the structural and historical characteristics of these structures [20,21]. However, there are challenges in implementing HBIM. These include representing unique geometric structures within BIM [18,22] as well as the potential loss of geometric accuracy when converting historical elements into parametric BIM objects, particularly in intricate architectural features [23]. The heterogeneity of elements also complicates the standardization process in BIM, which conflicts with its parametric procedures [24]. Documenting historical buildings using BIM functionality is another obstacle that requires methods for capturing data and producing engineering drawings from laser scans and image surveys [12].

One important aspect of BIM modeling is its ability to depict objects by incorporating data, attributes, parameters, material properties, and construction characteristics [25–27]. However, it is crucial to recognize that a BIM model is a representation of reality and does not precisely reproduce every detail of the object [28]. Portraying constructions, with variations and irregularities can be difficult when relying on tools that strongly prioritize orthogonality. This emphasis on orthogonality can occasionally result in inaccuracies.

The concept of tolerance and accuracy plays a role in BIM modeling. Tolerance refers to the level of precision required in a model with respect to the object guiding modelers in their decision-making process [29,30]. Accuracy is vital for achieving precision and reliability in the representation of building elements within the BIM environment, particularly when integrating point cloud data from laser scanning into the BIM model, and this concept is directly related to the intention for which the model is intended. Defining its intended use helps determine methods for achieving the level of accuracy, thereby avoiding creating overly complex models that could disrupt workflows and increase costs [28,31]. The Level of Accuracy (LOA) and Level of Development (LOD) are metrics used in this context to classify the precision and level of detail within a BIM model [31–33].

BIM goes beyond software platforms and the mere creation of a three-dimensional architectural representation; however, it still involves the development and use of a model as a foundational component. BIM is a methodology centered around a comprehensive digital model [27]. This model integrates data needed for managing the life cycle of a building, including design, construction, ongoing maintenance, and eventual decommissioning or repurposing stages. The methodology represents an approach to building life cycle management by utilizing the model as a central repository of information and a

platform for interdisciplinary collaboration [27,34–36]. At the same time, BIM also goes beyond reconstructing geometry. It is important to make sure that the 3D model accurately represents the features of the object being studied. This alignment should meet the project requirements for accuracy, tolerance, and purpose [28,30,31].

Working with heritage and historical buildings presents a challenge when it comes to grasping the geometry of a structure. In order to design a building that respects its cultural significance, it is crucial to comprehend its symmetries, design logic, proportions, and architectural principles. This understanding serves as the basis for preserving the integrity of the building's structure and ensuring its appeal. [37–39] By delving into the geometry, architects and conservationists gain insights into the original design intent, enabling them to honor and uphold the building's historical context and architectural heritage. By comprehending the symmetries and design logic, architects can ensure that any modifications or additions to the building are harmonious with the original structure, preserving its historical authenticity and architectural coherence. Moreover, an understanding of proportion and architectural laws enables designers to adhere to the building's original spatial relationships, ensuring that any alterations or adaptations are in line with the building's historical character and significance [37,38,40].

This study explores the use of BIM as a tool for aiding in the documentation and preservation of historic buildings, particularly those with complex geometries. Traditionally, BIM has been predominantly utilized in new construction projects [11]; however, its potential in the context of architectural heritage has not been fully explored. The central objective of this research is to create a BIM model of a heritage building, serving as a starting point for integrating the existing structure into a BIM-based methodology for conservation and restoration. This involves implementing form decomposition techniques in BIM, crucial for accurately representing the unique geometrical characteristics and original design intents of historic structures. This study navigates through the complexities of BIM modeling, addressing the challenges encountered in replicating these intricate geometries. This approach is key to understanding and preserving the architectural integrity of heritage buildings, facilitating their integration into contemporary conservation practices.

The objective extends to contrasting BIM and 3D laser scanning methodologies with traditional architectural surveying techniques. Key benefits of this approach include higher accuracy in detail representation, increased efficiency in data acquisition, and the creation of more dynamic, interactive architectural models [41]. These advantages are crucial for accurate preservation and restoration planning, offering a substantive improvement over conventional methods.

The digital reconstruction of existing buildings through BIM tools and surveys conducted via reality capture techniques is a subject increasingly addressed by various researchers. This applies to both traditional [14,42] and historic buildings [43–48] in the scan-to-BIM reconstruction process. Regardless of the building type, it is crucial to establish a clear and efficient methodology that encompasses all facets of the scan-to-BIM process, from architectural surveying, registration, processing, and alignment of point clouds, to the construction of the existing building's BIM model [10].

The case study of the Lisbon Agricultural Exhibition Pavilion illustrates the methodology, from the initial survey to the creation of a preliminary BIM model. It emphasizes strategies for modeling complex geometries and underscores the importance of understanding architectural proportions and symmetries. The aim is to provide a comprehensive methodological guide for integrating BIM into the conservation of architectural heritage, focusing on its potential to effectively capture the complexities of historic buildings.

2. Case Study

2.1. The Lisbon Agricultural Exhibition Pavilion

The Lisbon Agricultural Exhibition Pavilion, a property of the Instituto Superior de Agronomia, is located in Lisbon, Portugal, and is an integral component of the Tapada da Ajuda complex. This structure is part of the Tapada da Ajuda's intramural ensemble, which

is duly recognized as a Property of Public Interest. The pavilion was built in alignment with the architectural design by Luís Caetano Pedro de Ávila specifically for the 3rd Agricultural Exhibition, which commenced on the 4 May 1884. In 1984, in conjunction with its centenary, the pavilion underwent significant restoration, after which it was reinstated as a cultural asset within the city's heritage registry. Presently, it functions as a multipurpose venue, facilitating a broad spectrum of social and cultural events, with a maximum occupancy of 1000 individuals [49–51].

The Exhibition Pavilion structure is distributed over two levels. The main level features an open-space semi-oval floor plan that connects to three octagonal rooms, two located at the extremities and one located centrally. These octagonal wings are topped with ribbed dome structures supported by a metallic framework. The main wing of the pavilion, in contrast, is equipped with a gabled roof, underpinned by metallic trusses. Access to the pavilion is facilitated by staircases that navigate the site's inherent uneven terrain, leading to the main floor of the pavilion via exterior circulation corridors that encircle the building's perimeter [49].

The building's walls are constructed from brick masonry, while fenestration is achieved through the extensive use of iron and glass frameworks that envelop the principal façade and extend partially to the rear elevation. In addition to the principal exhibition floor, the pavilion's lower-level houses service and support facilities—including a kitchen, restrooms, and storage areas—strategically located beneath each dome. The exterior of the pavilion is adorned with cast iron railings, ornamental stonework, and columns that serve both structural and aesthetic purposes, further complemented by decorative elements atop the pavilion's roof and upper structure (Figures 1 and 2).



Figure 1. Main facade of the Lisbon Agricultural Exhibition Pavilion.

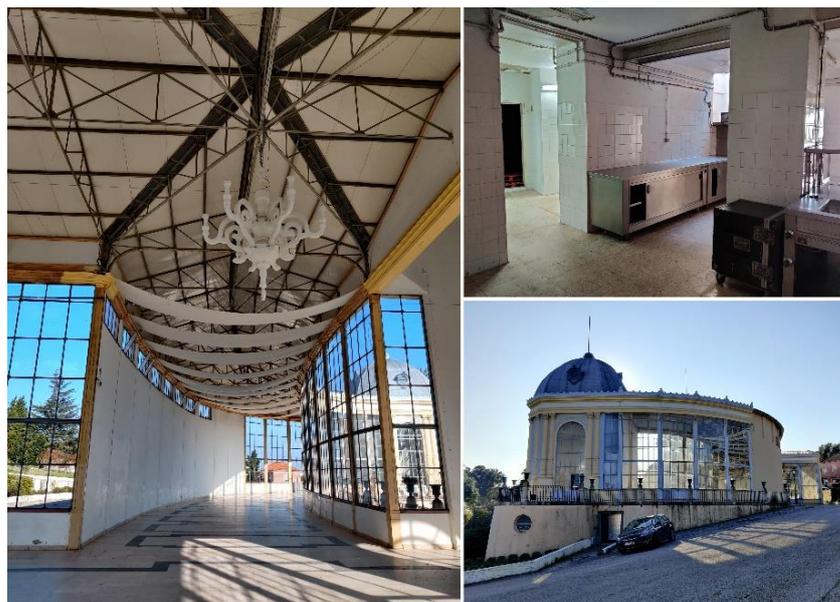


Figure 2. (Left): interior view of the pavilion’s main floor with its metallic roof support structure. (Upper right): photograph of the kitchen situated on the lower level. (Lower right): side view of the pavilion illustrating the terrain’s uneven topography.

2.2. Building Survey, Data Processing, and Point Cloud Registration

The building survey, including data acquisition, processing, registration, and point cloud creation, was executed with methodical precision. The planning was detailed to ensure all aspects of the structure were accurately captured. The Faro Focus 120 S 3D Laser Scanner was utilized for measurement capture. The Trimble R8 GNSS GPS was used for georeferencing, and a smartphone was used for photographic documentation to aid in the modeling process.

The survey operation was conducted over a total duration of 9 h and 25 min, divided across six field visits. The data acquisition phase involved the establishment of 176 scan stations that recorded the pavilion’s interior spaces, which include the main and lower floors, as well as the external walls, circulation paths, roofing, domes, and the immediate topography extending 50 m from the building’s perimeter. The area documented amounted to approximately 1655 m² for the pavilion, with an additional 700 m² for the external corridors and staircases, and 14,000 m² for the encompassing landscape. The collected data were then aligned and integrated to produce a detailed point cloud. For georeferencing, 21 geodetic reference frame coordinates were collected using GPS equipment around the exterior of the building, ensuring the point cloud was accurately situated within its real-world context.

The ornamental elements and facade details of the building were captured using the same terrestrial laser scanner employed for the main building scan. The scanner’s effective range and high resolution, along with the site’s varied topography, enabled adequate capture of these features, fulfilling the project’s requirements without the need for additional scanning equipment. In addition, photographic records and manual measurements with tape measures were undertaken. These were particularly useful for modeling finer details in areas such as junctions between structures, curtain walls, and specific wall profiles, ensuring a comprehensive and accurate representation in the BIM model.

In this particular case study, which focused on BIM modeling of the building, photogrammetry was not employed as a reality capture tool. The decision was influenced by the terrain’s geographical characteristics, marked by significant variations in elevation and slopes. These conditions enabled the 3D laser scanner to effectively capture the highest points of the building, such as roofs and domes. Consequently, all these elements could be modeled with a high degree of accuracy and without substantial difficulties.

The alignment of the scans and the subsequent registration of the point clouds were conducted using the Faro Scene software (version 7.5). The registration mode used was Cloud to Cloud (C2C) for all the point clouds and/or clusters of point clouds and Target Based (TB) for the final georeferencing. The scans were categorized into five distinct clusters aligned with their spatial locations—external areas, main level floor, lower-level floor-left, lower-level floor-right, and lower-level floor-center—to streamline the pre-alignment and facilitate subsequent data processing. For each group, a manual pre-alignment was performed. This initial step places the scans in approximate alignment to assist and expedite the software’s more precise and final alignment phase. Such preliminary procedures are critical for reducing computational load and decreasing the number of iterations the software must execute to determine the correct orientation of each scan.

Following the pre-alignment and the software’s final alignment within the individual groups, along with a rigorous visual check to ensure accuracy, a comprehensive final alignment was executed across all groups to produce the definitive point cloud (Figure 3). A concluding inspection was conducted prior to exporting the data as a 3D point cloud file in the *.e57 format, intended for modeling applications. This step was to rectify any errors undetected in previous stages. The building’s particular features—namely, the extensive use of glass, a paucity of opaque surfaces, and the abundance of reflective materials—introduced numerous artifacts and superfluous points stemming from reflections. This complexity necessitated a particularly thorough and careful point cloud processing procedure. Care was taken to prevent misalignment and to ensure the accurate interpretation of the final data set. The statistics from the final C2C registration of clusters, as indicated in Scene, show a Mean Distance Point Error of 4.6 mm, a Maximum Distance Point Error of 11.1 m, and a Minimum Overlap of 36.7%. Regarding the georeferencing, out of the 21 targets collected, 4 were used, following a TB approach, with each point externally located on one of the sides of the building. The Mean Horizontal Error observed was 20.1 mm, and the Mean Vertical Error was 21.1 mm. The final project of the point cloud was exported with a Homogenized Point Density of 10 mm.

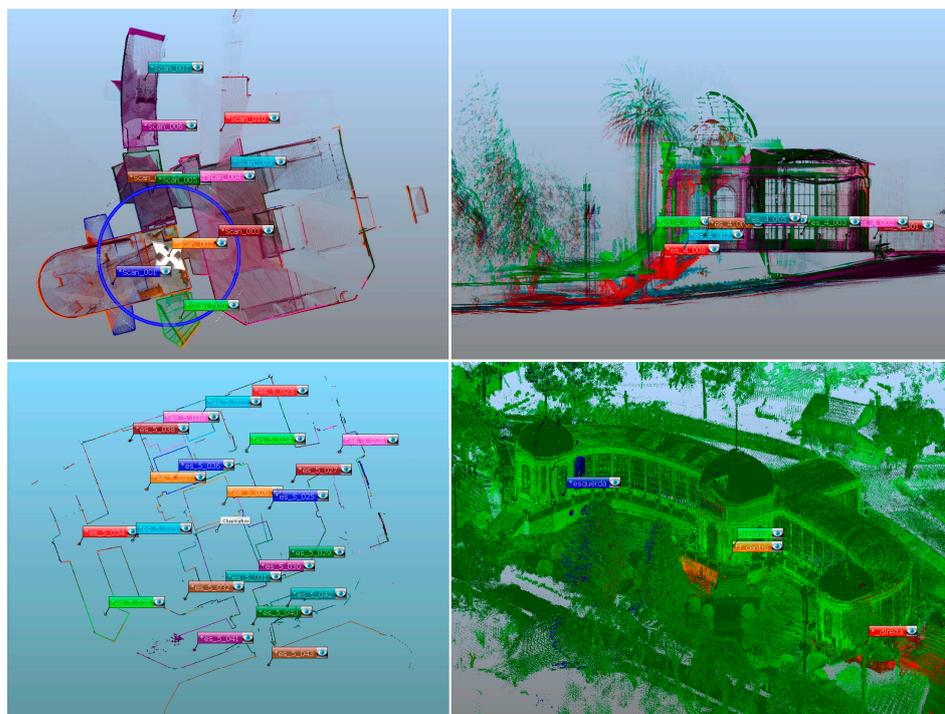


Figure 3. (Top Left): preliminary alignment of the “lower-level floor-left” scan group. (Top Right): lateral perspective of the “Exterior” group scans post-preliminary alignment and pre-Faro Scene processing. (Bottom Left): definitive alignment of the “lower-level floor-center” scan groups. (Bottom Right): consolidated point cloud resulting from the integration of all five scan groups.

2.3. BIM Modeling

For the BIM modeling of the Lisbon Agricultural Exhibition Pavilion, the initial phase involved defining the project's scope and objectives. The goal was to conduct an architectural survey of the building and create a BIM model of its current state so that the model could be utilized in a rehabilitation project and, in the future, for facility management as well, thereby supporting efficient building operations and maintenance. For this reason, the requested documentation was limited to basic building information, such as floor plans, roof plans, elevations, and building sections.

From the defined scope, the specific area for modeling was determined, architectural and structural components to be included in the model were identified, and the required levels of detail for different elements were set. Establishing these criteria was crucial for guiding the scan-to-BIM process, influencing modeling decisions, and ensuring that the final model met the client's needs while avoiding unnecessary work.

It was established that the BIM model would incorporate all primary architectural elements that are standard in most buildings. These elements include walls, floors, roofs, doors, windows, countertops, sanitary fixtures, and staircases. Moreover, exposed structural features such as beams, columns, trusses, and slabs were to be included. The scope also extended to modeling the site's topography within a 50-m radius around the building and onsite elements such as pavements, pathways, stairways, and retaining walls.

The project's level of detail was planned to range from LOD 200 to LOD 300 following the standards set by the BIM Forum [33], depending on the specific element's requirements. However certain elements such as trees, external vegetation, infrastructure equipment, stormwater drainage systems, outdoor lighting, and non-architectural or structural components like lighting fixtures and piping were not included in the project's scope. Nevertheless, these elements were captured and are present in the point cloud, offering the possibility of incorporating them into the model at a later stage. Moreover, internal compositions of walls, floors, and ceilings were not examined in depth during this project; hence, these elements were modeled without material layers. Similarly, any hidden structural foundation elements were omitted from the model. However, it is possible to integrate this information into the model through future updates, without affecting the quality of the current model.

Following the acquisition of the point cloud, the E57 file, resulting from the scans aligned using the Faro Scene software (version 7.5), was imported into Autodesk Recap for the cleaning of undesired points and the creation of an RCP file (Figure 4). This file would later be utilized in Autodesk Revit for the BIM modeling process. Before introducing the point cloud into Revit, the project and survey coordinates were configured to ensure that the Revit project remained aligned with the point cloud coordinates. After the cloud was added, the project north was rotated—without altering the true north—to ensure the building was oriented orthogonally on all plans, thereby simplifying drawing, modeling, and the interpretation of right angles and parallelisms within the software.

The Lisbon Agricultural Exhibition Pavilion, distinguished by its classical architecture, necessitates a modeling approach that is cognizant of the qualities of harmony, proportion, and symmetry—fundamental Vitruvian principles of *firmitas* (durability), *utilitas* (functionality), and *venustas* (beauty) [52]. These characteristics manifest in the classical building's elegant and symmetrical forms, where harmonic proportions are attained through the application of mathematically defined measurements, such as the golden ratio. Moreover, classical architecture prides itself on order and symmetry, fostering a formal balance that yields a harmonious aesthetic [53].

Given the intrinsic features of this edifice, it is imprudent to immediately commence the three-dimensional reconstruction by modeling the main walls from the point cloud as is typically conducted with conventional buildings. To ensure the model accurately mirrors the original structure's proportions and symmetries, it is critical to strategically plan all actions prior to the initiation of modeling. An analysis of the building's geometry should be conducted in alignment with the form grammar principles that govern the organization and

composition of forms and elements in art and architecture, ensuring equilibrium, harmony, and proportion in the constructions, and accentuating the architectural elements' order and symmetry [54].

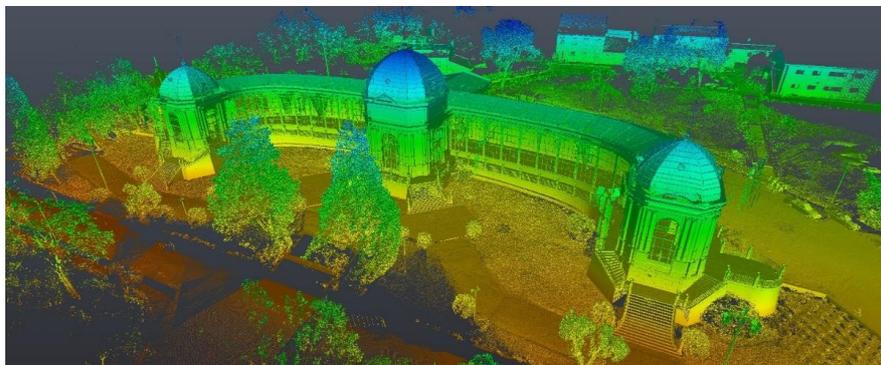


Figure 4. Point cloud of the Lisbon Agricultural Exhibition Pavilion obtained through 3D laser scanning technology.

The decomposition of the Pavilion's form commenced with identifying the most significant structural elements, as well as their arrangement and hierarchy within the construction plan. The BIM model, as a representation of an existing building, must adhere to the classifications of the elements and systems present in a building, such as structural elements, enclosure elements, connections, and decorative elements. Moreover, to ensure the digital reconstruction's efficiency and fidelity to the study object, it is imperative to follow the constructive hierarchy of elements, as well as the phases of design, construction, and the structure's location.

It is pertinent to note that in real construction, the structure is the foundational element positioned on the site, while walls and finishes are added subsequently. Orienting the three-dimensional model starting from the structure presents an effective alternative to minimize potential geometric inconsistencies that might emerge in the final model. Errors and deviations are more commonly observed in the position of the enclosure elements, which are constructed with less mathematical rigor than the structure itself.

After identifying the structural elements of the Pavilion, the initial step was to ascertain the construction axes present in the building's plan. The principal axes identified were: the vertical axis, which governs the symmetry of the pavilion, the horizontal axis at the center of the main nave, the diagonal axes connecting the center to the corners, and the axes corresponding to the columns and trusses that support the main roofing structure. Given the geometric properties of this edifice, the axes of the structural elements converge toward spatially harmonized focal points. It was imperative to pinpoint these centers to delineate the influence and to accurately position the columns' axes emanating from these central points (Figure 5). With the axes clearly defined and mapped out, the modeling process was initiated. By employing the point cloud as a referential guide, adherence to the original construction's proportion and symmetry was achievable in the generated model.

The architectural modeling of the building was executed using a top-down approach. This process commenced with the modeling of the macro elements and positioning of key structural components, including load-bearing columns, external walls, and the over-arching forms of the roofs. Subsequently, integration with the site's topography was accomplished by adding principal floors and slabs, followed by doors, windows, glazed walls, and staircases. In the third phase, supplementary architectural and structural features such as trusses, beams, handrails, and countertops were incorporated. The final stage entailed a refinement process, enriching the model with detailed elements like ornamental decorations, roofing details, cornices, reveals, plumbing fixtures, pathways, and other requisite components.

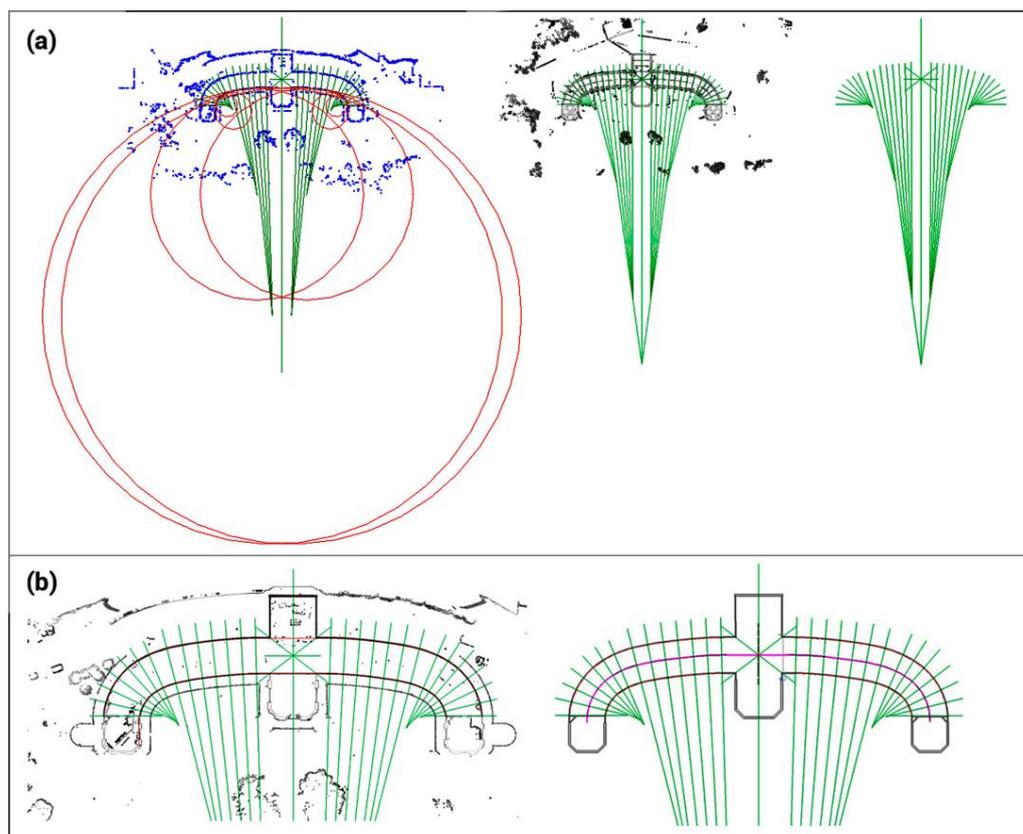


Figure 5. Planning stage prior to BIM modeling of the Lisbon Agricultural Exhibition Pavilion: (a) Evolution of the structural axis identification within the building's framework. Upper left: initial sketch marking the axes (green lines) and radii (red circles), over the point cloud (blue). Upper center: adjusted alignments providing a starting point for the axis development. Upper right: final drawing of the structural axes, ready for modeling reference. (b) Preliminary modeling studies using the structural axes (green lines) as guides. Lower left: positioning of the axes for the exterior walls (red lines), which is crucial for the building's perimeter definition. Lower right: identification and placement of the main roof's ridge axis (pink lines), which is essential for establishing the roof's peak and pitch.

In the BIM modeling of the Lisbon Agricultural Exhibition Pavilion, the application of parameters was tailored to each element type. System family elements in Revit, like walls, roofs, floors, and stairs, were modeled as parametric elements, allowing size adjustments as required. Conversely, loadable families or in-place families such as doors, windows, architectural details, columns, beams, and trusses received a unique treatment in each instance.

Initially, it was determined if an element was a common architectural feature or uniquely designed for this building. Standard elements, like common doors on the lower level and roof beams and trusses, were modeled with pre-existing families and parametric dimensions. Custom elements were parameterized only if they had varying dimensions within the project, like certain columns. If no replication with different dimensions was needed, dimension-related parameters were omitted to save time without sacrificing project quality.

In every case, regardless of dimension parameters, families were created with material finish parameters. As they are native Revit families, even those with custom modeling can have their attributes and other parameters updated as needed, facilitating integration into a facility management workflow.

The geometric reconstruction of this building posed significant challenges beyond the identification of structural logic, axes, and symmetries previously outlined. Notably,

the replication of intricate shapes deviating from standard forms accommodated by BIM tools proved demanding. Such complexities included dome structures, stair balustrades, classical facade details, columns, and the typologies of doors within curtain walls.

The pavilion features three polygonal domes based on an octagonal footprint, each representing a cloister vault typology (Figure 6), evenly spaced along its length with two smaller domes at either end flanking a larger central dome. The Revit 2020 software has inherent limitations in modeling non-standard geometries, thus necessitating a decomposition of the object into its fundamental geometric constituents [43]. A cloister vault emerges from the orthogonal intersection of two barrel vaults, whereas an octagonal cloister vault is formed by the intersection of two such vaults, one rotated by 45 degrees relative to the other. The Pavilion's domes bear distinct characteristics; for instance, the arch profiles of the barrel vaults are pointed and comprised of two arcs rather than regular circular forms. Moreover, the profile of the second cloister vault possesses a slightly wider base than the first, yielding a vault of varying dimensions. Consequently, the resulting octagonal base cloister vault, stemming from the intersection of these two vaults, presents an irregular base. This irregularity introduces a dynamic variance, imparting less uniformity and additional movement to the object's geometry, yet preserving symmetry (Figure 7).



Figure 6. Dome of the Lisbon Agricultural Exhibition Pavilion. (Left): interior view of the dome. (Right): exterior view of the dome.

In architectural modeling, Revit and similar BIM software often face limitations with their toolsets. Typically, each family within the software has a specific modeling logic, which generally meets the basic and simplified needs of architectural element reconstruction. Moreover, Revit provides a free-form modeling tool that allows the creation of more complex geometries. However, this tool is confined to basic primitive geometry techniques, including extrusion, sweep, revolution, and blending, applicable for both solid and void modeling. Nonetheless, the software lacks native options for NURBS modeling, which would be more suitable for intricate geometries.

In the case of the domes at the Exhibition Pavilion, the mass modeling tool was initially employed to generate the surface of the dome, which would later be used to accommodate the dome's construction elements, such as roofing and structural components. This was achieved by extrapolating profiles from the dome's primitive geometry and applying solid and void extrusion techniques, as well as form subtraction, to form the corresponding mass for each dome. Subsequently, the mass surface served as a base to create the exterior layer of the roof cladding using the "wall by face" tool. Although Revit's "roof by face" tool is available, it was unsuitable for the roof's significant incline and complex shape, necessitating the creation of a custom roof family that includes all

essential physical characteristics, similar to what would be achieved using the standard roof tool functionality. Following this, the “curtain system by face” tool was utilized to create a sloping glazed curtain panel system, which also provided the framework for implementing the existing steel structural profiles within the dome. Lastly, finishing details and ornamentation were added, and while the mass layer was disabled to declutter the model, it was preserved within the design for potential future adjustments to the dome’s form (Figure 8).

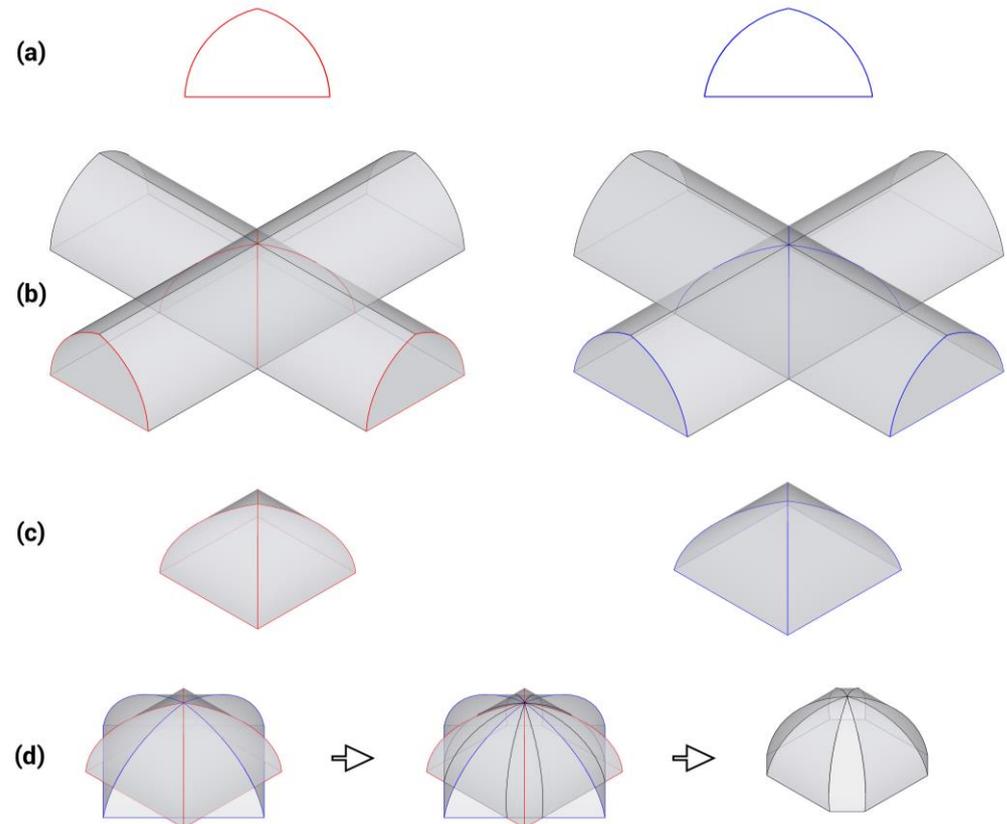


Figure 7. Geometric composition of the Exhibition Pavilion’s dome: (a) illustration of the basic arch profiles derived from the vault, (b) formation of two intersecting barrel vaults at right angles, (c) resultant cloister vault created from the interlocking of the barrel vaults, and (d) overlay of two cloister vaults with a 45-degree rotation of one, leading to the formation of the final octagonal-based cloister vault.

The modeling strategy for other building components was adapted based on the nature of the element and the desired level of detail. Decorative features, such as moldings and cornices on the walls and ceilings, were sculpted using the in-place free-form modeling tool in Revit. This method involved utilizing profiles that were extracted and drawn from the point cloud data. Complex wall geometries located on the lower level, particularly those beneath the main staircases, necessitated the use of the free-form modeling tool due to their non-standard, curvilinear shapes, exhibiting distinct variations from base to top.

The balustrades of the external handrails required the construction of a dedicated family within the Revit family editor. To achieve the required detail for these organically shaped elements, a mesh—created using CloudCompare—was imported into the family editor to provide a precise reference for modeling and to aid in the accurate depiction of ornamental details (Figure 9).

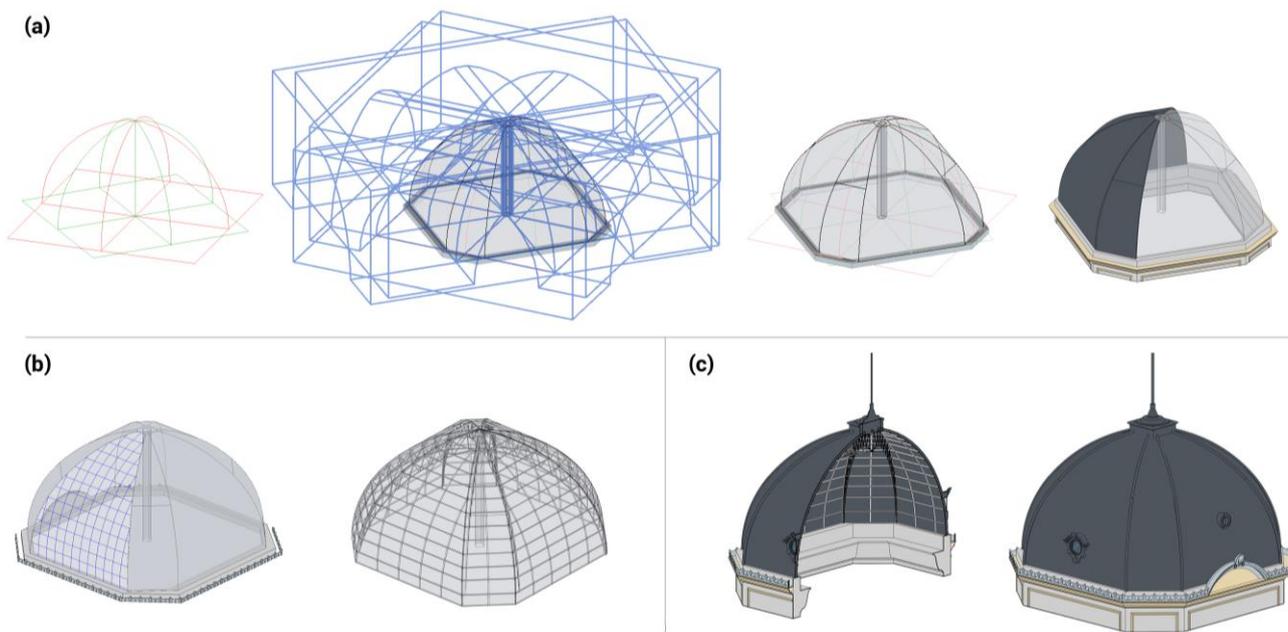


Figure 8. Scan-to-BIM Modeling Workflow for the Lisbon Agricultural Exhibition Pavilion Domes: (a) Extraction and identification of primitive geometric profiles for the domes; application of solid union and subtraction operations to derive the geometric form and implementation of the “wall by face” tool to model the dome’s external BIM cladding elements. (b) Employment of the “curtain system by face” tool to assemble the structural components. (c) Three-dimensional sectional view and the completed model of the dome.

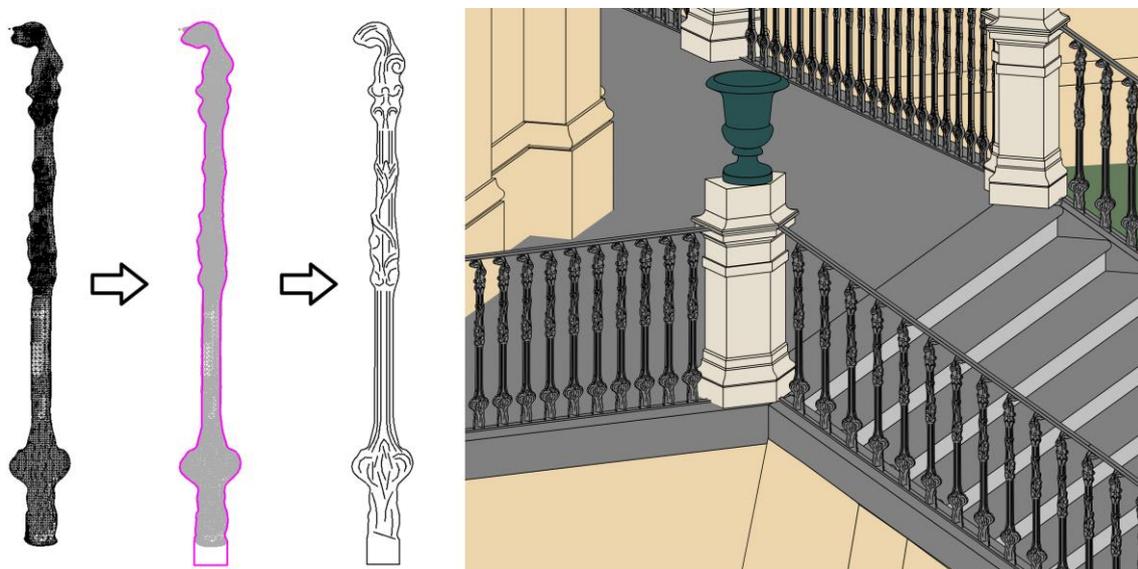


Figure 9. Modeling of the baluster family for the guardrails of the Exhibition Pavilion.

The modeling of ornamental elements was effectively achieved using the point cloud’s resolution, supplemented by survey photographs and manual measurements from the site. This approach ensured that each element was represented accurately, focusing on preserving the essential proportions and dimensions (Figure 10). For elements with non-uniform or organic details, the modeling was approximated to reflect reality while maintaining coherence (Figure 11). This method of representation, balancing detail and simplification, was tailored to fulfill the project’s objectives and scope efficiently. Some building elements, such as the external glass doors, the ocular features in the domes, and the intricate roof

eaves, were initially modeled in-place within the Revit environment. Upon completion, these were converted into loadable families for integration and potential reuse. Finally, the site's topographic surface was created using the "Scan Terrain" plugin, a method that allowed for an accurate representation of the actual terrain within the BIM environment.

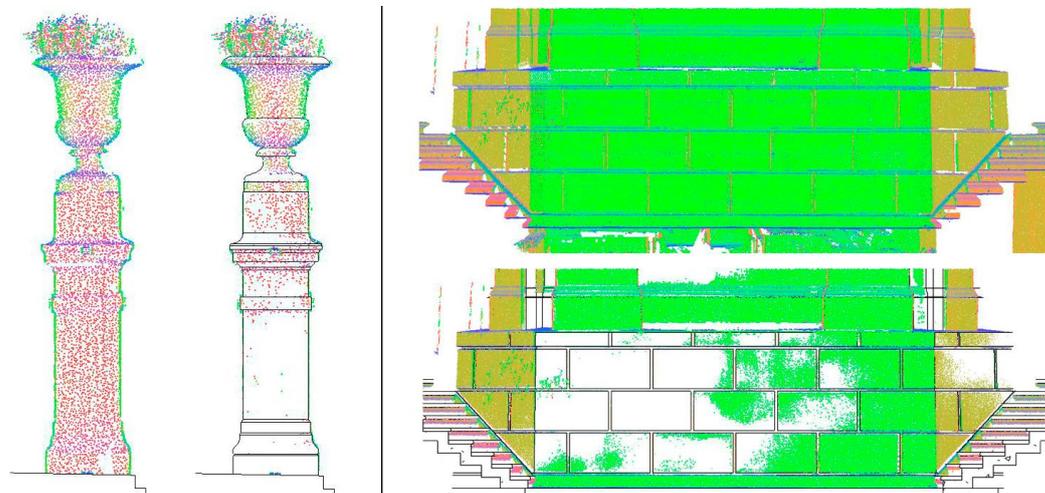


Figure 10. Representation of architectural details. (Left): comparison between the point cloud, colored based on the normal direction of each point, and the BIM model created for a post with ornamental details. (Right): comparison between the point cloud and the BIM model created for the ornamental details on the building's exterior wall cladding.

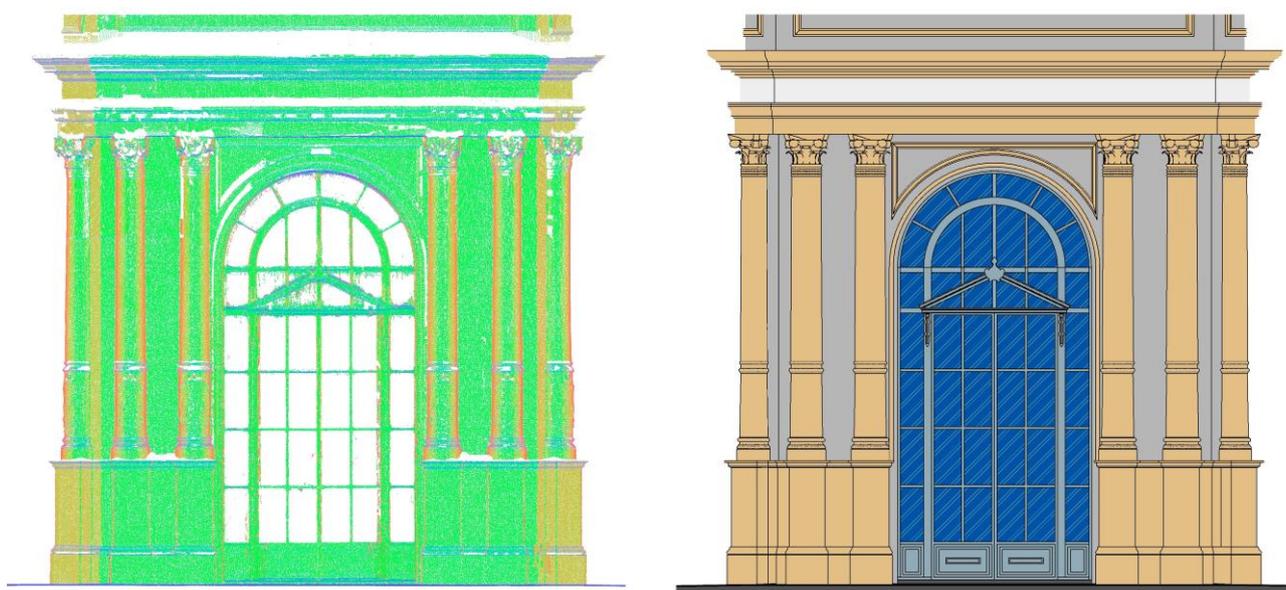


Figure 11. (Left): point cloud of the main entrance door and ornamental columns on the facade of the Exhibition Pavilion. (Right): BIM model generated from the point cloud data.

3. Results

The BIM modeling process was undertaken with a top-down approach, enhancing the LOD as the project progressed (Figure 12). This started with the establishment of the Pavilion's geometric framework and the creation of its main components. Subsequently, detailed elements were incrementally added. This systematic approach made the modeling more manageable by emulating the actual construction logic, adhering to the order and hierarchy of the building's elements.

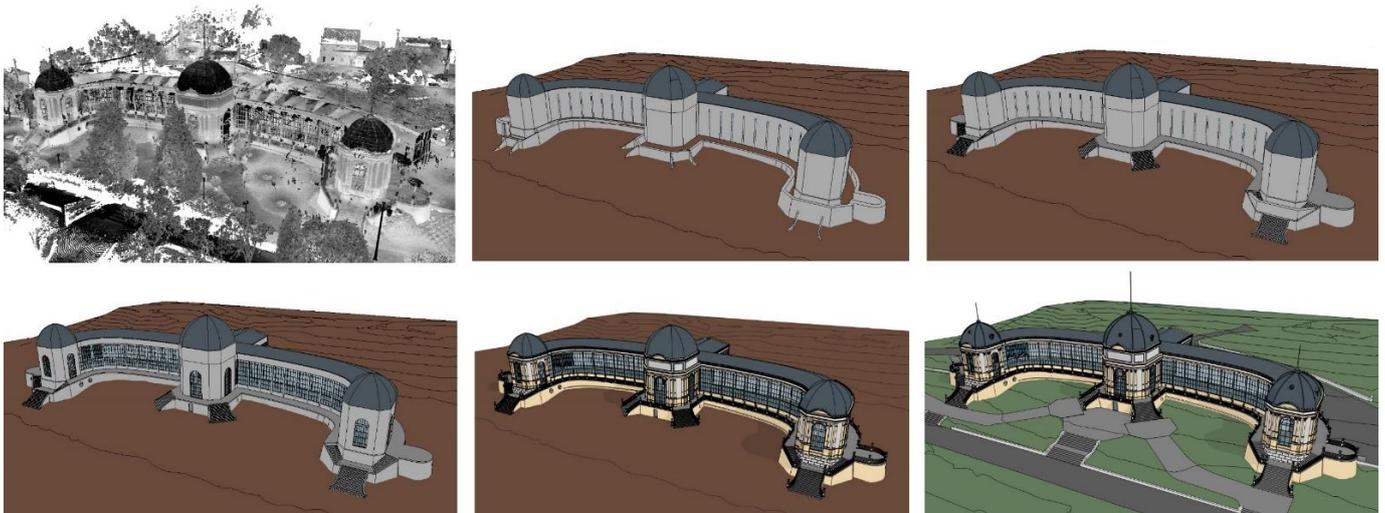


Figure 12. Evolution of the BIM model construction for the Lisbon Agricultural Exhibition Pavilion, from the point cloud data to the final BIM model.

For the creation of a coherent BIM model suitable for integration into subsequent BIM workflows for renovation and restoration projects, organized and precise categorization of elements and components is essential. In the Pavilion case study, modeling solutions relying on models created in other software or mesh modeling were consciously avoided. Instead, all elements in the model were developed using the tools available in Revit, ensuring they were correctly classified and categorized. Such a methodical approach enables the accurate extraction of information, including precise measurements, material quantities, and details about the geometric and constructive characteristics of the building's current state. This case study aimed to model all the main architectural elements of the building. Some were modeled using a traditional approach common to the element, others required customized modeling with in-place solutions or through mass studies, and some were automated using plugins (Table 1).

Table 1. List of architectural elements modeled and the type of approach used.

Element	Modeling Type	Element	Modeling Type
Columns—Decorative	In-place	Plumbing Fixtures	Standard
Columns—Structural	Standard	Posts/Balusters	In-place/Standard
Domes	Mass/Standard	Railings	Standard
Domes' Structures	Mass/Standard	Roofs	Standard/In-place
Doors—Glass	In-place	Stairs	Standard
Doors—Standard	Standard	Topography	Automatic
Floors—Exterior	Automatic/Standard	Trusses	Standard
Floors and Slabs—Interior	Standard	Walls	Standard/In-place/Mass
Ornamental Elements	In-place	Windows	Standard

The comparative analysis between the BIM model and the point cloud data of the existing building reveals the level of accuracy achieved through manual modeling methods. The images show the deviations between the BIM model and the actual structure, with the color gradients on the heatmap indicating different levels of distance from the point cloud (Figure 13). The histogram quantifies these differences, with a distribution of signed distances primarily clustered around zero, indicating an alignment of the manual BIM model with the physical measurements (Figure 14). This alignment results in an average distance discrepancy of 12 mm for both the complete building model and the isolated wall structures, illustrating the method's consistency across different modeling scenarios.

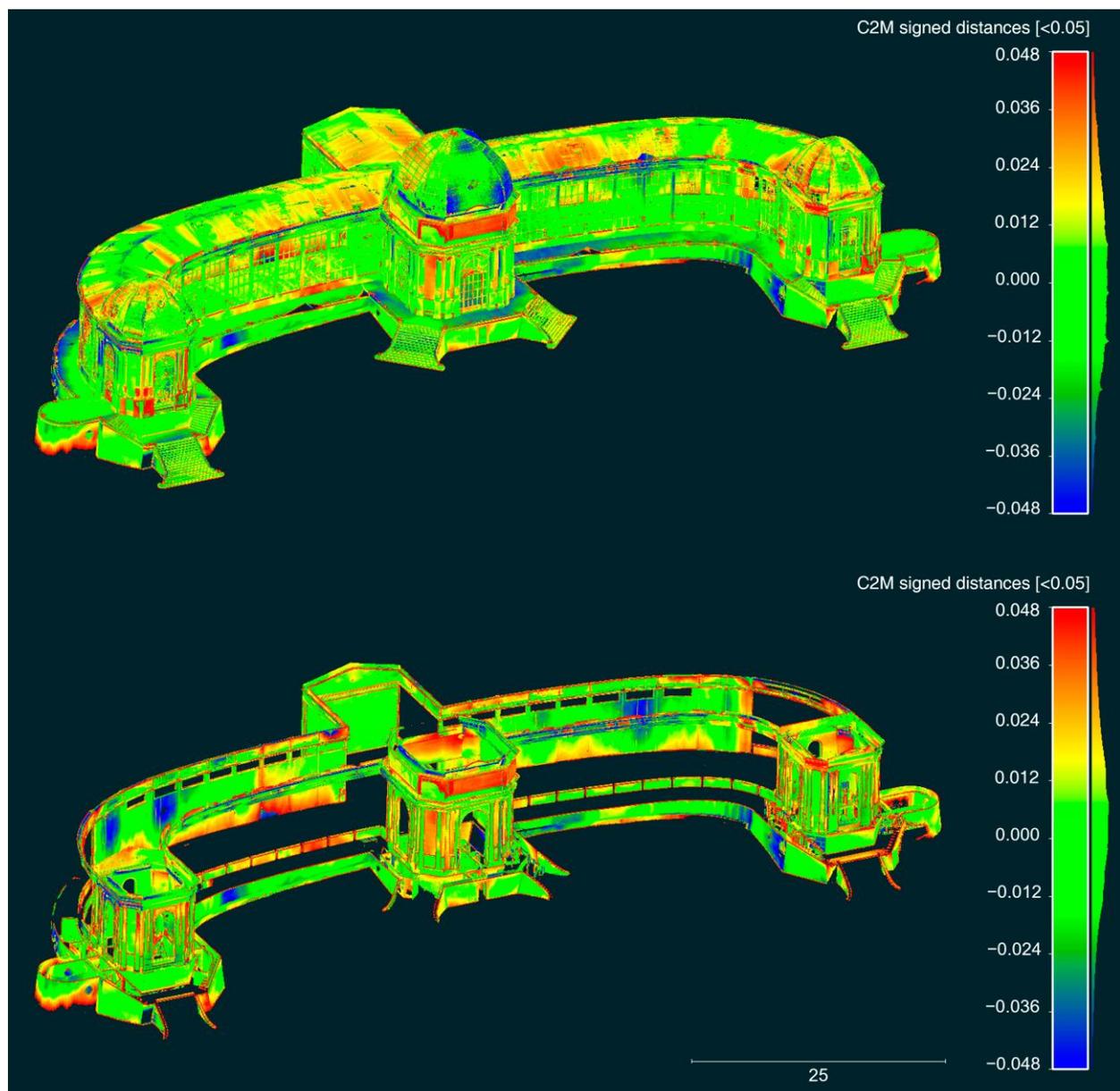


Figure 13. Model accuracy and deformation of the existing structure analysis. (**Top**): comprehensive analysis of the complete building model. (**Bottom**): specific analysis of the building's wall structures.

Beyond quantifying the model's accuracy, these analyses offer valuable insights into the current condition of the building's structural elements and wall integrity. Since the BIM model was constructed to disregard surface deformations, the resulting discrepancies highlighted by the heatmap provide a detailed map of imperfections on the building's surfaces. This allows for a thorough assessment of potential structural anomalies, such as deviations, inclinations, and deformities. Through this meticulous evaluation, the model serves not only as a record of the building's current state but also as a diagnostic tool, revealing areas that may require intervention or closer monitoring.

In a BIM model, different elements have varying levels of development following guidelines established by the American Institute of Architects (AIA) [32]. Each element in the BIM model is assigned a LOD which indicates how much information it contains. The majority of the model adheres to LOD 300 and LOD 350 standards. LOD 300 focuses on modeling building elements with geometry and spatial relationships, while LOD 350 includes elements modeled with enough detail to show their interaction with various

systems and neighboring components [32,33]. This approach ensures that every aspect of the building is represented with a level of detail striking a balance between accuracy and providing information.

C2M signed distances[<0.05] (91,278,019 values) [256 classes]

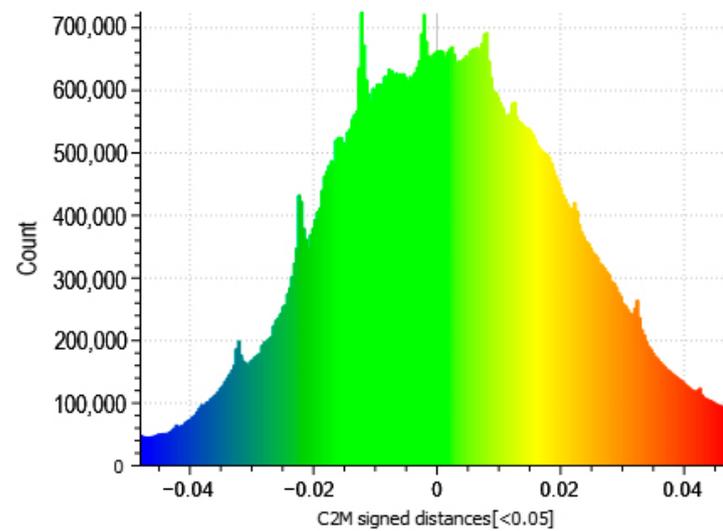


Figure 14. Histogram of signed distances: distribution of discrepancies between the BIM model and point cloud data, indicating the precision of the model's geometric representation.

The completion of the BIM model for the Lisbon Agricultural Exhibition Pavilion involved a cumulative effort of 147 h, ranging from the initial architectural surveying to the final model creation. The architectural survey phase, encompassing the building's digitization via TLS and survey data acquisition using GNSS technology, was conducted over a period of 6 days, totaling 12 h and 30 min. Subsequent office tasks, including scan registration, processing, georeferencing, and both the generation and refinement of the point cloud, were executed over 15 days, accounting for 48 h and 8 min of work. The construction of the BIM model represented the most significant portion of the timeframe, consuming 99 h and 22 min across 18 dedicated workdays. These stages are documented in detail in Table 2.

Table 2. Tools Used and Time Spent on Each Stage.

Phase	Tools	Hours
Survey		
3D Laser Scanning	Faro Focus 120 S Scanner laser 3D	11 h 30 min
GPS	Trimble R8 GNSS GPS	1 h
Data Processing and Alignment		
3D Laser Scanning Point Cloud	Faro Scene	41 h 20 min
Georeferencing	Faro Scene	6 h 2 min
Cleaning and Optimization	Cloud Compare, Autodesk Recap	45 min
BIM Modeling		
Standard Modeling	Autodesk Revit 2018	85 h 32 min
Automatic Modeling	Scan Terrain Revit Plug-in	7 min
Documentation	Autodesk Revit 2018	13 h 42 min
Total		147 h 30 min

Upon the finalization of the BIM model, the requisite technical drawings and key graphical representations of the project were produced (Figures 15–17). By leveraging the advanced functionalities of BIM technology, these outputs were generated with greater speed and precision than is typically achievable through conventional methods, such as those employed in CAD systems.

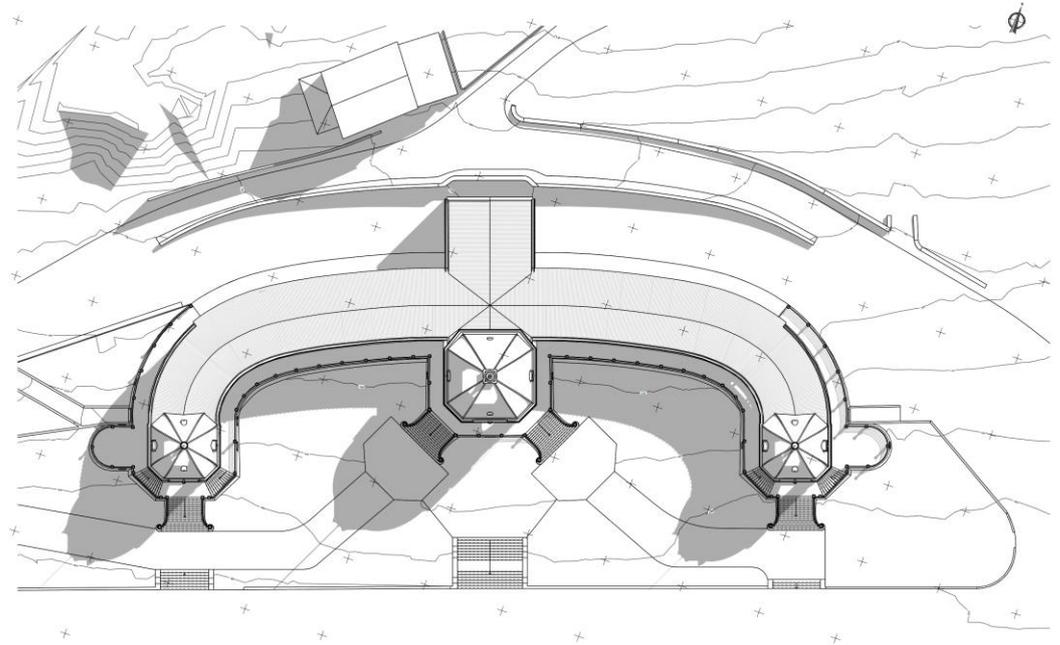


Figure 15. Site plan of the Lisbon Agricultural Exhibition Pavilion.

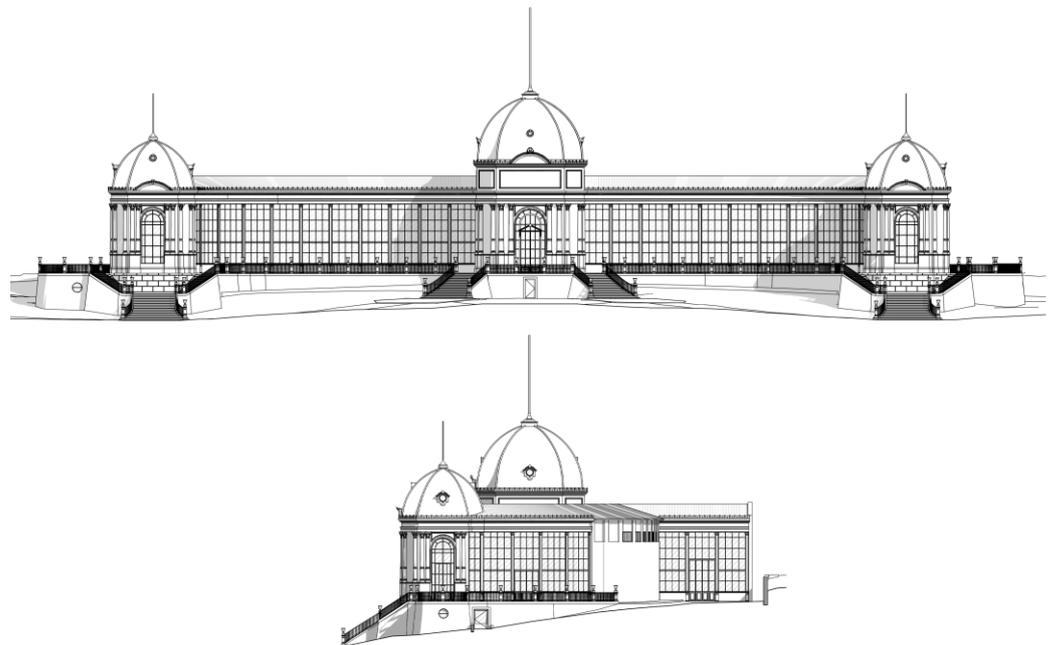


Figure 16. Exterior elevations of the Lisbon Agricultural Exhibition Pavilion.

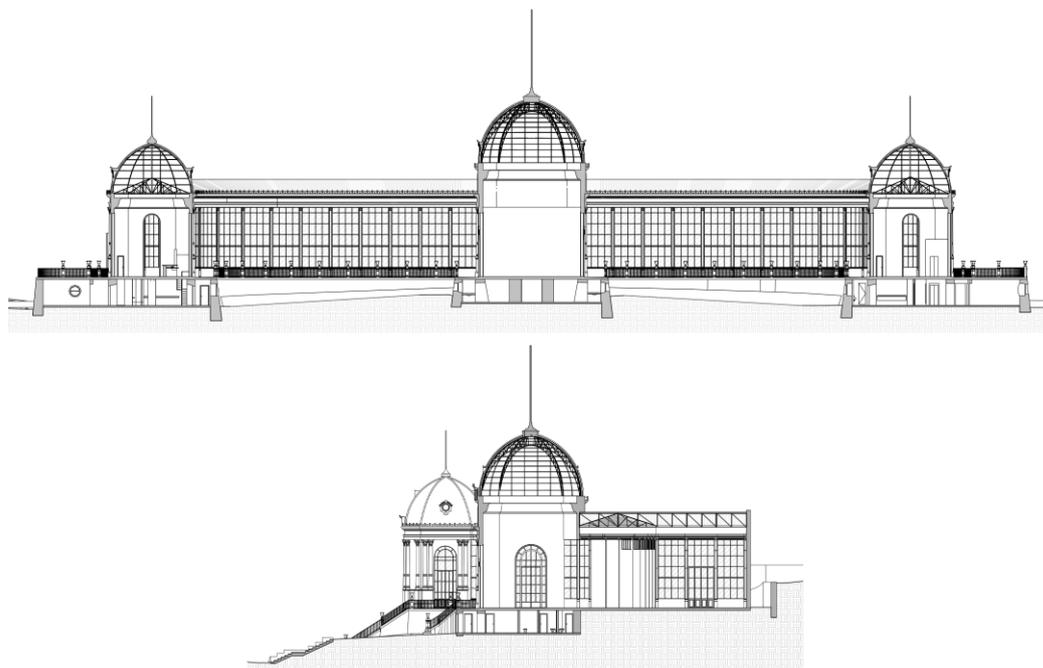


Figure 17. Building sections of the Lisbon Agricultural Exhibition Pavilion.

4. Discussion

Reality capture technologies, such as 3D laser scanning, provide a highly accurate and detailed methodology for the recording and surveying of architectural objects. Transforming these data into point clouds and subsequently into BIM models is of significant importance in the fields of conservation, restoration, and rehabilitation of historical heritage. This conversion enables the detailed digital reconstruction of historically valuable buildings, facilitating structural analyses, architectural documentation, and the planning of preservation interventions. Owing to these benefits, the scan-to-BIM process was applied to the Lisbon Agricultural Exhibition Pavilion for thorough documentation and detailed analysis of the structure to support future projects.

The objective of this case study was to capture the current state of the Pavilion, generate a 3D model, and create necessary graphic documents, such as floor plans, sections, and elevations for use in the rehabilitation design by the owner of the building. The BIM model produced notable results, offering a detailed three-dimensional view of the Pavilion and providing precise measurements of spaces, locations of windows and doors, the geometry of decorative elements, and details of the existing construction method. Furthermore, the model facilitated the simulation of rehabilitation scenarios and the evaluation of their impact on the structure.

The modeling of the Exhibition Pavilion presented unique challenges. Its complex design features numerous details and ornaments on its external facades, and it follows a distinctly classical style, characterized by specific rules of proportion and symmetry [52,53]. Before starting the modeling process, it was crucial to analyze and break down the building's geometry. This step involved identifying symmetrical axes and understanding the underlying design principles. Modeling such classical structures requires a deep comprehension of their architectural language and the rules used in their composition [39]. The ability to understand and apply these concepts ensures that the model is created with precision, making certain that all elements fit together appropriately and form an accurate representation of the building. Moreover, comprehending the logic behind the geometric design also aids in identifying potential errors and inconsistencies in the model, which is crucial for the integrity of subsequent studies. Therefore, it is imperative that professionals involved in the modeling process possess a robust understanding of these concepts and are capable of applying them accurately.

In the process of modeling the Exhibition Pavilion, a significant emphasis was placed on grasping the building's geometric logic and the architectural principles governing its design as these also consist of a specific type of heritage value. The Pavilion, with its intricate details and classical style, necessitated a comprehensive understanding of the rules of proportion and symmetry inherent in its architecture. Grasping the original architect's intent was essential to ensure the BIM model accurately reflected the reality of the structure. This understanding was crucial not only for achieving geometric precision in the model but also for maintaining the building's historical authenticity. It involved a meticulous deconstruction of the Pavilion's design, paying close attention to the way various elements aligned and interacted. By thoroughly understanding and applying these architectural principles, the modeling process could effectively replicate the building's inherent aesthetic and structural nuances, ensuring a faithful digital representation of this historical building. While our approach ensures a model coherent with the architect's intentions, it is crucial to remember that even the most accurate digital model is still an abstraction of reality. It represents a real object in a simplified form, adhering to a pre-established level of tolerance [28,30,31].

Our case study serves as an early stage in the BIM workflow, focusing on integrating an existing building into a BIM environment to leverage the full capabilities of this methodology. Architectural elements were modeled to ensure a smooth transition into BIM systems, structured to be augmented with detailed attributes and parameters progressively. The model's current form is focused on accurately capturing the geometry and complex structural elements, laying the groundwork for a subsequent HBIM process that can incorporate non-geometric data such as historical context, cultural significance, and material condition [30,47,48,55,56]. This initial model is essential for progressing into detailed heritage conservation and effective building lifecycle management.

One limitation of the point clouds is that they only capture the building's visible surfaces and require expert interpretation to transform them into an architectural model [25]. This task necessitates not only an understanding of the raw data but also an ability to integrate supplementary information from photographs, existing technical drawings, and on-site observations. It is advantageous for the modeling professional to participate in field surveys to gain direct insights.

When interpreting the point cloud data, expertise in architecture and construction is vital. While some elements like walls and their thicknesses are straightforward, others, such as structural connections obscured within the point cloud, demand a more nuanced analysis to ensure accurate representation in the BIM model.

In the domain of architectural conservation, the scientific contribution of this research lies in the advanced application of Terrestrial Laser Scanning and its integration into BIM processes. The novelty of this study is manifested in the methodical approach to capturing every visible aspect of the Lisbon Agricultural Exhibition Pavilion with high precision, while preserving the geometric generative logic, facilitating a level of accuracy in the digital representation that surpasses traditional surveying methods.

The benefits of this technological synergy include not only time efficiency and enhanced data accuracy but also the capacity to maintain the structural and historical integrity of heritage sites [41]. This is achieved through a rigorous initial survey, leading to a high-quality point cloud that forms the foundation for a BIM model that accurately reflects the original structure's geometric integrity. This study introduces a novel form grammar-based modeling approach that adheres to the building's intrinsic symmetries and proportions, preserving its historical and architectural significance. This customized BIM reconstruction process showcases the potential of integrating advanced digital technologies in capturing the complexities of historic buildings, offering a methodological advancement in the preservation and analysis of cultural heritage architecture.

Our approach, integrating BIM with laser scanning, contrasts with traditional methodologies, offering both distinct advantages and notable challenges. The detailed data from laser scanning enhance BIM models' accuracy, especially valuable for complex historical

structures, allowing for a more nuanced representation than conventional surveying. However, the increased costs and need for technical expertise with these advanced technologies may impact accessibility and extend the initial stages of data collection and modeling.

Moreover, in contrast to traditional CAD-based methods, the application of BIM in historic building modeling can integrate several key advantages. It goes beyond capturing geometric details to include material properties and historical context within its dynamic, integrated models. This capability facilitates an in-depth understanding crucial for heritage conservation efforts. BIM's comprehensive approach, enabling improved information management and enhancing collaboration among various stakeholders, demonstrates its capacity to outperform CAD in complex conservation and restoration projects [41].

5. Conclusions

The results of this study demonstrate the efficacy of using Terrestrial Laser Scanning (TLS) in conjunction with Building Information Modeling for the detailed documentation and analysis of historical structures and heritage architecture. The case study of the Lisbon Agricultural Exhibition Pavilion highlights the strengths and challenges of integrating advanced digital technologies in architectural conservation.

The advent of 3D laser scanning has significantly revolutionized the process of architectural surveying, especially for structures with complex designs like the Exhibition Pavilion. In traditional surveying methods, capturing the intricate details and unique geometries of such a building posed a considerable challenge, often resulting in time-consuming and less accurate data. However, with 3D laser scanning, every visible element of the Pavilion can be captured and precisely mapped.

Achieving accuracy in geometric modeling centers on conducting a detailed and precise initial survey. An inadequately captured point cloud, especially one with significant occlusions, can detrimentally affect the accuracy of the BIM process. In some cases, such deficiencies can even prevent the successful construction of a BIM model. In light of this, the meticulous steps undertaken in the surveying phase are of immense importance. It is crucial to ensure that every visible aspect of the building's geometry is thoroughly and accurately documented. This rigorous approach in the survey phase is aimed at producing a high-quality point cloud, which is a vital foundation for the subsequent modeling process. A well-captured point cloud not only aids in creating a precise BIM model but also plays a significant role in the overall utility and reliability of the final architectural product.

In the creation of the BIM model of this heritage building, a departure from standard modeling practices was necessary to capture its unique architectural essence. The model's development, guided by form grammar principles, was critical in achieving an accurate reflection of the original structure's geometrical integrity. This approach, focusing on the building's intrinsic symmetries and proportions, facilitated a model that resonates with the building's historical and architectural significance. The strategic decomposition of the Pavilion's form into its fundamental structural elements, adhering to their inherent arrangement and hierarchy, was instrumental in preserving the architectural fidelity.

The process emphasized the importance of understanding and respecting the building's constructive hierarchy and design phases. By starting the modeling from the structural base and aligning it with the identified construction axes, potential discrepancies in the less precise enclosure elements were effectively mitigated. This methodology not only ensured geometric consistency but also highlighted the necessity of a thorough and nuanced approach in heritage building BIM reconstruction. This study underscores the value of a point cloud as a foundational reference, essential for achieving a harmonized spatial representation that aligns with the building's historical context. These insights demonstrate the potential of BIM methodologies in enhancing the accuracy and authenticity of digital models of historic structures.

In conclusion, this study demonstrates the efficacy of integrating BIM with laser scanning for architectural rehabilitation, especially in documenting and analyzing historical structures. The case study of the Lisbon Agricultural Exhibition Pavilion illustrates

how this approach offers a more detailed and accurate representation than traditional methods, particularly because it took into consideration the geometric generative logic of the building. The detailed 3D models generated provide invaluable data for planning future designs, demonstrating the substantial benefits of this technology in preserving architectural heritage.

However, it is important to acknowledge the challenges, including the need for technical expertise and higher costs associated with these advanced technologies. Future research should focus on addressing these challenges, optimizing the integration process, and exploring the potential for broader application in heritage conservation. The insights gained from this study pave the way for further advancements in digital preservation techniques, contributing to the field of architectural heritage conservation.

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