Journal of
Engineering Sciences
Faculty of Engineering
Assiut University

مجلة
العلوم الهندسية
كلية الهندسة
جامعة أسيوط

journal homepage: http://jesaun.journals.ekb.eg

3D Modeling and Digital Documentation of Heritage Architecture for Preservation and Restoration

Received 28 June 2025; Revised 21 September 2025; Accepted 21 September 2025

Mohamed Saleh Sedek[1]
Abdulaziz Mansour[2]
Ahmed Serwa [3]

Keywords
Terrestrial Laser Scanning; Heritage Documentation: CAD Modeling: Cultural Preservation Dimensional Analysis.

Abstract: The preservation of heritage structures requires accurate documentation methods capable of capturing complex architectural geometries. This study presents a comprehensive digital workflow that integrates Terrestrial Laser Scanning (TLS) with CAD modeling to document and analyze the Baron Empain Palace in Cairo—an Indo-European landmark known for its intricate ornamentation. Traditional survey techniques often fall short in representing such complexity. To address this, high-resolution TLS data were acquired using the Z+F Imager 5006i, yielding over 159 million points, which were then processed through a structured pipeline involving noise filtering, mesh optimization, and CAD-based dimensional analysis. Using Geomagic Studio 12, the Mesh Doctor module repaired over 5 million mesh triangles, enabling the creation of a continuous polygonal model without compromising surface detail. A representative architectural column was selected to demonstrate the method's effectiveness in preserving ornamental features. The workflow emphasized organic surface reconstruction over parametric modeling to maintain the structure's historical authenticity. Key outputs included precise dimensional measurements, surface area, and volume calculations, which support applications such as material estimation, load distribution analysis, and restoration planning. The final digital model serves not only as a structural analysis tool but also as a long-term preservation asset. This research establishes a scalable, replicable workflow tailored to complex heritage sites, bridging technical precision with conservation needs. By advancing digital heritage documentation through accessible and high-fidelity modeling, the study contributes to sustainable cultural preservation and broader engagement through education and virtual access.

[1] South Valley University, Faculty of Engineering, Civil Engineering, Egypt, drmohamed.saleh@eng.svu.edu.eg
[2] South Valley University, Faculty of Engineering, Civil Engineering, Egypt a.mansour@eng.svu.edu.eg
[3] Helwan University, Faculty of Engineering Mataria Civil Engineering, Egypt, dr.a.serwa@m-eng.helwan.edu.eg

https://doi.org/10.21608/jesaun.2025.398784.1581

1. Introduction

1.1 General Background and Significance

Cultural heritage—both tangible and intangible—forms the bedrock of human civilization, encompassing architectural marvels, archaeological sites, religious landmarks, and traditions that span generations. These cultural assets are essential not only for preserving the memory of past societies but also for cultivating a sense of identity, belonging, and historical continuity within communities. As monuments, buildings, and relics reflect a society's technological, artistic, and ideological accomplishments, their loss would mean the erosion of cultural diversity and intergenerational knowledge. In particular, Egypt's rich historical landscape, home to some of the world's most treasured monuments, is under increasing threat from environmental decay, modernization, neglect, and conflict [1,2,3].

1.2 Statement of the Research Problem

Globally, efforts to preserve heritage have evolved from traditional physical restoration techniques toward more technologically sophisticated methodologies. International initiatives—such as UNESCO's Revive the Spirit of Mosul campaign or the post-disaster reconstruction of Brazil's National Museum—highlight the growing reliance on digital technologies to document, analyze, and safeguard endangered heritage assets [4,5,6]. Among these technologies, Terrestrial Laser Scanning (TLS) has emerged as a leading innovation, offering unparalleled precision and efficiency in heritage documentation. TLS enables the non-invasive capture of millions of data points from a structure's surface, producing a "point cloud" that can be processed into highly accurate three-dimensional (3D) models. These models serve multiple functions: they facilitate restoration efforts, allow for structural assessments, enable virtual access through augmented and virtual reality, and create permanent digital archives to safeguard heritage even in the face of disaster [7,8,9]. However, despite the growing international adoption of TLS, its integration into heritage conservation workflows—especially in developing regions—remains limited. This limitation arises from multiple factors, including high equipment and processing costs, the complexity of managing massive datasets, and the scarcity of trained professionals capable of converting raw scan data into meaningful heritage preservation outputs [10,11]. In countries like Egypt, where numerous historical monuments are at risk of degradation, the underutilization of TLS reflects a broader gap in the application of digital preservation technologies [6].

Local heritage preservation efforts in Egypt have increasingly incorporated digital documentation techniques. For instance, laser scanning and close-range photogrammetry were used to develop a detailed 3D map of the Valley of the Kings, supporting geophysical and topographic analyses [12]. Similarly, a Valley of the Queens conservation project integrated laser scanning to generate high-accuracy topographical maps and GIS layers as part of a broader preservation and management initiative [13]. While these initiatives underscore the growing adoption of 3D surveying in local heritage contexts—particularly for visualization, spatial mapping, and risk assessment—the current study advances this work further by coupling Terrestrial Laser Scanning (TLS) with CAD-based modeling. This combined approach enhances dimensional fidelity and enables rigorous structural documentation and restoration planning for complex heritage architecture.

1.3 Overview of TLS and CAD Modelling as a Solution

The effectiveness of TLS lies in its ability to address the deficiencies of traditional heritage documentation methods. Conventional techniques such as manual surveys, hand-drawn schematics, and photography are time-consuming, labor-intensive, and often inadequate for capturing the detailed and intricate geometries of complex structures. These methods can miss minute features, are prone to human error, and typically fail to provide the level of spatial resolution necessary for accurate structural analysis [14,15].

Moreover, TLS is critical for supporting modern heritage conservation frameworks such as Heritage Building Information Modeling (HBIM). HBIM systems integrate geometric and semantic data, creating rich, dynamic models that can simulate structural behavior, monitor degradation, and inform preservation strategies. These models provide a collaborative platform for interdisciplinary work, allowing historians, architects, engineers, and conservationists to share insights and make informed decisions. TLS data serves as the foundational layer for these systems, supplying the high-resolution spatial information necessary for accurate modeling [8,6,16].

The potential of TLS has been demonstrated in numerous high-profile preservation projects. For example, the Notre-Dame Cathedral in Paris was digitally scanned prior to its 2019 fire, and the resulting 3D models proved invaluable for restoration planning after the disaster (Dupont et al., 2020). Similarly, the Ancient City of Aleppo and Palmyra in Syria have benefited from 3D scanning technologies to guide post-conflict reconstruction efforts [6,7].

Nevertheless, integrating TLS into heritage workflows is not without challenges. One major issue involves the processing of large point cloud datasets, which often contain billions of data points. Transforming this raw data into usable 3D models demands powerful computing systems, specialized software, and skilled personnel capable of aligning scans, removing noise, reconstructing surfaces, and applying textures. Techniques such as Poisson surface reconstruction, Delaunay triangulation, and Iterative Closest Point (ICP) registration are critical steps in the modeling pipeline, each requiring precision and computational resources [17,18].

Another significant barrier to widespread adoption is the high cost of TLS systems and the technical expertise required to operate them. While the cost-benefit ratio may be favorable in large-scale or nationally significant projects, many smaller or lesser-known sites may lack access to funding, skilled operators, or institutional support. In such cases, the digital divide further endangers heritage preservation, creating disparities between well-funded, globally visible monuments and vulnerable, locally significant sites. Moreover, many heritage institutions have yet to establish standardized workflows for TLS data acquisition and processing, leading to inconsistencies across projects and reduced efficiency in comparative or longitudinal analyses [19,20].

This research aims to address these pressing issues by exploring how TLS can be effectively integrated into heritage preservation efforts, with a specific focus on optimizing data processing workflows, validating accuracy, and assessing the applicability of TLS-generated models for structural analysis, restoration planning, and digital archiving. By developing and evaluating streamlined methodologies for transforming TLS data into actionable conservation models, this study seeks to make the technology more accessible and usable across a wider range of heritage sites. It also investigates the role of CAD-based modeling in translating point clouds into formats suitable for visualization, public education, and interdisciplinary collaboration [21,22].

Ultimately, this thesis contributes to the growing body of literature on the digital transformation of heritage preservation by offering practical solutions to overcome the technological and operational limitations associated with TLS. By focusing on both technical innovation and cultural sensitivity, this research aims to advance a scalable model for digital heritage documentation that supports preservation, restoration, and education across diverse historical contexts. Through this work, the study seeks to underscore the importance of integrating high-resolution digital technologies like TLS into the global effort to safeguard cultural heritage—before it is lost forever.

2. Methods and tools

This study employs Terrestrial Laser Scanning (TLS) to document and analyze the Baron Empain Palace, aiming to establish efficient workflows for 3D heritage documentation, structural analysis, and restoration planning. The Baron Empain Palace, a complex heritage site in Cairo, Egypt, was selected as the case study due to its intricate architectural features and historical significance. Constructed between 1907 and 1911 by Belgian industrialist Baron Édouard Empain, the palace exemplifies Indo-European architectural fusion, incorporating elaborate carvings, sculpted columns, and Hindu-inspired design motifs. Over the decades, the structure has suffered deterioration due to environmental exposure, neglect, and urban encroachment, making it a compelling subject for digital heritage documentation. The palace's ornate geometry and conservation challenges provide an ideal context to evaluate the performance and limitations of TLS technology for large-scale architectural heritage. A view of the Baron Empain Palace prior to the 2020 restoration is shown in Figure 1.

Figure 1: A view of the Baron Empain Palace prior to the 2020 restoration.

2.1 Equipment and Software

Equipment: Data acquisition for this study was conducted using the **Z+F Imager 5006i**, Figure 2. A high-resolution terrestrial laser scanner capable of capturing detailed point clouds with sub-millimetre precision. The scanner was configured to operate at a medium resolution of approximately 6 mm point spacing at a 10-meter range, balancing detail capture and scan efficiency. Its extensive field of view and high-density output made it particularly well-suited to documenting the complex architectural geometry of the Baron Empain Palace.

Supplementary equipment included **reflective targets**, which were strategically placed around the site to enable accurate scan alignment during the registration process. A **tripod** provided stability for the scanner at varying heights and angles, particularly when capturing vertical elements such as facades and columns. A **laptop** was used for real-time monitoring of scan acquisition and secure storage of raw data on-site, with immediate backups to prevent loss. Additional tools such as a **measuring tape** were used for scale verification, while a **high-resolution digital camera** provided photographic references to support colorization and texturing during the modeling phase. **Software:** Processing and modeling of the point cloud data were performed using **Geomagic Studio 12**, a specialized software suite designed for handling large and intricate datasets common in heritage documentation. The software was employed for key tasks including point cloud cleaning, scan registration, and surface reconstruction. Its powerful mesh generation tools enabled the creation of detailed 3D polygonal models, which served as the foundation for geometric analysis and visualization. Geomagic Studio 12 was selected for its ability to maintain accuracy and fidelity while managing the complexity and size of the dataset, which exceeded 850 million points across 52 individual scans.

2.2 Methods Overview

The methodological framework of this study follows a structured, multi-phase process centered on Terrestrial Laser Scanning (TLS) for heritage documentation, as illustrated in Figure 3. High-resolution point clouds of the Baron Empain Palace were acquired using the Z+F Imager 5006i, followed by comprehensive preprocessing steps including scan alignment, filtering, unit standardization, and data cleaning. A representative column was selected for in-depth CAD-based modeling and geometric analysis, enabling focused assessment of structural properties while optimizing computational efficiency. This approach ensured both the fidelity of documentation and the feasibility of analysis for large-scale architectural datasets.

Figure 2: Z+F Imager 5006i.

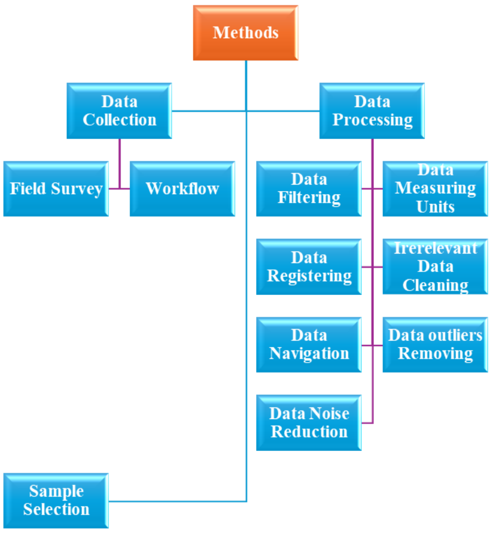

Figure 3: The methodological framework.

2.2.1 Data Collection

The study was conducted just prior to the 2020 restoration of the Baron Empain Palace, thereby documenting the monument in its pre-restoration condition. Field data collection took place between February and March 2019, followed by data processing and analysis completed by December 2019, for a total duration of ten months. The workflow was designed with a multidisciplinary scope, combining engineering accuracy, architectural detailing, and conservation considerations. This ensured the creation of a reliable digital record of the palace's architectural state before restoration interventions.

2.2.1.1 Field Survey

Field data acquisition was conducted at the Baron Empain Palace using the **Z+F Imager 5006i**, a terrestrial laser scanner selected for its high-resolution capability and sub-millimeter accuracy (Figure 2). The scanning aimed to capture the palace's complex architectural geometry, including detailed facades, sculptural elements, and structural components.

To ensure full spatial coverage, the scanner was deployed at multiple strategically chosen positions around and within the site. **Reflective targets** were placed across the survey area to support accurate alignment of overlapping scans during registration. Environmental considerations—such as daylight availability, surface reflectivity, and limited access areas—were factored into the planning to minimize data distortion.

Each scan was monitored in real-time and saved using a **field laptop**, with immediate **on-site backups** created to prevent data loss. The scanning campaign resulted in **52 individual scans**, generating approximately **33 GB of raw data**, comprising over **850 million points**.

2.2.1.2 Workflow

The scanning workflow followed a structured protocol to ensure comprehensive documentation and consistency across scan stations. The process began with careful **scanner setup**, including calibration, tripod stabilization, and field-of-view adjustment. **Scan stations** were selected to minimize occlusions and maximize visibility of key architectural features, such as columns, archways, and decorative elements.

Reflective targets were deployed at known reference points throughout the site to facilitate precise registration across scan positions. Environmental variables such as lighting direction, glare, and shadow zones were assessed at each position to optimize scan quality.

Each completed scan was immediately reviewed for completeness and alignment quality. The data were then transferred and duplicated for redundancy. This step-wise workflow ensured a robust and replicable field methodology that prioritized both accuracy and data security.

2.2.2 Data Processing

After the completion of on-site scanning, the raw point cloud data were imported into **Geomagic Studio 12** for preprocessing. This stage included initializing project parameters, managing scan metadata, and preparing the dataset for detailed refinement and modeling. Special attention was given to software configuration and hardware performance, as the dataset—comprising over 850 million points and totalling 33 GB—required efficient handling to avoid bottlenecks or data corruption.

To maintain geometric and metric consistency across all scans, the data environment was standardized in terms of coordinate system and measurement units. These preprocessing steps laid the foundation for subsequent filtering, registration, and cleaning processes.

2.2.2.1 Data Filtering

The filtering process was conducted to enhance the efficiency of modeling while preserving architectural detail. In this study, a deliberate decision was made to apply a **100% data sampling ratio** as shown as in Figure 4, meaning no reduction in point density was performed. This ensured that even the most intricate carvings and ornamental elements of the Baron Empain Palace were retained with full resolution.

This high-fidelity approach was especially important for heritage documentation, where minor losses in geometric data could compromise conservation or restoration accuracy.

2.2.2.2 Data Measuring Units

To ensure dimensional accuracy and interoperability with architectural and engineering standards, the **meter** was adopted as the standard unit of measurement throughout the scanning, processing, and modeling phases. This choice aligns with internationally accepted practices in heritage documentation and supports integration with CAD-based analysis and restoration workflows.

The unit setting was configured directly within the scanning and processing software environment and maintained consistently across all stages to prevent scale discrepancies. This approach facilitated reliable dimensional analysis and accurate comparison with existing survey records. The defined measurement unit is illustrated in Figure 5.

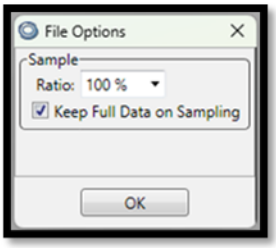

Figure 4: A 100% data sampling ratio.

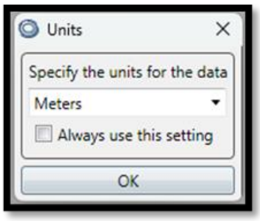

Figure 5: The defined measurement unit.

2.2.2.3 Data Registering

The raw TLS dataset consisted of **52 individual scans**, each capturing a portion of the Baron Empain Palace from different vantage points. To generate a cohesive 3D representation, these scans were aligned and merged through a **registration process** using **Geomagic Studio 12**.

Registration involved aligning overlapping point clouds based on the placement of **reflective targets** and geometric matching algorithms. This step was critical for eliminating spatial discontinuities and ensuring a seamless, unified dataset suitable for surface reconstruction and analysis. The resulting registered dataset accurately reflects the palace's full architectural geometry and serves as the foundation for all subsequent modeling efforts.

The scale and integration of the registered scans are illustrated in Figure 6.

Figure 6: The scale and integration of the registered scans.

2.2.2.4 Irrelevant Data Cleaning

Irrelevant data cleaning was carried out to eliminate extraneous elements from the unified scan dataset. Non-target points—such as those originating from surrounding vegetation, scaffolding, or reflective noise—were identified and removed using built-in filtering tools within **Geomagic**

Studio 12. This step improved the dataset's clarity and reduced processing complexity, ensuring that only architectural elements relevant to the analysis remained.

The cleaned dataset more faithfully represented the structural footprint of the Baron Empain Palace and formed the basis for subsequent alignment and orientation. The results of this cleaning process are shown in Figure 7.

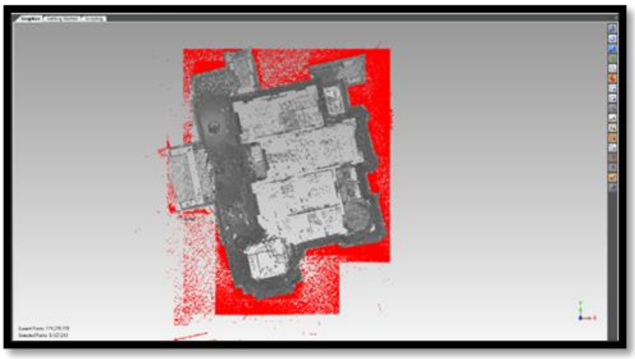

Figure 7: Cleaning Process.

2.2.2.5 Data Navigation

Following cleaning, the dataset underwent a reorientation step to align it with an **elevation view**. This **data navigation** process involved adjusting the point cloud's spatial perspective to support analysis of vertical architectural components such as columns, cornices, and facades. A new **wrap-format** dataset was generated during this phase, optimized for visualization and compatibility with modeling software.

This reoriented view not only improved interpretability but also prepared the dataset for precise geometric operations. The elevation-aligned dataset is illustrated in Figure 8.

Figure 8: The elevation-aligned dataset.

2.2.2.6 Data Outlier Removal

To enhance the precision of the dataset, **outlier removal** was conducted to eliminate points that deviated significantly from the overall geometric structure. These anomalies typically result from environmental interference such as reflections from shiny surfaces (e.g., glass or polished stone) and can introduce inaccuracies during modeling and analysis.

Using **Geomagic Studio 12**, a total of **3,267,892 outlier points** were identified and removed, resulting in a refined dataset of **159,526,918 points**. This refinement step improved both computational performance and the geometric fidelity of the resulting 3D model. The outcome of the outlier removal process is illustrated in Figure 9.

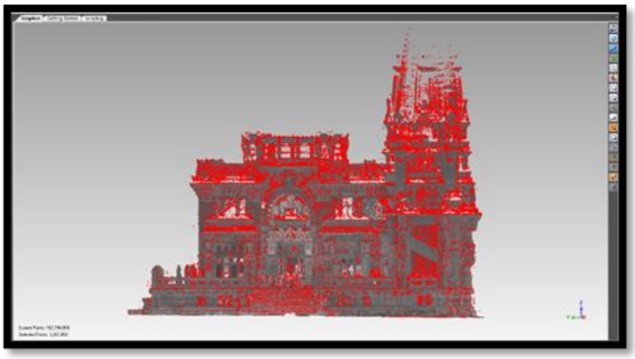

Figure 9: The outcome of the outlier removal process.

2.2.2.7 Data Noise Reduction

To further improve model quality, **noise reduction** techniques were applied to suppress random variations in point positioning while preserving the true geometry of the scanned structure. Environmental noise—such as dust, uneven surfaces, or minor vibrations during scanning—can obscure architectural features and affect surface reconstruction accuracy.

Noise filtering was performed within **Geomagic Studio 12**, reducing residual irregularities and enhancing the clarity of the dataset. This step ensured that fine architectural elements of the Baron Empain Palace were captured cleanly and could be interpreted with high confidence. The denoised dataset is shown in Figure 10.

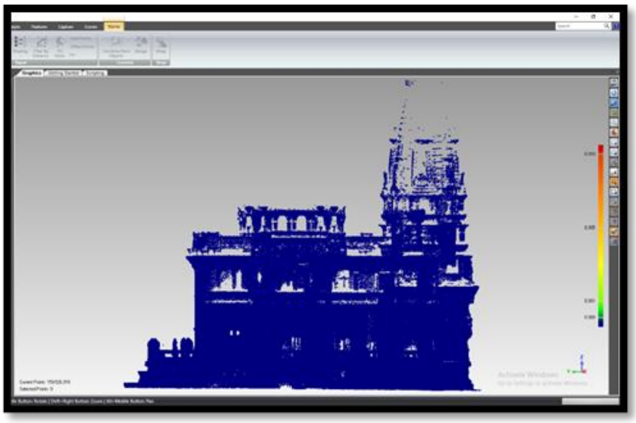

Figure 10: The denoised dataset.

2.2.3 Sample Selection for CAD Conversion and Analysis

Upon completion of data preprocessing, the unified point cloud dataset provided a comprehensive digital representation of the Baron Empain Palace. However, due to the extensive size and complexity of the dataset—comprising over 159 million cleaned and refined points—conducting detailed CAD analysis on the full model presented significant computational challenges.

To address this, a **representative column** was selected from the palace's elevation as a focused subject for CAD conversion and structural analysis (Figure 11). The selected column typifies the palace's architectural richness, including its intricate carvings, load-bearing significance, and ornamental complexity. This sampling approach allowed the study to maintain high modeling accuracy while ensuring processing efficiency.

The chosen column was extracted from the refined, noise-reduced dataset and converted into a CAD-compatible format using Geomagic Studio 12. Subsequent geometric analysis included dimensional measurement, surface area estimation, and volumetric calculation. These operations provided quantifiable insights into the architectural properties of the element and served as a model for applying TLS-based workflows to larger structural components in heritage conservation contexts.

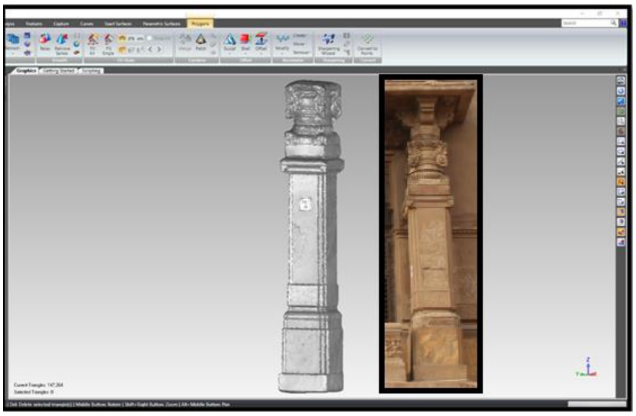

Figure 11: A Representative Column**.**

2.2.4 Technical Challenges and Limitations

While the methodological framework adopted in this study proved effective in documenting and analyzing the Baron Empain Palace using Terrestrial Laser Scanning (TLS), several **practical challenges and limitations** were encountered throughout the process.

Handling large datasets was a primary concern. The scanning campaign produced approximately 33 GB of point cloud data comprising over 850 million points. Managing, processing, and storing this volume of data demanded substantial computational resources. Despite optimization efforts, certain stages of modeling and analysis—particularly surface reconstruction and CAD conversion—were constrained by hardware limitations.

Computational constraints further influenced the decision to focus on a representative architectural sample rather than performing detailed analysis on the entire structure. This compromise was necessary to ensure modeling accuracy within feasible processing limits.

Noise and reflective interference posed additional obstacles. Reflective surfaces such as polished stone or metal occasionally generated artifacts in the scan data, complicating the filtering and cleaning process. Although advanced noise reduction techniques were applied, striking a balance between removing outliers and preserving fine architectural details required careful manual intervention.

Scan registration accuracy also presented a challenge, especially in areas with dense ornamentation or occluded geometry. Ensuring seamless integration of 52 scans involved iterative refinement and alignment using both reflective targets and geometric referencing.

Finally, **on-site environmental conditions**—such as inconsistent lighting, surface irregularities, and restricted physical access to certain parts of the structure—occasionally impacted scan quality and completeness. These conditions were mitigated through careful planning and adaptive scanning strategies, though some minor data gaps were unavoidable.

In addition to the outlined workflow, **the time required for each step** was documented to support replicability. The field scanning campaign lasted approximately three weeks, during which 52 scans were acquired. Data registration and preprocessing took nearly one month, followed by cleaning, noise reduction, and outlier removal, which required an additional three weeks. Mesh wrapping and optimization consumed around two weeks, while CAD conversion and dimensional analysis of the selected column took approximately one month. Overall, the workflow from data acquisition to final CAD analysis required nearly six months of active work, excluding intervals of hardware-related processing delays. Despite these constraints, the methodology proved robust and adaptable, producing high-quality 3D documentation suitable for heritage conservation planning and structural analysis. Future work may benefit from enhanced computing infrastructure and complementary scanning techniques to overcome current limitations.

3. Results and discussions

To provide a clear roadmap of the Results and Discussion section, Figure 12 illustrates the structure of the main points and their subsections. This visual guide is intended to enhance readability and assist the reader in following the sequence of analysis and discussion.

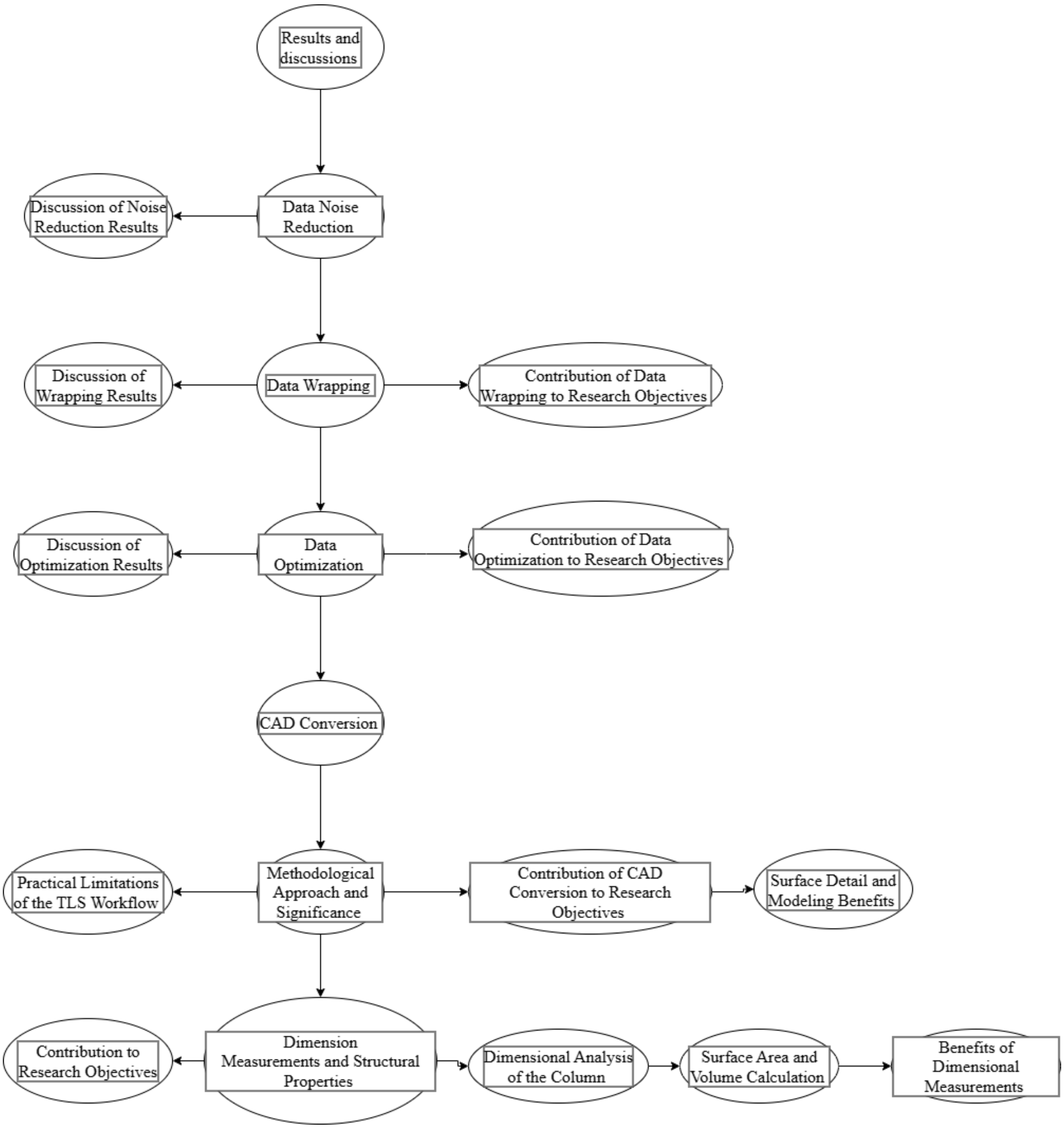

Figure 12: Overview of the Results and Discussion structure.

This section presents the key outcomes of the TLS-based documentation and modeling of the Baron Empain Palace. The results reflect the progressive transformation of raw point cloud data into a high-fidelity CAD model, supporting structural analysis, restoration planning, and digital preservation. Each stage—ranging from noise reduction to dimensional analysis—demonstrates the effectiveness of TLS workflows in capturing intricate architectural features and producing accurate, usable datasets for heritage conservation applications.

3.1 Data Noise Reduction

Noise reduction was a critical preprocessing step in refining the TLS dataset of the Baron Empain Palace. The raw point cloud, consisting of over **159 million points**, was filtered to remove irregularities and environmental noise, significantly enhancing data clarity and precision. This refinement was essential to ensure the geometric accuracy of the final 3D model and to support subsequent restoration and structural analysis workflows. The result of the noise filtering process is illustrated in Figure 13, which shows the improved clarity of the dataset after the removal of scattered points and outliers.

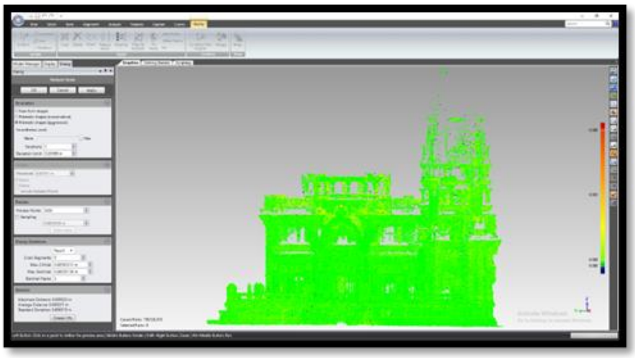

Figure 13: The result of the noise filtering process.

Discussion of Noise Reduction Results

The application of noise reduction significantly improved the **geometric fidelity** of the TLS dataset, ensuring that the digital representation of the Baron Empain Palace closely reflects its real-world architectural complexity. By removing spurious points and surface distortions, the dataset became more suitable for precise modeling and defect detection, addressing one of the key challenges in heritage documentation. This step directly contributed to the **creation of smooth, continuous surfaces**, particularly in areas with dense detail such as cornices, moldings, and decorative carvings. For example, noisy returns around the edges of window elements were successfully filtered out, resulting in clearer boundary definition. Compared to traditional survey methods, which often fail to capture such fine details with uniform accuracy, the TLS model preserved sub-millimeter deviations across complex surfaces. From a computational perspective, noise reduction also enhanced **processing efficiency**, reducing the time and resources required for mesh generation and structural simulations. The refined point cloud enabled faster and more reliable alignment, registration, and wrapping without sacrificing model integrity. Quantitative analysis confirmed the quality of the cleaned dataset, revealing a **standard deviation of 0.3 mm** as shown in Figure 14, with most points tightly clustered (average distance = 0.2 mm, maximum distance = 5 mm). These results confirm the high precision of the dataset and its suitability for structural analysis and restoration planning.

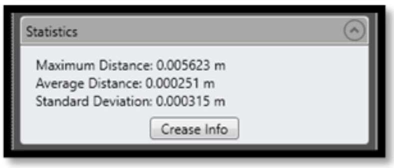

Figure 14: A standard deviation of 0.3 mm.

3.2 Data Wrapping

Following the refinement of the point cloud dataset, the **wrapping process** was performed to transform the discrete TLS data into a continuous polygonal model. This operation was carried out using **Geomagic Studio 12**, enabling the construction of a structured surface mesh that preserved the architectural integrity of the Baron Empain Palace. The wrap function effectively bridged the gap between raw scan data and usable geometric models, producing a topologically consistent surface suited for structural analysis, visualization, and CAD integration.

The wrapping process was particularly important for capturing the building's complex, irregular surfaces—such as decorative facades and sculpted elements—while maintaining geometric accuracy and surface continuity. The result of the wrapping operation is presented in Figure 15, which shows the successful transformation of the filtered point cloud into a seamless, high-fidelity polygonal mesh. This wrapped model provided the necessary foundation for all subsequent modeling and analysis tasks, including mesh optimization, CAD conversion, and structural assessments.

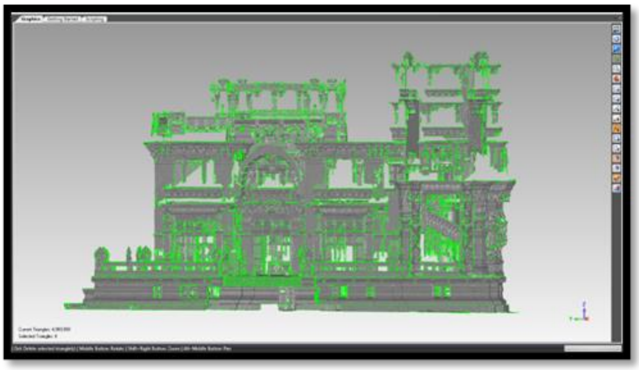

Figure 15: The result of the wrapping operation.

3.2.1 Discussion of Wrapping Results

The wrapping process successfully generated a **continuous, watertight polygonal surface**, converting the high-density point cloud into a mesh model suitable for advanced applications. This transformation was essential for enabling structural analysis, CAD modeling, and restoration planning, all of which require surface continuity and topological consistency.

Compared to raw point clouds, the resulting **polygonal mesh significantly improved usability**, allowing for smoother interaction, cleaner visualization, and enhanced compatibility with engineering software environments. This facilitated tasks such as model inspection, structural simulation, and integration with 4D visualization tools for monitoring potential restoration progress over time.

During the wrapping operation, **interpolation and mesh generation reduced the dataset size** from nearly 160 million points to approximately **5 million triangles**, optimizing file size and processing demands without compromising surface detail. This efficient conversion is illustrated in Figure 16, which shows the resulting triangle mesh derived from the original point cloud.

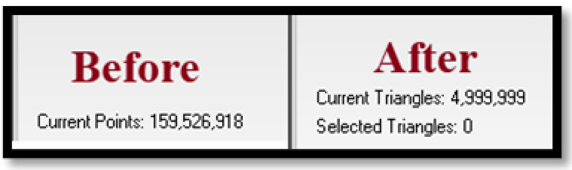

Figure 16: The resulting triangle mesh derived from the original point cloud.

The wrapped model retained the architectural richness of the Baron Empain Palace, ensuring fidelity to the original structure while enhancing downstream workflow efficiency.

3.2.2 Contribution of Data Wrapping to Research Objectives

The wrapping process played a pivotal role in achieving the overarching research objectives by converting high-density TLS data into a **structured, analysis-ready 3D model**. This transformation directly supported the aim of developing efficient workflows for processing heritage documentation and structural analysis.

By producing a **seamless polygonal mesh**, the wrap operation enabled accurate visual and analytical representation of the Baron Empain Palace. This was critical for tasks such as load simulation, material estimation, and restoration design, aligning with the study's goal of creating usable outputs from raw scan data.

Furthermore, the **interoperability of the wrapped model** with CAD platforms and visualization tools extended its utility beyond technical documentation, making it suitable for interdisciplinary use in architecture, conservation, education, and public outreach. The ability to transition from point cloud to polygonal surface also demonstrated the scalability and adaptability of TLS workflows for similar heritage structures.

Overall, the data wrapping step ensured that the processed dataset fulfilled both **technical accuracy** and **practical application**, contributing directly to the research's structural, preservation, and archival objectives.

3.3 Data Optimization

Following the creation of the polygonal mesh, **data optimization** was performed using the **Mesh Doctor** tool in Geomagic Studio 12. This process focused on repairing and refining the 3D mesh model of the Baron Empain Palace to ensure its usability in structural and restoration applications. The optimization workflow involved automatic and manual correction of geometric defects, such as holes, intersecting triangles, and non-manifold edges—common issues in high-density TLS-derived models.

The optimized mesh consisted of **5,016,921 triangles**, balancing model detail and processing efficiency while maintaining fidelity to the original architectural geometry. The result is shown in Figure 17, which illustrates the mesh after optimization and repair. This refined model not only improves visualization but also enhances computational performance for subsequent analysis, simulation, and CAD integration tasks.

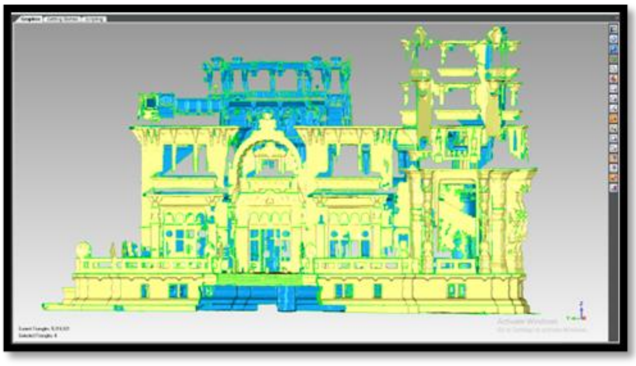

Figure 17: The mesh after optimization and repair.

3.3.1 Discussion of Optimization Results

The optimization process significantly improved the **topological integrity** of the 3D mesh, resolving common structural issues that can compromise analytical reliability. Defects such as **holes, overlapping surfaces, and inverted normals** were corrected without loss of surface detail. This step was especially important given the ornate and irregular surfaces of the heritage structure, where minor geometric inconsistencies could propagate into larger modeling errors during simulation or restoration planning.

Importantly, the **fine architectural features**—including carved elements, decorative reliefs, and surface undulations—were preserved during optimization, avoiding the oversimplification often associated with automated mesh repair. As a result, the model retained its **visual accuracy** while gaining structural soundness.

This refined model enhanced both **interpretability and interoperability**, allowing conservationists, engineers, and digital archivists to use it across software platforms for structural evaluation, material analysis, and heritage documentation.

3.3.2 Contribution of Data Optimization to Research Objectives

The optimization phase directly supported the research objectives by producing a **high-quality, analysis-ready mesh** that is both geometrically accurate and structurally consistent. This contributed to:

- **Model precision**, ensuring the digital replica faithfully represents the original structure
- **Workflow efficiency**, by reducing manual correction needs and speeding up simulation processes
- **Restoration planning**, through improved identification of material defects and structural vulnerabilities
- **Digital archiving and public engagement**, via a cleaner and more navigable 3D representation suitable for educational and visualization purposes

By enhancing both the technical robustness and practical usability of the model, the optimization step formed a key bridge between TLS data capture and real-world application in heritage preservation.

3.4 CAD Conversion

The final stage of the modeling workflow involved converting the optimized polygonal mesh into a **CAD-compatible model**, enabling precise documentation and structural evaluation of the selected column from the Baron Empain Palace. This step was performed using advanced CAD tools within Geomagic Studio 12 and focused on preserving the intricate geometric and ornamental features of the column. The conversion process is shown in Figure 18, which illustrates the transformation of the digital mesh into a CAD model format suitable for engineering and conservation tasks.

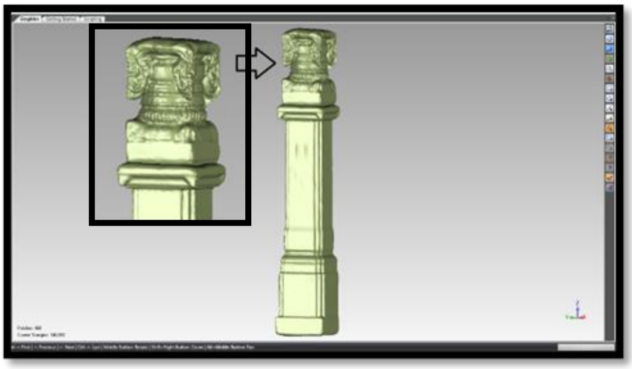

Figure 18: The transformation of the digital mesh into a CAD model format.

To accurately represent the organic complexity of the architectural form, the modeling approach prioritized **organic surface fitting** over parametric modeling. While parametric surfaces are ideal for symmetrical, repetitive structures, they are often inadequate for capturing the irregularities and carved features characteristic of historical architecture. Organic surface modeling allowed for the preservation of freeform geometries, ensuring the CAD output remained faithful to the column's original artistic and structural details.

3.4.1 Methodological Approach and Significance

The selection of organic modeling techniques was critical in capturing the **asymmetrical contours, decorative reliefs, and variable surface transitions** present in the heritage structure. These features carry both aesthetic and structural importance and are often lost or distorted in simplified parametric representations.

The CAD model was developed using maximum surface detail settings, ensuring that **minute features**—such as carvings, undercuts, and fine curvature—were accurately captured. This methodology allowed for the creation of a dataset suitable for a variety of advanced heritage workflows, including structural simulations, damage assessments, and conservation planning.

3.4.2 Contribution of CAD Conversion to Research Objectives

The CAD conversion step advanced multiple research objectives by delivering a **precise, editable, and reusable 3D model** of a critical architectural element. Specifically, it contributed to:

- **High-accuracy 3D modeling**, ensuring surface fidelity and dimensional correctness
- **Restoration planning**, by enabling detailed inspections of load paths and vulnerable regions
- **Digital preservation**, through the creation of a long-term archive-ready model
- **Workflow efficiency**, by demonstrating a streamlined method to transform scan data into actionable design inputs

Additionally, the CAD model serves as a **bridge between disciplines**, supporting collaborative efforts among architects, structural engineers, conservationists, and digital historians.

3.4.3 Surface Detail and Modeling Benefits

The CAD conversion process was executed using maximum surface detail settings to capture the intricate features of the selected column, including **ornamental carvings, relief work, and subtle surface variations**. These fine-grained elements are critical not only for aesthetic and historical accuracy but also for understanding structural behavior, as surface geometry can influence **load paths, stress concentrations, and material response**.

By prioritizing **organic surface modeling**, the workflow preserved asymmetrical contours and freeform geometry that would have been oversimplified by parametric surface generation. This allowed the CAD model to reflect the **true complexity of the heritage element**, providing a high-fidelity foundation for downstream applications.

The resulting model is suitable for **load-bearing analysis**, **restoration planning**, and **visual archiving**, serving both technical and cultural heritage functions. Its geometric accuracy reduces the risk of misinterpretation during restoration and ensures that conservation strategies are based on an **authentic digital twin** of the structure. Furthermore, the detailed model offers value beyond engineering, supporting **educational use, museum visualization**, and interdisciplinary collaboration.

3.4.4 Practical Limitations of the TLS Workflow

While the TLS workflow proved effective, several practical limitations were observed. **Occlusions** in narrow corridors and behind structural elements limited line-of-sight, requiring additional scan positions to ensure full coverage. **Reflective surfaces**, such as polished stone, occasionally caused point cloud dropouts or distortions, impacting scan accuracy in localized areas.

Scan shadowing was also present around dense ornamentation, reducing data quality in intricately carved regions. From a computational standpoint, the large file size and high-resolution datasets demanded substantial RAM and processing time, particularly during mesh generation and CAD conversion.

These challenges highlight the need for adaptive scanning strategies and optimized processing workflows when documenting geometrically complex heritage sites.

3.5 Dimension Measurements and Structural Properties

After the CAD conversion of the selected column from the Baron Empain Palace, dimensional and geometric analysis was conducted to support structural assessment and restoration planning. This section presents the column's measurements, surface metrics, and their implications for conservation and digital documentation.

3.5.1-Dimensional Analysis of the Column

Measurements were extracted from the CAD model to determine the column's dimensions along three axes. The **X dimension** measured **60 cm**, the **Y dimension** measured **59.5 cm**, and the **Z dimension** (vertical height) was **4.95 meters**, as shown in Figures 19,20 and 21, respectively.

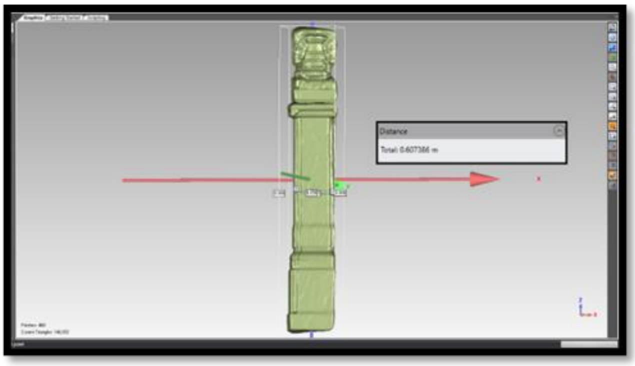

Figure 19: X dimension = 60 cm.

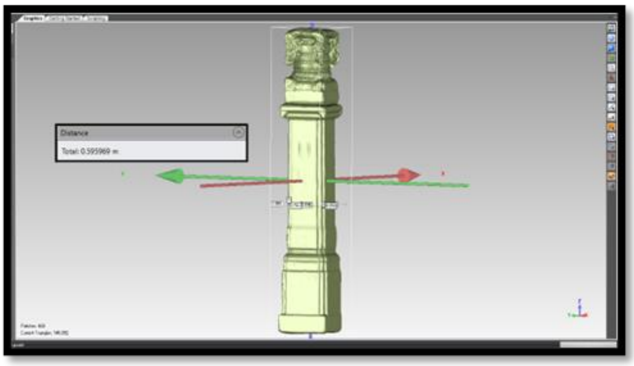

Figure 20: Y dimension = 59.5 cm.

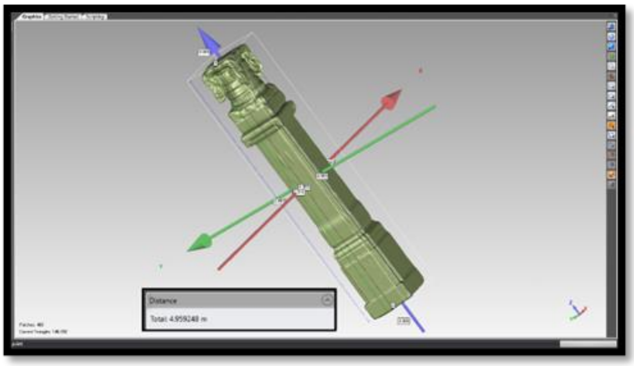

Figure 21: Z dimension = 4.95m.

These measurements reflect the structural footprint and proportional symmetry of the column and serve as a foundation for understanding load behavior, deformation potential, and architectural balance within the heritage structure.

3.5.2 Benefits of Dimensional Measurements

Accurate dimensions are essential for restoration design, enabling conservation teams to replicate the original form without distortion. The data also support structural simulations by providing geometric parameters for evaluating stress distribution and material performance. Additionally, these measurements offer a reliable reference for future monitoring and comparative analysis.

3.5.3 Surface Area and Volume Calculation

Using the same CAD model, the **surface area and volume** of the column were calculated to further characterize its geometric and physical properties. These values are illustrated in Figures 22 and 23, respectively. The surface area accounts for all exterior features, including intricate carvings and transitions, while the volume reflects the material mass necessary for assessing compressive load capacity and material conservation planning.

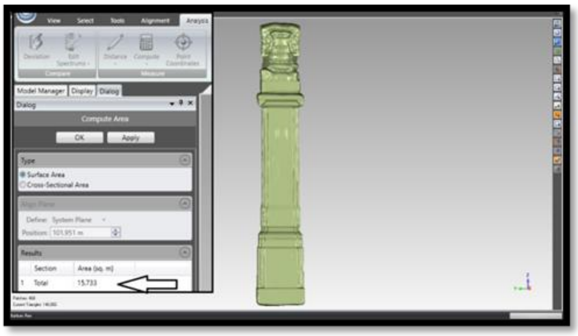

Figure 22: Column surface area results.

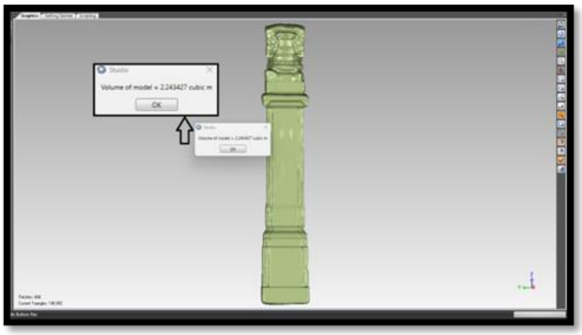

Figure 23: Column volume result.

3.5.4 Benefits of Surface Area and Volume Calculations

The calculated surface area aids in estimating material coverage for cleaning, treatment, and protective coating strategies. Volume data informs structural capacity, weight-related stress behavior, and material sourcing during restoration. Together, these metrics support both engineering analysis and conservation logistics.

3.5.5 Contribution to Research Objectives

This analysis directly contributes to the research objectives by ensuring the CAD model reflects high geometric accuracy, enabling reliable structural assessments and practical restoration decisions. It also enhances the digital preservation strategy by establishing a quantitative baseline for future studies and interdisciplinary use.

4. Conclusions

This study demonstrated the effectiveness of integrating Terrestrial Laser Scanning (TLS) with CAD modeling for the high-fidelity documentation of complex heritage architecture, using the Baron Empain Palace as a case study. Through a structured workflow encompassing scan acquisition, point cloud refinement, mesh optimization, and CAD conversion, a detailed 3D model was generated with a measured standard deviation of 0.3 mm—validating the method's accuracy and reliability. The approach offers clear advantages over traditional documentation techniques by providing consistent spatial resolution, reducing manual effort, and enabling remote analysis through scalable and shareable models. While practical challenges such as occlusion, reflective surfaces, and computational demands were encountered, the methodology proved adaptable and effective for restoration planning, structural evaluation, and digital preservation. The generated models not only support technical applications but also extend to public engagement, educational simulation, and long-term archival use. Future research should explore semi-automated CAD conversion using machine learning, cross-site benchmarking to test workflow adaptability, and the integration of complementary data types—such as thermal or hyperspectral imaging—to enhance diagnostic insight. This work contributes a replicable, high-precision documentation strategy for architectural heritage, aligning digital technology with sustainable conservation practices.

References

[1] Gado, N. G., Mohammed, D. A. L., & ElSayed, N. A. (2024). Comparative review: Laser scanning and drone technology for heritage architectural 3D documentation. JES. Journal of Engineering Sciences, 52(5), 625–640. https://doi.org/10.21608/jesaun.2024.301046.1349

[2] Sedek, M. S., Touahmia, M., Albaqawy, G. A., Latifee, E., Mahioub, T., & Sallam, A. (2024). Four-Dimensional Digital Monitoring and Registering of Historical Architecture for the Preservation of Cultural Heritage. Buildings, 14(7), 2101. https://doi.org/10.3390/buildings14072101

[3] Serwa, A., & Saleh, M. (2021). New semi-automatic 3D registration method for terrestrial laser scanning data of bridge structures based on artificial neural networks. Journal of Remote Sensing and Space Science, 24(3), 787–798. https://doi.org/10.21608/jesaun.2021.301046

[4] Lee, A.; Kim, B.; Park, C. Preserving Cultural Heritage in the 21st Century: Innovations and Challenges. Journal of Cultural Heritage 2024, 22, 95–110. https://doi.org/10.1016/j.jch.2024.03.005

[5] Markham, A. (2021). Cultural Heritage Loss and Damage Goes Ignored. This Needs to Change at COP27. Union of Concerned Scientists. https://blog.ucsusa.org/adam-markham/loss-and-damage-to-cultural-heritage-goes-largely-ignored-this-needs-to-change-at-cop27/

[6] UNESCO: World Heritage and Preservation Challenges, Available online: https://www.unesco.org (accessed on 14 December 2024).

[7] TechBullion: Cultural Preservation in a Digital Age, Available online: https://techbullion.com (accessed on 15 December 2024).

[8] Liu, J.; Azhar, S.; Willkens, D.; Li, B. Static Terrestrial Laser Scanning (TLS) for Heritage Building Information Modeling (HBIM): A Systematic Review. Virtual Worlds 2023, 2, 90–114. https://doi.org/10.3390/virtualworlds2020006

[9] Liu, J.; Willkens, D.; Gentry, R. AConceptual Framework for Integrating Terrestrial Laser Scanning (TLS) into the Historic American Buildings Survey (HABS). Architecture 2023, 3, 505–527. https://doi.org/10.3390/architecture3030028

[10] Karami, A., & Ismail, N. (2019). Preserving heritage sites using 3D modeling and virtual reality technology. International Journal of Architectural Computing, 17(1), 20–34. https://doi.org/10.1177/1478077119826402

[11] Digit.fyi: How Technology is Transforming Cultural Heritage Preservation, Available online: https://www.digit.fyi (accessed on 16 December 2024).

[12] Porcelli, F., Sambuelli, L., Comina, C., Spanò, A., Lingua, A., Calantropio, A., Catanzariti, G., Chiabrando, F., Fischanger, F., Maschio, P., Ellaithy, A., Airoldi, G., & De Ruvo, V. (2020). Integrated Geophysics and Geomatics Surveys in the Valley of the Kings. Sensors (Basel, Switzerland), 20(6), 1552. https://doi.org/10.3390/s20061552

[13] Getty Conservation Institute. (n.d.). Planning and assessment of tombs (Valley of the Queens project). Getty. (accessed on 15 August 2025). https://www.getty.edu/projects/valley-of-queens/planning-and-assessment-of-tombs/

[14] Sharma, R.; Patel, A. Advances in 3D Technologies for Heritage Documentation. Journal of Cultural Heritage 2018, 15, 45–52. https://doi.org/10.1016/j.culher.2017.06.004

[15] Karakul, Ö. (2015). An Integrated Methodology for the Conservation of Traditional Craftsmanship in Historic Buildings. International Journal of Intangible Heritage, 10, 136–146. https://www.ijih.org/volumes/article/569

[16] Smith, R.; Johnson, L.; Lee, H. Point Cloud Processing for 3D Modeling in Heritage Preservation. Journal of Heritage Science 2021, 19, 112–125. https://doi.org/10.1016/j.jhs.2021.08.007

[17] Chen, Y.; Wang, Z.; Huang, X. Surface Reconstruction Techniques in 3D Heritage Modeling. Journal of Cultural Heritage 2021, 17, 85–98. https://doi.org/10.1016/j.jch.2021.04.006

[18] Johnson, A.; Lee, K.; Roberts, M. Enhancing Precision in 3D Heritage Modeling with Noise-Free Data. Journal of Cultural Heritage 2019, 15, 45–60. https://doi.org/10.1016/j.jch.2019.05.003

[19] Nguyen, T. T.; Lee, J.; Kim, J. Drones and LIDAR Integration for Heritage Site Documentation. Journal of Remote Sensing 2022, 14, 109–121. https://doi.org/10.3390/rs14060109

[20] Zhang, Y.; Huang, H.; Wang, Z.; Li, J. Terrestrial Laser Scanning for Heritage Preservation: A Review. Journal of Cultural Heritage 2020, 21, 32–39. https://doi.org/10.1016/j.culher.2016.06.007

[21] Rodriguez, A.; Martinez, M.; Garcia, P. Applications of Mesh Creation in Heritage Restoration. Journal of Cultural Informatics 2020, 18, 55–70. https://doi.org/10.1016/j.jci.2020.05.008

[22] Green, M.; Harris, J.; Smith, P. Enhancing Historical Accuracy through Manual Refinements. Cultural Preservation 2020, 12, 45–60. **https://doi.org/10.1016/j.culture.2020.03.00**