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ORIGINAL ARTICLE

Construction of 3D models of the Cracow Fortress Powder Magazine and determination of their accuracy using photogrammetric and terrestrial scanning methods

Agnieszka Malec [1] and Izabela Piech [1*]

[1]Faculty of Environmental Engineering and Geodesy, University of Agriculture in Krakow, Mickiewicza 24/28, 30120 Krakow, Poland

[*]izabela.piech@urk.edu.pl

Abstract

This study presents a comparative analysis of two three-dimensional reconstruction models of Powder Magazine no. 2 of the 19h-century Cracow Fortress, developed using terrestrial laser scanning (TLS) and close-range digital photogrammetry to assess the suitability of both methods for the documentation and reconstruction of heritage structures, as well as to evaluate their geometric accuracy and visual quality. The investigated structure was scanned from four positions using a Leica ScanStation P40 and photographed using a Canon EOS 400D camera. Based on the acquired point clouds, two 3D models were generated: a TLS-based model in Autodesk Revit and a photogrammetric model in Trimble SketchUp, both at Level of Detail (LOD) 200. Accuracy assessment was conducted in CloudCompare using the Cloud-to-Cloud (C2C) method, supplemented by visual and historical comparisons. The results show high geometric consistency between the datasets (with deviations below 0.2 m) and confirm the effectiveness and complementarity of both techniques in the documentation of cultural heritage. The developed models provide valuable material for scientific research, conservation planning, education, and digital heritage presentation.

Key words: Cracow Fortress powder magazine, terrestrial laser scanning, close-range digital photogrammetry, 3D modelling

1 Introduction

Recent advancements in modern surveying technologies and digital spatial documentation methodologies have significantly influenced contemporary approaches to research, preservation, and dissemination of cultural heritage. One key direction involves the development of three-dimensional (3D) reconstruction models, which serve not only as a means of archiving but also as essential tools for conservation analyses, educational applications, and visualization in Virtual Reality (VR) and Augmented Reality (AR) environments. Earlier studies clearly prove that high geometric fidelity combined with photorealistic texture mapping has become a standard requirement in the digital documentation of architectural and archaeological heritage sites (Saad et al., 2023; Scianna et al., 2020; Skrzypczak et al., 2022; Zachos and Anagnostopoulos, 2023).

Two key approaches are widely employed in 3D documentation and reconstruction: close-range photogrammetry and terrestrial laser scanning (TLS). The former, based on the processing of photographic images using Structure-from-Motion (SfM) and Multi-View Stereo (MVS) algorithms, offers relatively low operational costs, high mobility, and the ability to utilize diverse data sources – from contemporary photographs and archival images to datasets acquired using Unmanned Aerial Vehicles (UAVs) (Bolognesi et al., 2014; Elkhrachy, 2019; Jo and Hong, 2019; Luhmann et al., 2020; Se and Jasiobedzki, 2006; Zarnowski et al., 2015). Its usefulness has been demonstrated through numerous applications involving the

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modelling and visualization of historical structures, where accuracies of several centimetres have been achieved (Elkhrachy, 2019; Shashi and Jain, 2007; Guarnieri et al., 2004). It also enables the reconstruction of structures that no longer exist – for example, the reconstruction of the Sant'Alberto tower using archival photographs combined with contemporary TLS data (Bitelli et al., 2017). The limitations of this method include susceptibility to lighting conditions, the need for acquiring a large number of overlapping images, and the risk of errors caused by insufficient control point distribution (Nazim et al., 2024; Surmen, 2023).

The latter method, developed in parallel with photogrammetric techniques, provides very high measurement accuracy – often at the millimetre level – and enables the acquisition of dense point clouds regardless of lighting conditions(Borkowski and Józków, 2012; Kwoczyńska et al., 2023; Nazim et al., 2024; Skrzypczak et al., 2022; Stal et al., 2012). TLS is widely used in the documentation of both individual historical buildings and large architectural structures. Research conducted at the Piast Castle in Brzeg confirms the high applicability of this method, enabling the creation of models compliant with LOD 3 standards (Borkowski and Józków, 2012). TLS is also frequently used as a reference for evaluating the quality of photogrammetric models, demonstrating an advantage in geometric accuracy while also highlighting limitations related to equipment cost and difficulties in capturing inaccessible structural elements (Guarnieri et al., 2004; Maghiar et al., 2016; Novel et al., 2015; Stal et al., 2012).

A growing body of research shows that the most effective strategy is the integration of photogrammetric and TLS datasets. Photogrammetry provides highly detailed textures and colour information, whereas TLS offers precise geometric representation, allowing the creation of reconstruction models that combine the strengths of both technologies (Balsa-Barreiro and Fritsch, 2018; Guidi et al., 2004; Jo and Hong, 2019; Luhmann et al., 2020; Scianna et al., 2020; Zachos and Anagnostopoulos, 2023). Examples include the documentation of religious buildings in Korea and Georgia (Jo and Hong, 2019; Luhmann et al., 2020), large-scale archaeological sites such as the Roman Forum in Pompeii using multi-resolution methodologies (Guidi et al., 2009), and the highly accurate digital reconstruction of Donatello's *Maddalena* sculpture (Guidi et al., 2004).

Particular attention in the literature is also given to the assessment of the accuracy of the resulting models. For this purpose, comparative methods involving tacheometric measurements, statistical analyses, and point cloud matching algorithms are commonly applied (Guarnieri et al., 2004; Maghiar et al., 2016; Nazim et al., 2024; Saad et al., 2023; Stal et al., 2012). Research confirms that carefully planned data integration allows for the creation of models that meet high requirements in terms of both geometry and photorealistic visualization (Chevrier et al., 2009; Giżyńska et al., 2022; Głowacka and Pluta, 2016; Zarnowski et al., 2015).

A considerable part of the literature is devoted to the assessment of model accuracy. Comparative analyses often employ tacheometric measurements, statistical evaluation, and point cloud matching algorithms (Guarnieri et al., 2004; Maghiar et al., 2016; Nazim et al., 2024; Saad et al., 2023; Stal et al., 2012). Research findings consistently show that a carefully planned data integration workflow enables the creation of models that meet high standards of geometric precision and photorealistic visualization (Chevrier et al., 2009; Giżyńska et al., 2022; Głowacka and Pluta, 2016; Zarnowski et al., 2015).

The aim of this study is to develop two three-dimensional reconstruction models of a historical military structure – a powder magazine – using independently acquired close-range photogrammetry and TLS datasets. This approach enables a comparison of both measurement methods in terms of representation quality, suitability for documenting military architecture, accuracy, visual evaluation, and the degree of historical authenticity achieved in the reconstructed models.

Figure 1. Adjacent powder magazine (National Archives in Cracow, A-IV-247)

2 Methodology

2.1 Examined facility

For the testing and further developing the applied measurement techniques, the ruins of Powder Magazine No. 2 were selected as a case study. The structure is located near the "Liban" Quarry, in the area of the former village of Wola Duchacka, currently within the administrative boundaries of District XI, Podgórze Duchackie, in Cracow.

The construction of the first powder magazines in this structure – facilities intended for storing ammunition and explosive materials – began around 1870. These buildings featured a single internal chamber and entrances located in avant-corps extensions attached to the longer facade. In many cases, including the powder magazine examined in this study, the avant-corps formed a separate, small structure connected to the main building by a covered passage, which allowed the loading and unloading of wagons under shelter. All powder magazines were erected using mixed masonry–timber construction, which did not provide effective protection against potential explosions of stored ammunition (Mikulski, 2024).

A particularly significant event in the history of the Cracow Fortress was the explosion of the powder magazines in Wola Duchacka. It showed the scale of danger associated with maintaining large explosive storage facilities in close proximity to Cracow and Podgórze. was severely damaged during the catastrophic explosion in June 1909. During an intense thunderstorm, lightning struck the roof of one of the magazines, triggering a series of explosions that caused extensive destruction throughout Wola Duchacka and left hundreds injured. Figure 1 illustrates the consequences of this event.

During World War II, the area holding the powder magazines and ammunition depots fell within the boundaries of the German concentration camp KL Płaszów, which indirectly contributed to its preservation by preventing intensive post-war development.

The surviving remains of Powder Magazine No. 2 (Figures 2 and 3) constitute a key component of the military heritage of the Cracow Fortress and represent a material testimony to the evolution of Austro-Hungarian fortifications in the region of Galicia.

2.2 Data preparation

The ruins of the powder magazine were measured using two independent methods: terrestrial laser scanning and close-range photogrammetry.

Figure 2. Ruins of of the Cracow Fortress in Wola Duchacka – visible front and north elevation. (March 2025, phot. A. Malec)

Figure 3. Ruins of of the Cracow Fortress in Wola Duchacka – visible western and southern elevation (March 2025, phot. A. Malec)

The TLS survey was conducted using a Leica ScanStation P40 scanner. Point clouds were acquired from four stations positioned evenly around the structure – north, south, east, and west. To ensure proper scan orientation and geometric continuity, 12 reference spheres were used. Six spheres were visible from each station, with three remaining fixed between neighbouring stations. The angular resolution in both the vertical and horizontal directions corresponded to a point spacing of 2 cm at a distance of 100 m. This configuration enabled the acquisition of detailed point clouds with adequate sphere visibility and sufficient overlap. The data were preprocessed in Leica Cyclone Core, where the scans were registered with a mean alignment error of 6 mm, cleaned, and resampled to a point spacing of 2 mm. The resulting unified point cloud was subsequently converted into a triangular mesh in CloudCompare.

As the second measurement technique, digital ground-based photographs were taken using a Canon EOS 400D camera equipped with a 50 mm prime lens. The images were acquired in the vertical orientation, forming a continuous sequence around the object and ensuring full coverage of all facades and the surrounding area. A constant photographing distance of 12.35 m enabled a Ground Sampling Distance (GSD) of 1.5 mm, ensuring high-quality image data. The chosen image orientation and fixed distance facilitated the optimisation of the number of photographs and the minimisation of occlusions. The images were processed in Agisoft Metashape Professional, resulting in a dense point cloud and a triangular mesh with a geometric accuracy of approximately 2 cm. Field sketches documenting the photogrammetric measurement are shown in Figure 4.

The processed datasets provided the foundation for constructing two realistic three-dimensional reconstruction models of Powder Magazine No. 2 of the Cracow Fortress.

3 Creation of reconstructive 3D models

The processed measurement datasets – TLS- and photogrammetry-based point clouds – served as the basis for constructing two independent three-dimensional reconstruction models of Powder Magazine No. 2. Both models were developed at a Level of Detail corresponding to LOD 200 and were supplemented with archival photographs and historical descriptions of powder magazines (Mikulski, 2024).

The first reconstruction model uses a triangular mesh generated in CloudCompare from the TLS point cloud. This mesh served as a precise geometric reference for modelling the structure in Autodesk Revit – a BIM environment that enables parametric representation of architectural elements and facilitates the creation of models that preserve both geometric logic and constructional relationships.

The modelling process began with the preparation of a dedicated project environment: a suitable template was selected, measurement units were defined, and the mesh was imported in .dxf format. Three principal construction levels were introduced: the foundation level (0 m), the ceiling level (3 m), and the roof level (6 m). A structural grid was also created to provide a consistent spatial reference system.

The first stage of geometric reconstruction involved modelling the external walls. A custom wall type was defined to reflect historical masonry techniques, with a thickness of 0.45 m and a height of 3 m. These elements were aligned precisely with the geometric envelope of the imported mesh in both plan and 3D views.

The next phase involved recreating architectural openings – doors and windows. As Revit operates on parametric families, these elements were modelled as custom components reflecting the architectural style of the period. The door openings, sized at 130×230 cm, were placed directly according to the geometry identified in the mesh. Window openings, for which historical documentation was incomplete, were placed symmetrically on the longer elevation of the building, with approximate dimensions of 90×140 cm, based on proportion analysis and analogies from similar structures.

The roof structure represented a crucial part of the reconstruction. Analysis of the TLS mesh showed that the original building featured a gable roof with a height of approximately 3 m. Using the predefined construction levels, the roof geometry was recreated with appropriate slopes, ridge alignment, and structural proportions characteristic of military utilitarian architecture. Additional architectural features, such as the concrete entrance steps, were modelled based on the geometric cues present in the mesh.

Upon completion of the geometric model, material textures were applied. High-resolution photographs of brickwork and concrete surfaces, captured during field documentation, were processed and imported into Revit. These textures were mapped onto the corresponding surfaces and adjusted to achieve realistic scale and orientation. Textures for the roof, door, and window elements were selected from Revit's material library, prioritising options consistent with historical materiality.

A preliminary stage of the model created in Autodesk Revit is shown in Figure 5. The final model, shown in Figure 6, represents a visually coherent and structurally grounded reconstruction of Powder Magazine No. 2.

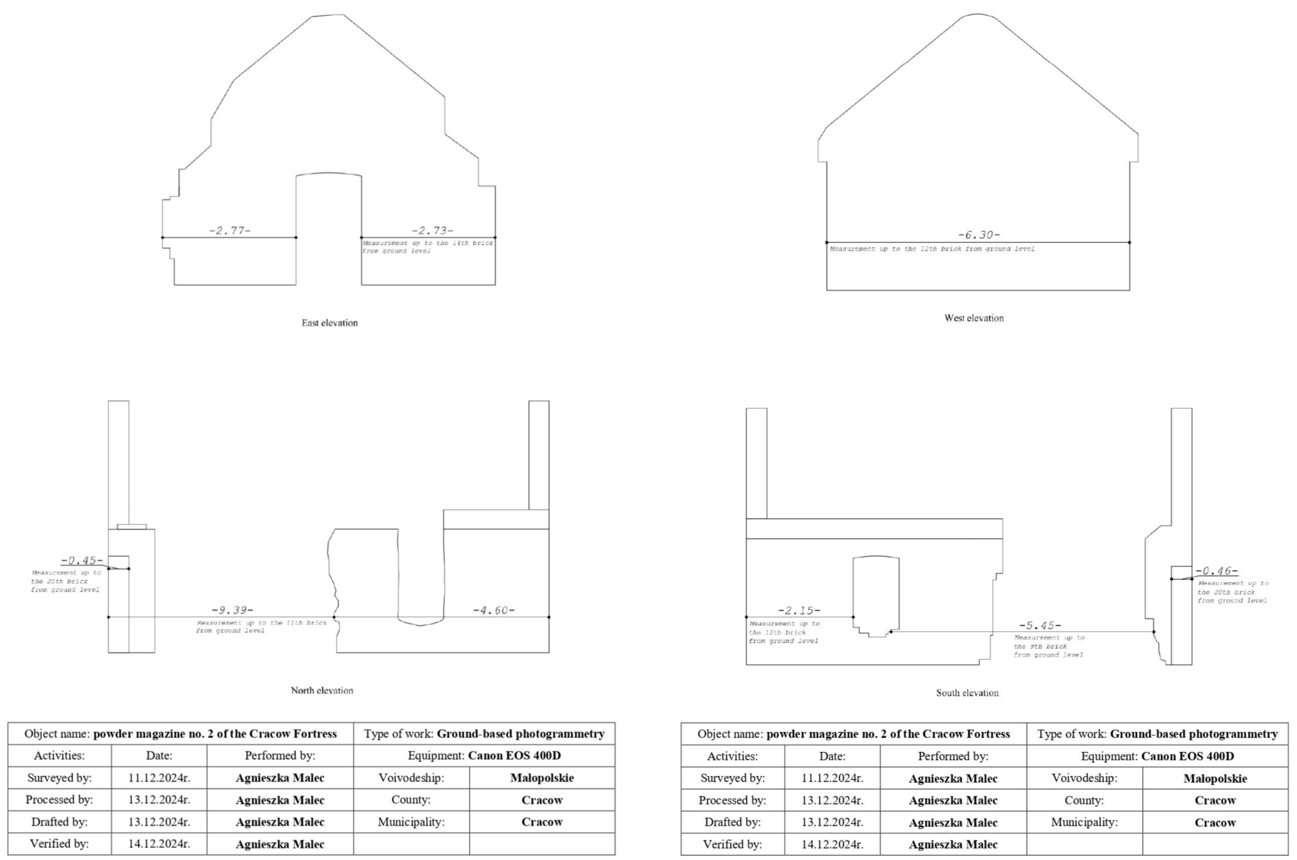

Figure 4. Field sketches from measurements using digital terrestrial photogrammetry

Figure 5. Preliminary model of Powder Magazine No. 2 of the Cracow Fortress created in Autodesk Revit

Figure 6. Model of Powder Magazine No. 2 of the Cracow Fortress created in Autodesk Revit – isometric view

The second reconstruction model was developed in Trimble SketchUp using the triangular mesh generated from ground-based photogrammetry in Agisoft Metashape Professional. SketchUp's intuitive interface and surface-based modelling capabilities made it suitable for reconstructing the architectural form of the powder magazine.

The project began by setting the measurement units to meters and importing the mesh, which was then scaled and oriented to correspond to the project coordinate system. The building footprint was traced directly from the imported geometry, recreating exterior walls with a thickness of 45 cm. The "push/pull" tool was subsequently used to extrude these walls to their full structural height of 3 m, following the proportions visible in the photogrammetric dataset.

In the following phase, the door and window openings were modeled. The primary entrances – measuring 130 × 230 cm – were modelled in direct alignment with the opening visible in the mesh. As in the Revit model, window openings were reconstructed using symmetric placement and approximate dimensions of 90 × 140 cm due to the absence of detailed historical information.

The model was enhanced with additional architectural elements, including concrete steps and the roof structure. Based on the analysis of the mesh, it was determined that the building had a gable roof with a height of 3 m. It was reproduced following the visible geometry of the front of the building and extended over its entire outline (Figure 7).

The final stage of the workflow involved assigning realistic material properties to the model surfaces, conducted through a process of manual texturing. High-resolution images of bricks and concrete, captured during fieldwork, were imported as material textures, scaled appropriately, and fitted to the corresponding surfaces. Materials for the roof and joinery were selected from the SketchUp library with attention to historical plausibility. This workflow made

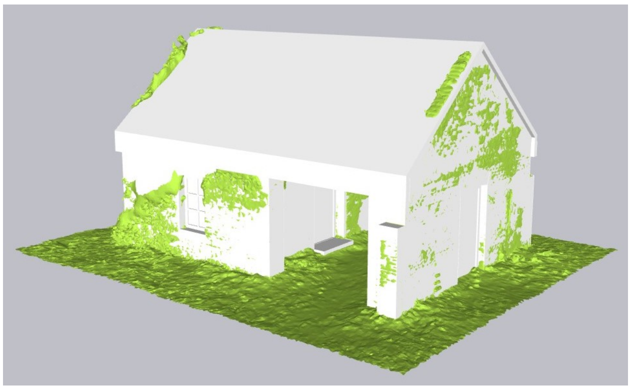

Figure 7. Preliminary model of Powder Magazine No. 2 of the Cracow Fortress made in Trimble SketchUp

Figure 8. Model of Powder Magazine No. 2 of the Cracow Fortress created in Trimble SketchUp – isometric view

it possible to achieve an elevated level of visual consistency with the object's actual appearance, ensuring that the reconstructed surfaces closely reflected the material qualities and aesthetic characteristics seen on site.

To conclude the modeling process, an isometric view of the reconstructed powder magazine was generated (Figure 8).

4 Determining the accuracy of the reconstruction

The accuracy of the reconstructed three-dimensional models was evaluated based on the consistency of the measurement datasets as well as visual and historical verification. The assessment focused on both the geometric differences between the two independently acquired point clouds and the degree to which the reconstructed architectural features reflect their historical authenticity.

4.1 Point cloud conformity analysis

The first step consisted of comparing clouds: the reference cloud obtained through terrestrial laser scanning and the cloud generated from the set of ground-based digital photographs processed using photogrammetric methods. The Cloud-to-Cloud (C2C) tool available in CloudCompare was used to determine absolute distance differences between corresponding points in the two datasets.

The results were presented using colour-coded spatial visualisation and a histogram of distance values. The C2C difference map (Figure 9) shows the distribution of point-to-point errors in metres, using a colour scale ranging from blue (minimal differences) to red (maximum deviations). The predominance of blue tones shows a high degree of geometric agreement between most points.

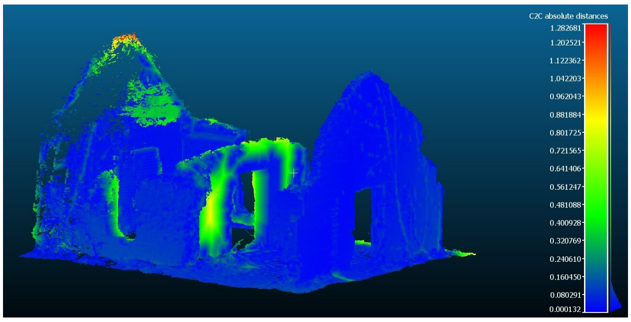

Figure 9. C2C plugin effects: Cloud-to-Cloud Comparison of the two 3D models

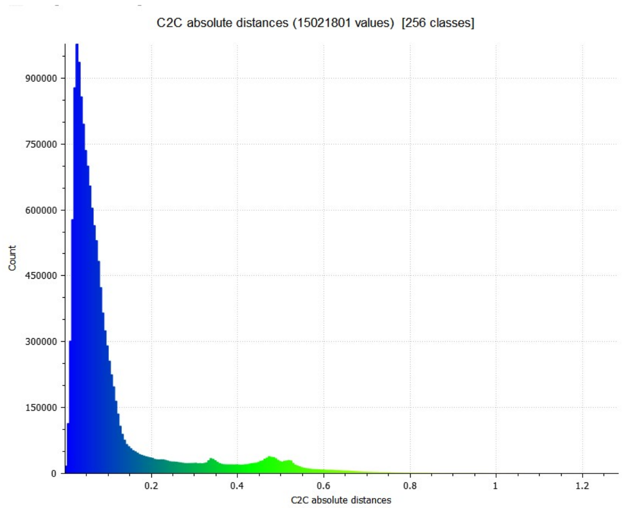

Figure 10. Histogram of the numerical distribution of points compared to C2C distance

Local areas of green and yellow (0.20 – 0.60 m) correspond to reduced geometric accuracy in surfaces that are difficult to measure or poorly textured –such as roof ridges or door openings. Deviations exceeding 1.00 m, shown in orange and red, appear mainly on the rear façade overgrown with vegetation and were treated as unreliable due to measurement disturbances.

The histogram (Figure 10), representing 15,021,801 C2C values grouped into 256 classes, confirms the prominent level of photogrammetric accuracy compared to the TLS reference. For nearly 90% of the points, the differences do not exceed 0.20 m, with a clear peak around 0.06 m. Two secondary peaks, at approximately 0.35 m and 0.55 m, correspond to areas of reduced precision shown earlier. The largest deviations (1.00 – 1.28 m) occur sporadically and most likely result from vegetation or incomplete coverage in some regions of the object.

The C2C analysis was performed on two independently acquired point clouds, which were only preliminarily cleaned before comparison, consisting of removing obvious disturbances and elements not directly related to the geometry of the object. However, no advanced filtering procedures or systematic outlier detection were applied. Consequently, local deviations – particularly visible in areas obscured or covered by vegetation – should be interpreted as the result of photogrammetric data limitations, such as heterogeneous surface texture or incomplete photographic coverage, rather than actual geometric differences between the compared models. The results show that in future comparative analyses, the use of a photogrammetric point cloud filtering stage – including outlier detection and manual data editing in problematic zones – could further reduce the impact of systematic errors and increase the clarity of results interpretation.

4.2 Comparison of models and authenticity assessment

A comparative analysis of the reconstruction models created in Autodesk Revit and Trimble SketchUp showed both similarities and differences arising from the nature of the modelling tools used. Both models represent a compact, simple building volume with a gable roof and similarly located window and door openings, confirming their consistency with the triangular meshes.

Differences primarily concern the presentation of details and the overall visual character. The Revit model shows a more technical, structured appearance consistent with the BIM approach, which emphasises exact representation of construction parameters and materials. In contrast, the SketchUp model is more sketch-like and visually light, reflecting the software's intuitive surface-modelling workflow.

A historical authenticity assessment was also conducted: Based on descriptions of powder magazine architecture (Mikulski, 2024), both models reflect the characteristic features of these structures: single interior chambers, entrance avant-corps, and mixed masonry–timber construction. Due to the lack of detailed documentation of windows and doors, these components were reconstructed using historically plausible assumptions. Full verification of these elements would require additional archival research.

5 Results and conclusion

This study developped two reconstructive 3D models of Powder Magazine No. 2 of the Cracow Fortress using terrestrial laser scanning and ground-based photogrammetry. The project was conducted according to the planned methodology, covering all stages from field measurements and data processing to the construction of 3D models.

A comparison of the obtained results confirmed that both methods – despite technological differences – provide sufficiently precise spatial data suitable for reconstructing historical structures. The accuracy analysis proved high agreement between the models: most point differences did not exceed 0.2 m, with a dominant value around 0.06 m.

Both the TLS-based model created in Autodesk Revit and the photogrammetric model developed in Trimble SketchUp reached a Level of Detail corresponding to LOD 200, including the main architectural elements. The use of photographic and library textures enabled high visual quality despite challenges arising from incomplete archival documentation and field conditions.

The Level of Detail – LOD 200 – applied in this study corresponds to the schematic design stage and allows for an exact representation of the object's general shape, spatial relationships between its elements, and approximate geometric parameters. Adopting this level was a conscious methodological decision, conditioned by both the scope of available survey data and the state of preservation of the analyzed object. However, this level does not encompass detailed modeling of structural elements, architectural details, or the precise geometry of joinery, which are characteristic of LOD 300–400. Achieving higher levels of detail would require supplementing the data with additional as-built surveys, more extensive archival documentation, and in-depth structural analysis. In the case of severely damaged structures, this would necessitate the use of reconstructive assumptions with a higher degree of interpretative subjectivity.

The study leads to the following conclusions:

1. Both photogrammetry and TLS are highly suitable for precise documentation and reconstruction of historical objects, even in cases of partial destruction.
2. Modern 3D technologies allow for the creation of digital models of historical buildings even when source materials are limited.
3. The reconstructed models can be used for heritage protection, conservation activities, education, tourism, and virtual presentation of monuments.
4. Despite measurement challenges, the resulting models constitute valuable research and documentation material that supports the wider use of digital technologies in heritage science.

The obtained results also show the potential for further development toward creating an integrated, hybrid BIM model that combines precise geometry acquired from Terrestrial Laser Scanning (TLS) with high-quality textural information derived from terrestrial photogrammetry. This approach would allow for the simultaneous preservation of high metric accuracy and a photorealistic representation of the object's surface. While, in this study, both models were developed independently, which enabled their direct comparison and an assessment of the suitability of both measurement methods. Integrating the data within a single BIM environment could be the next stage of research, particularly significant in the context of comprehensive documentation, conservation analyses, and the digital archiving of historical objects.

In summary, the developed 3D models of Powder Magazine No. 2 demonstrate not only the effective integration of measurement techniques with spatial modelling tools but also the potential of digital technologies in documenting material cultural heritage.

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