Digital Investigation of Modern Building Elements: A Case Study on Facade Details of Munich's to be Demolished Main Building of the Central Station

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Abstract. Three-dimensional (3D) digitisation of material culture has long been practised and is now integral in cultural heritage (CH) preservation and conservation efforts. These efforts, however, have rarely considered capturing small-scale elements of modern architectural heritage. Their hard-to-capture surface properties pose specific challenges, often leading to their omission in 3D conservation practices. Due to their serial industrial production, modern building elements are repetitive, seemingly similar in their fine structures. Still, because of manual assembly, reworking, and decades of use and maintenance, they need to be seen as individual and original artefacts requiring a high degree of measuring accuracy and differentiation ability. This paper highlights the accurate digitisation of window frames using different 3D-surveying tools, post-processing steps, and deviation assessments. The main goal is to understand the windows' current state and investigate how they conform to the original production according to detailed construction plans, which are used to compare and verify the scanned objects. While close-range terrestrial laser scanning (TLS) and photogrammetry were tested, the primary tool for our survey of windows at the Main Building of Munich`s Central Station was an industrial measurement arm (Hexagon 8325-7) with a high-accuracy laser scanner (Hexagon AS1). Two novel methods are proposed to investigate the conformity of the scanned window frames to the historical sources. This investigation showed the advantage of using a metrology arm in digitising small-scale, reflective and feature-poor modern architectural elements.

Keywords: Modern Building Heritage, Window Frames, 3D-Scanning, Digitisation

1 Introduction

Cultural heritage (CH) objects display various shapes, materials, and states of preservation, highlighting the diversity of our past material culture and the possibility of different methods with which they could be digitised. So far, research has focused on more “ancient” objects such as archaeological finds, monuments or historical buildings. Due to their production technology, these objects are more amorphous in form and usually possess non-reflective surfaces. In contrast, modern building elements often show reflective and feature-poor surfaces, which adds a layer of additional challenge to their 3D digitisation. As a result of serial industrial production, modern building elements are repetitive and seemingly similar in their structural details. Still, they must be seen as individual artefacts because of manual reworking and assembly, as well as decades of use and different maintenance phases.

The challenges of digitising industrial objects with reflective and feature-poor surfaces are long known in 3D surveying [1]. Different methods and tools have been used to facilitate this process, especially in manufacturing/industrial processes, for quality control, reproduction, or reverse engineering tasks [2, 3]. Specific problems manifest in the 3D digitisation of modern building elements: a) sharp profiles and edges, b) feature-poor surfaces, and c) reflective materials. These properties pose difficulties when creating digital surrogates through 3D-surveying methods. Thus, new workflows targeting digital documentation and investigation of these industrialised heritage elements must be developed.

This paper discusses the methodology for 3D digitisation developed and currently used within the EU-funded research project ‘CONSTEMO: Recurring Elements of Modern Facades (1960–1990)’. The project's main goal is to investigate and further develop the digital documentation and semi-automatic identification of facade elements produced between 1960 and 1990 in Germany.

To discuss the proposed methodology, the exemplary digital documentation of window frame samples at the Main Building of Munich Central Station (1955–1960), originally manufactured by Josef Gartner & Co. from Gundelfingen, is showcased. The building, designed by the architect Heinrich J. Gerbl and the *Bundesbahndirektion*, is currently being demolished. The survey on site was aimed at digitally preserving the exemplary condition of the aluminium window frames and the delicate features of the facade.

This paper highlights the accurate digitisation of window frames using different 3D-surveying tools, post-processing steps, and deviation assessments. The main goal is to understand the windows’ current state and investigate how they conform to the original production according to detailed construction plans of the facade, which are used to compare and verify the scanned objects. The extraction of ground truth (GT) models from archival data and their comparison against 3D scans has not been practised as part of a production investigation of modern heritage. For this reason, accurate 3D data acquisition and detailed analyses were key in justifying our approach as a potential digital investigation solution.

2 Background and Related Works

The question of accurate and noise-free acquisition of hard-to-capture architectural elements remains an open issue. Prior research has explored new ways to digitise modern building elements using active and passive sensors. Lachat, Landes and Grussenmeyer investigated TLS and Kinect V2 sensor to produce complete indoor modelling using a data fusion approach, capturing building elements such as window frames and door jambs with more detail [4]. Automated data extraction and segmentation of facade elements, especially windows, using TLS [5] or mobile laser scanning [6] have also been proposed by prioritising shape extraction from building facades using sparse point cloud data. A recent study at ETH Zürich attempted to document building facades and reproduce small-scale components of high-tech architecture using additive manufacturing for repair and conservation purposes [7]. The study made use of TLS and photogrammetry to acquire the 3D data. Extraordinary weather conditions brought Saharan red dust to the city during the acquisition campaign, coating the building's surface and facilitating its digitisation.

Yet, TLS and photogrammetry are not particularly suitable for capturing objects with reflective properties. TLS is mainly suited for the mid-to-long-range acquisition of relatively larger objects and is less successful in capturing challenging surfaces that are intricate in detail. Being a passive acquisition method, photogrammetry depends on a combination of situational and technical factors such as lighting conditions, feature richness of the object/scene, image overlap, image sharpness and exposure for accurate scene reconstruction. For instance, an under- or overexposed image will hinder an object's details, which are critical for feature detection algorithms. Similarly, unsharp images will result in inaccurate scene descriptions [8]. However, reflections and feature-richness of objects pose a more significant challenge as they are inherent to the object/scene itself.

Various methods have been tested to overcome these issues. Among them are artificially generated noise functions to enhance the appearance of a surface to assist feature detection algorithms [9, 10]. These artificially produced noise patterns add a synthetic structure to the object, facilitating the photogrammetric acquisition by enhancing the tiepoint detection algorithms. On the other hand, they involve other problems, e.g. extra post-processing procedure and the object's full coverage (all sides) with a stable projection setup and camera rig without causing occlusions on the object, features which usually are not feasible at on-site surveys.

Other authors have addressed the issue of reflections by integrating cross-polarised lighting, even combining it with pattern projection systems to get enhanced results [10]. The integration of polarisation in photogrammetry has been discussed in detail, concluding that its contribution to the accuracy when used in photogrammetry is limited [11]. On another note, polarisation filters do not apply to metal objects due to the physics involved. Therefore, photogrammetric accuracy is not improved for metallic objects [12]. Working with metallic surfaces remains challenging unless the objects are coated with a synthetic, non-reflective material, such as a scanning spray.

3 Methodology

3.1 Overview

The on-site scanning was conducted in February 2024 within two days by three people. Due to access restrictions, four rooms in the second storey of the northern section of the building and two corridors were scanned, digitally documenting ten window frames in total. In the data management protocol, each scanned window was assigned a unique identifier composed of the room designation (R) followed by the original room number (#), and the window designation (W) followed by its sequential number (#). For example, 'R216_W04' represents the fourth window in room 216.

The as-built 3D floor documentation was carried out with a Leica BLK360 G1 terrestrial laser scanner to provide a spatial context for the window frames. This step was crucial for virtually revisiting the floor and examining the relationships between individual windows, enabling an overall context for the project. A second goal was to test and observe how the window frames could be captured with TLS and photogrammetry. Their feasibility was tested to evaluate their potential for the digitisation of such challenging objects in-situ. Even though the window frames are not unused, and therefore not fully reflective, they nevertheless posed problems in their digitisation.

Due to the abovementioned challenges, accurate documentation was necessary to capture the geometry of the window frame samples. An industrial measurement arm (Hexagon 8325-7) with a blue line laser scanner (Hexagon AS1) was deployed as the primary tool for our surveying task. With this instrument, the source information to generate the deviation analyses compared to a nominal model could be acquired.

Since a physical model of an original, unused window frame for GT was not available, the company archive of Josef Gartner GmbH was used to find the manufacturing drawings of the window frames. The measured drawings had been miniaturised to a microfiche size of only a few centimetres, from which they were scanned by a reader device and digitised. The digitised drawings were traced in a CAD software (Vectorworks 2024) to generate a 3D model, which served as our GT model.

Deviation assessments were performed using two methods: in the first method, the mesh generated from scan data was compared against the GT model. In the second approach, a 2D profile was created from the best-preserved section of the scan data and extruded into a 3D model, which was then converted into a mesh for the comparison step. In addition, different line/profile sections were extracted in a single model to validate the second method.

3.2 Historical Sources

After its completion in 1960, Munich's Central Station's new Main Building was noted in contemporary literature. The architectural journal *Baukunst und Werkform* published a brief article, for instance [13]. The so-called *Ostfrontgebäude*, a 147 m long block facing the city center, was constructed as a steel skeleton structure and housed a central counter hall, different shops, a travel agency, a bank, custom clearance, and more services at ground level, while the upper floors served for administration offices, and the 4th and 5th floor for two parking decks. The building was clad with a grid-like metal-curtain wall. In the 1960s, this design represented a then-new architectural attitude and mid-century modernism following US-American examples. Despite its characteristic features, the existing Main Building was never listed or given appropriate recognition. The demolition began in summer 2019 and is currently still underway.

Besides other components, Josef Gartner & Co. provided the aluminium curtain wall construction with built-in pivoting and tilt-and-turn windows for the app. 5.000 square metres in total. The aluminium components were technically anodised [14]. In the post-war decades, aluminium had become the material of choice in the building sector. The extruded material allowed construction and processing methods to be aligned with its characteristics. It is lightweight, weather-resistant, and affords lower maintenance than wood or steel. Anodising allowed for additional surface protection and colouring. Besides that, insulating glass units (IGUs) were installed in the facade. IGUs were not part of a standard design but became more popular from the 1960s onwards.

The facade construction was published in the company's advertisement calendar in 1960 and 1961. It contains data, technical information, and original facade photos [14]. Original manufacturing drawings and technical information were available in the company's archive. The fully dimensioned manufacturing drawings consist of elevations of all facades on a scale of 1:100, the design of fixture components, and different horizontal and vertical detail sections of connection and joint details of the facade on a scale of 1:1.

3.3 Sampling Strategy

Owing to the building's high number of window frames, it was decided to concentrate on an approach similar to clustered data [15]. The rooms served as the samples, and the strategy was to scan all the window frames found within these rooms. The rooms were chosen based on accessibility and safety, resulting in a constrained random selection. The windows are, however, representative of the repetitive, industrially produced elements according to the available historical sources by Gartner.

The data acquisition was carried out each for the (a) window frame and the (b) open sash frame with the AS1 laser scanner (Fig. 1). Apart from the floor documentation, TLS was tested only in room 216 (R216), targeting frames of a window wall in a close-range manner when the windows were shut. Similarly, the same window wall was captured with photogrammetry with high overlap due to the assumption that the images would lack the redundant tie points for a successful registration.

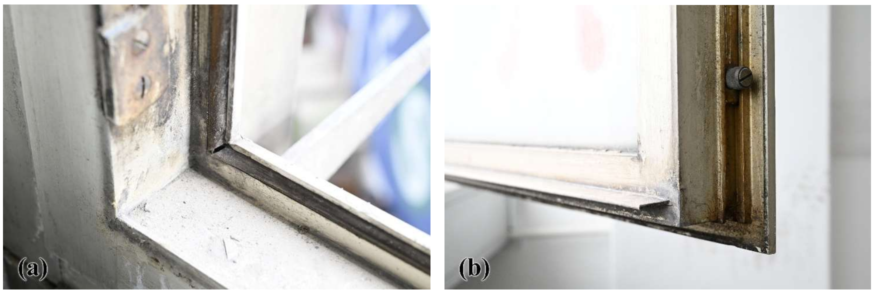


Fig. 1: (a) Example of a window frame. (b) Example of a sash frame.

3.4 Terrestrial Laser Scanning

To provide a spatial context for the window frames and to experiment with how the window frames are captured using TLS technology, a Leica BLK360 G1 was used on-site. This laser scanner allowed for practicality on-site due to its lightweight and suitability for indoor acquisitions.

The floor was scanned in 33 scan positions. In addition, room 216 was also individually scanned with 8 scan positions. A local coordinate system was used due to the goals and technical restrictions of the project. Both scan projects resulted in a 4 mm deviation after the cloud-to-cloud registration performed in Leica Cyclone REGISTER 360 (BLK Edition) software. The point cloud collected from room 216 was transformed into a mesh in Reality Capture (now Reality Scan) to inspect its structure as a solid surface (Fig. 2a).

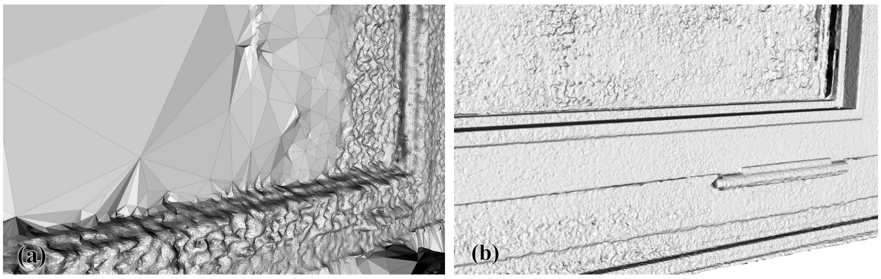


Fig. 2: (a) Tessellated surface derived from the TLS point cloud. (b) Photogrammetric result.

3.5 Photogrammetric Acquisition

Photogrammetry was only carried out in a single room (216) to see its possible integration as a passive acquisition technique. Employing the free-hand imaging technique, approximately 1.000 images of the complete window wall were taken with a focus on the lower part of the window frames. The images were acquired in 14-bit RAW, which were pre-processed in Sony DxO PhotoLab 8 to correct their optical errors and enhance their overall visual quality. The pre-processed images were afterwards exported in *.jpg format to be used for scene reconstruction in Reality Capture.

The alignment of the images was carried out in iterations. One of the main goals was to avoid using manual tiepoints or artificial targets. Specific problems occurred due to insufficient natural tiepoints, surface homogeneity, and glass surfaces (Fig. 3a). These issues stemmed from the reflective nature of the window frames, the scarcity of features and the amplified noise (ISO) due to signal processing. Some inconsistencies in the resulting texture draping have also been observed due to minor misalignment problems and the noisy surface of the mesh. Still, photogrammetry provided a high-quality model with a texture, which allows an interactive assessment of the window's current condition in a more holistic manner. It is important to note, however, that the textured model still does not correctly replicate the materiality of the anodised aluminium frames without acquiring and integrating their reflective properties. The blunt texture gives an impression similar to PVC frames. (Fig. 3b)

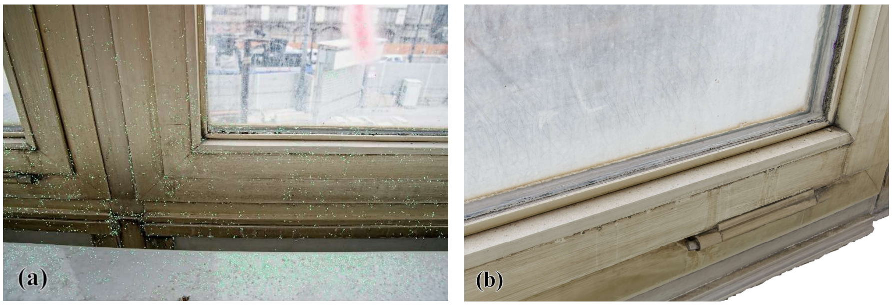


Fig. 3: (a) Image showing the detected tiepoints (green) in Reality Capture. (b) Photogrammetric reconstruction showing the window frame with high-resolution textures.

3.6 Industrial Metrology Arm

The application of a metrology arm in heritage documentation is not a common practice compared to other digitisation methods. It can be used to ensure an accurate spatial reference system when documenting, for instance, archaeological artefacts through tactile measurement [16]. This research project took advantage of a Hexagon 8325-7 Absolute Arm equipped with a blue-line Absolute Scanner (AS1) to capture the window frames in 3D to overcome the challenges exemplified above (Fig. 4a). This state-of-the-art metrology instrument has seven degrees of freedom in rotation. The Hexagon AS1 scanner delivers an intrinsic form accuracy of up to 16 µm. When integrated with the Absolute Arm 8325-7, the combined system achieves a certified scanning accuracy of 65 µm (ISO 10360-8 Annex D)[17].

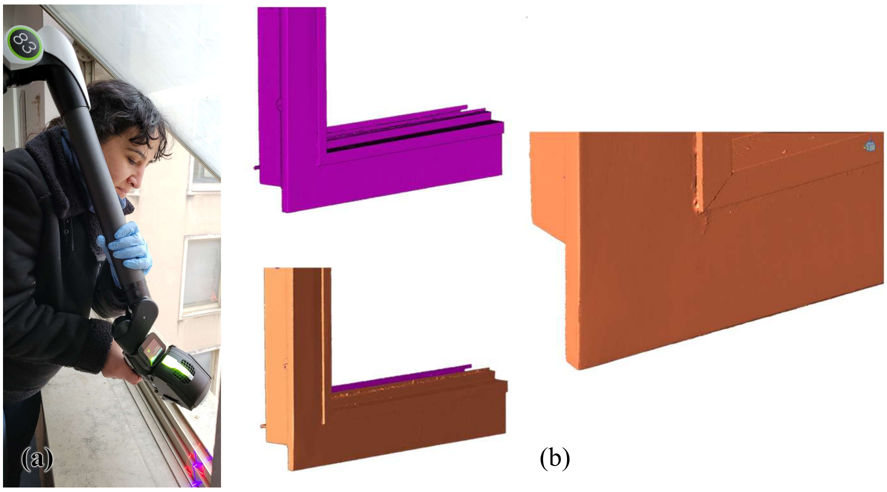


Fig. 4: (a) Data acquisition with the measurement arm on-site. (b) Images showing the resulting 3D data: the point cloud (purple), the mesh (orange) and a close-up of the mesh

The 3D scans only covered the outer form of the window and sash frame profiles, resulting in a model without any shell thickness. Even though the resolution of the point clouds varies per model, on average, the models were captured in high resolution with a minimum of 8,7 million and a maximum of 12,1 million points. The point clouds were noise-filtered and tessellated with Hexagon's proprietary software, Inspire (Fig. 4b).

With a theoretical accuracy of 65 µm, the high-resolution scans posed novel challenges for analysis and interpretation. The 3D model visualised fine surface features which could either be traced back to manufacturing processes, traces of wear and tear, or measuring errors. The high number of seemingly identical window profiles surveyed was to account for and eliminate potential errors during the survey.

4 Digital Investigation of Window Frames

The resulting scan data were assessed both qualitatively and quantitatively. In the first case, deformations were visually detectable in the resulting scans thanks to their high resolution, even though they were unclear to the naked eye on-site. However, this paper's primary goal was to quantitatively analyse the window frames by comparing the scanned data and GT models, not least to test the accuracy of the 3D digitising methodology.

The absence of unused physical copies or original CAD data required an alternative solution for creating our GT model, as described in Chapter 3.1. Using the available data, two novel methods are proposed to investigate the captured window frames' deformation and their conformity to the historical sources.

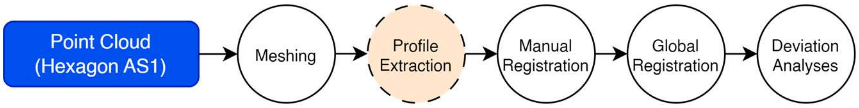


Fig. 5: Diagram showing our workflow from capture to generating deviation analyses. Profile extraction is only carried out for Method II.

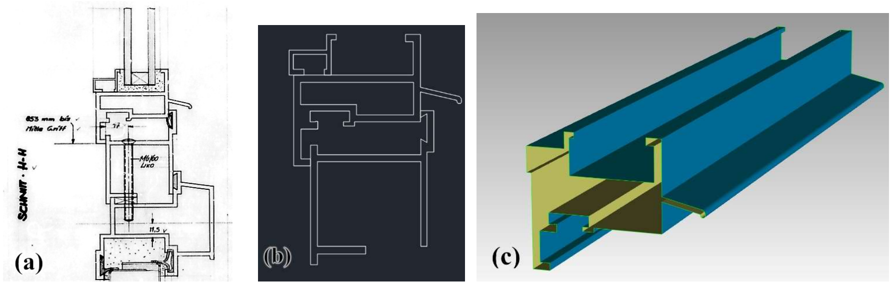


Fig. 6: (a) Vertical detail section, plan #260066/2, Archive of Josef Gartner GmbH, Gundelfingen/Donau. (b) The plan was traced and reduced in CAD software to generate our GT (c) The resulting GT in 3D.

4.1 Method I: Direct 3D Scan Comparison

In Method I, a mesh-to-mesh comparison was performed between the scans and the GT. Prior to their comparison, GT was converted into a mesh and subdivided to provide consistency and facilitate the registration process. Following this, both models were cleaned for redundant data and made ready for the registration step.

As a first step, the models were registered manually using correspondence-based registration by selecting point pairs in both models to run a coarse alignment due to their individual coordinate systems. Once successful, a global registration was executed until a convergence was reached to fine-register the models. In the last step, the superimposed models were visually inspected, and a 3D deviation map was generated. This made it possible to observe the differences between the scanned models and the GT, both visually as a false colour map and numerically as statistical values. All these steps were performed using Geomagic Wrap, an advanced software solution for mesh processing and editing. Statistical values from the deviation analyses were then recorded for each model and compiled in an Excel spreadsheet.

A shortcoming of this method was that only portions of the objects were scanned on-site, resulting in limited data. Furthermore, the samples did not represent the original cross-section due to surface pollution and deformations. Therefore, a second method was developed to bypass these issues.

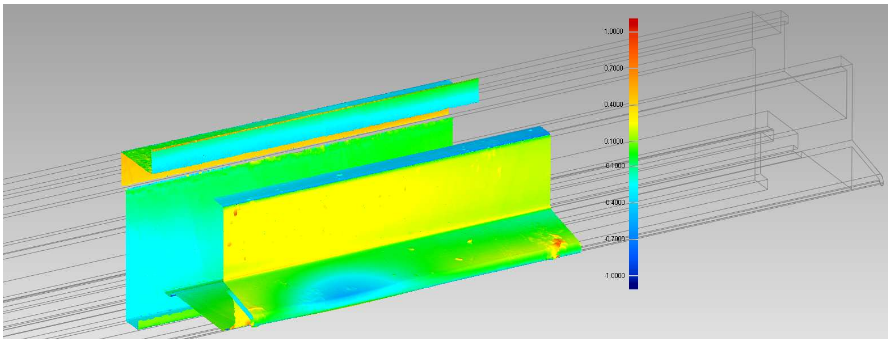


Fig. 7: 3D deviation map (in mm) of R236_W03 using Method I. GT is displayed in grey lines.

4.2 Method II: Profile-Based Surface Approximation

Method II aimed at generating a 3D model by extracting a cross-section from the best-captured part of the scan data (Fig. 8a). The hypothesis behind this approach is that the extraction of an intact cross-section would allow for the generation of a 3D model by extruding it, which would resemble the original production. The aluminium window profiles are produced with extrusion machines; in practice, their surface is an extrusion of the original cross-section and the same along the whole frame. To carry out this specific task, Autodesk Fusion360 was used, in which a cross-section was created, edited and extruded (Fig. 8a – smaller image). As highlighted in Fig. 5, this was the step that differentiated Method I from Method II.

Relying on only a single cross-section was not robust due to the pollution and damage on the surface. Therefore, it was decided to extract five cross-sections from the sample R214_W02 with distances of 20 mm from each other to test how much the resulting models would differ from each other. Following the same procedure, these cross-sections were extruded and individually compared to the GT model (Table 3).

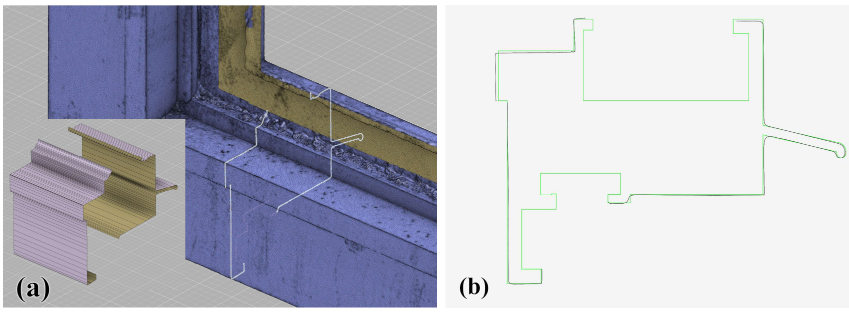
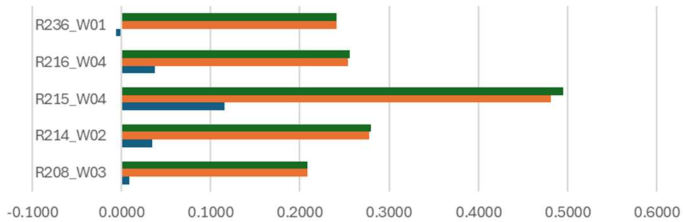


Fig. 8: (a) Extraction of a cross-section and the resulting extruded model. (b) The superimposed (orthographic side view) 3D models showing the GT (in green) and the model derived from Method II (in grey).

5 Results

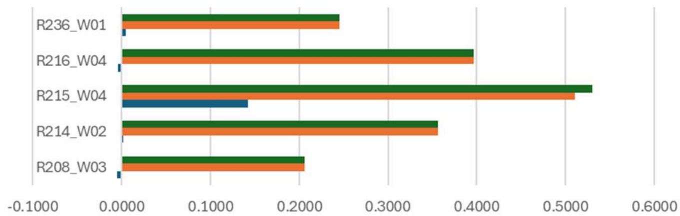
The use of TLS proved helpful for the spatial documentation of the building floor. However, the results produced high surface noise when the window frames were targeted. On the other hand, photogrammetric reconstruction surpassed the results of TLS when digitising the window frames. Although there were misalignment problems on the less sampled upper parts of the window frames, the more densely photographed lower parts succeeded in geometric and texture descriptions. Still, the reconstructed mesh was not helpful for our analyses due to surface noise.

Table 1. Deviation metrics (in mm) for Method I.



	R208_W03	R214_W02	R215_W04	R216_W04	R236_W01
RMSE	0.2089	0.2794	0.4953	0.2563	0.2410
Std	0.2088	0.2772	0.4816	0.2536	0.2410
Avg. Dis.	0.0085	0.0347	0.1157	0.0371	-0.0062

Table 2. Deviation metrics (in mm) for Method II.



	R208_W03	R214_W02	R215_W04	R216_W04	R236_W01
RMSE	0.2058	0.3566	0.5301	0.3966	0.2454
Std	0.2058	0.3566	0.5108	0.3966	0.2454
Avg. Dis.	-0.0048	0.0016	0.1418	-0.0037	0.0050

The metrology arm produced the most reliable results thanks to its high accuracy, resolution, and ability to capture reflective surfaces. The 3D deviation analyses showed a very low error margin for all the samples, with a maximum standard deviation (Std) and root mean square error (RMSE) close to 0.5 mm in both methods (see Table 1., Table, 2). The most biased sample was R215_W04 in each method. R208_W03 showed the best overall conformity to the GT, again consistent in both methods. The Std and RMSE values are close in all comparisons, indicating a symmetric distribution of errors.

The validation approach for Method II using sample R214_W02 produced better results than our initial estimation based on visual inspection. The first three cross-sections (Table 3) showed slightly greater accuracy, differing by 0.15 mm from our original choice (Table 2, R214_W02). However, cross-sections 4 and 5 yielded values close to the initial estimations.

Table 3. Deviation metrics of validation (in mm) for Method II, sample: R214_W02.

	Section 1	Section 2	Section 3	Section 4	Section 5
RMSE	0.2048	0.2012	0.2051	0.3114	0.3681
Std	0.2048	0.2011	0.2026	0.3067	0.3465
Avg. Dis.	0.0012	0.0066	0.0322	0.0537	0.1243

6 Discussion and Conclusion

With the aim of high-quality digitisation, this study has presented various surveying methods to capture and investigate the in-situ window frames. This investigation showed the advantage of using a blue-light scanner mounted on a measurement arm in capturing small-scale modern architectural elements.

The investigated sash frames closely resembled the original production, and even after decades of use and maintenance, they remained highly intact. There are, however, still open issues regarding how to capture the window frames without surface noise. This raises the question of using scanning sprays to monitor the differences between the two approaches. Additionally, the accuracy of the 2D-scanned historical plans and their manual tracing in CAD software must be inspected in detail.

In future work, it is aimed to address these issues and develop methods of automatic vectorising of the 2D plans and integrating the models into a 3D database. A validation protocol based on physical GT will also be visited. New methods to enhance the photogrammetric acquisition will be developed, specifically focusing on geometric accuracy, colour fidelity, and data fusion using a blue-light laser scanner (Hexagon AS1) and photogrammetry as well as integrating real-world reflectance values to produce high-fidelity digital models.

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