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From Archives to 3D Models: Managing Uncertainty with Paradata in Virtual Heritage

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Abstract

This article examines the methodological challenges inherent in the digital 3D reconstructions of historical buildings using archival documentation. Unlike photogrammetry or laser scanning, archival-based modeling is crucial for buildings that never existed, no longer exist, or have undergone extensive modifications. Present research insights from a pilot educational project where 65 university students reconstructed 70 heritage buildings from Budapest (Hungary) in Archicad based solely on archival sources. In total, 75% of the buildings lacked at least one façade drawing, while nearly 20% showed contradictions between different plans (e.g., floor plan and section). Common challenges were identified, including missing drawings, contradictory plans, stylistic uncertainty, and software constraints, and their patterns were analyzed. To enhance modeling transparency, structured methods for recording paradata were proposed. Findings contribute to methodological rigor in virtual heritage reconstruction and support the reuse of archival models in architectural practice, research, and conservation. This study is among the first to propose a structured paradata framework tailored explicitly to archival-based 3D reconstructions, bridging methodological gaps between educational practice and professional heritage research.

Keywords: archival architectural drawings; built heritage visualization; digital reconstruction; historical building modelling; paradata in heritage modelling; 3D modelling

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1. Introduction

Digital technologies have fundamentally transformed the way cultural heritage is documented, interpreted, and communicated. Among these, 3D modeling techniques have gained particular importance in architectural heritage, not only enabling the recording of current conditions [1], but also the reconstruction of altered or lost buildings. The resulting digital artifacts serve multiple functions, from research and conservation planning to public engagement, education, historical studies, and virtual tourism, positioning them at the intersection of technological innovation and historical inquiry [2–7].

The most widely used methods for 3D documentation of standing heritage buildings include terrestrial or aerial photogrammetry and terrestrial laser scanning (TLS) [1–3,8–14]. These techniques provide precise, high-resolution point clouds and surface textures, capturing a building's geometrical and material conditions with minimal subjectivity, eliminating the need for physical exploration.

Among the most renowned international efforts in digital heritage preservation is CyArk, a nonprofit founded in 2003 that has digitally recorded over 200 cultural heritage sites (including Angkor Wat, Brandenburg Gate, Pompeii, and Teotihuacán), mainly using

laser scanning and aerial photogrammetry [15]. CyArk's work focuses on the digital documentation of existing structures at risk due to conflict, natural disaster, or environmental degradation, relying on on-site data acquisition. A notable example is their work in Pakistan, where they captured the Alamgiri Gate in Lahore and the Baltit Fort in Hunza Valley using detailed 3D scanning and photogrammetry as part of cultural heritage protection initiatives [1].

However, not all heritage buildings are accessible, intact, or even extant. In cases where buildings have been demolished, severely altered, or never constructed despite detailed plans, archive-based digital reconstruction becomes the only viable method to bring them back to life [16]. This practice utilizes historical architectural drawings (such as floor plans, sections, and elevations), along with photographs, maps, written descriptions, and occasionally permit procedure documents, to virtually reconstruct a building's original or planned state. Unlike laser scanning or photogrammetry, which "captures," archival modeling inherently "interprets." It requires modelers to translate 2D archival materials into 3D elements, often bridging gaps and resolving contradictions in the source material [17].

Although research in archive-based modelling is expanding, case studies involving non-extant buildings remain relatively scarce. Existing examples include digital reconstructions of historic Warsaw based on 1930s photographs and plans [16], using historical maps, archival drawings, and modern technology (e.g., photogrammetric surveying of the building remains) [18], the reconstruction of a French abbey [19], and the virtual restitution of destroyed synagogues in Greece [6]. These works showcase the scientific and pedagogical potential of reconstructing "absent architecture," but also highlight the need for methodological transparency [6] and a clear distinction between empirical accuracy and informed conjecture.

During modelling, the central problem relates to uncertainty. Archival records are often incomplete, degraded, contradictory, or ambiguous [6,20,21]. For example, missing façades may necessitate speculative extrapolation based on geometry or style; contradictions between floor plans and sections may require judgment calls about dimensional hierarchy; undocumented interior courtyards may only appear in fragmented sectional views; and, in the case of multiple design states (see Figure 1), modelers have to choose which one to model. Without explicit documentation of these decision points, the resulting 3D models may convey a misleading sense of completeness or precision.

In response to these challenges, the concept of paradata has gained traction. Borrowed from archaeological and digital humanities practice, according to the London Charter for the Computer-Based Visualisation of Cultural Heritage, paradata is "information about human processes of understanding and interpretation of data objects" [23]. Paradata are essential contextual metadata that document how a digital model was created, including the sources used, interpretative decisions made, and uncertainties encountered. Their inclusion ensures transparency by revealing the reasoning behind specific reconstruction choices, especially when multiple interpretations are possible. This enhances the credibility and reproducibility of 3D heritage models for future researchers and users [24].

In recent years, artificial intelligence (AI) and machine learning (ML) approaches have increasingly been applied to heritage reconstruction, complementing both survey-based and archival-based methodologies. Croce et al. (2023) propose a semi-automatic Scan-to-BIM reconstruction workflow in which raw surveying data (point clouds) are segmented via machine learning, followed by the templated geometric reconstruction of architectural elements [25]. Similarly, Zhang et al. (2025) examined the integration of AI techniques in 3D reality-based modelling, focusing on image classification, object detection, and point cloud processing to improve automation and efficiency in modelling architectural heritage [26]. Another recent study employs deep learning together with

space syntax to quantify and assess the physical disorder of façades in urban contexts, thereby proposing data-driven criteria for prioritizing renovation [27]. These developments show that computational methods are increasingly capable of addressing gaps in archival records and visual evidence, but also that they introduce new interpretative uncertainties (e.g., algorithmic inference, occluded geometry, stylization). Hence, explicit documentation of paradata—distinguishing between elements supported directly by archival or survey evidence, and those reconstructed or inferred—becomes essential for heritage reconstruction to be transparent, reproducible, and academically robust.

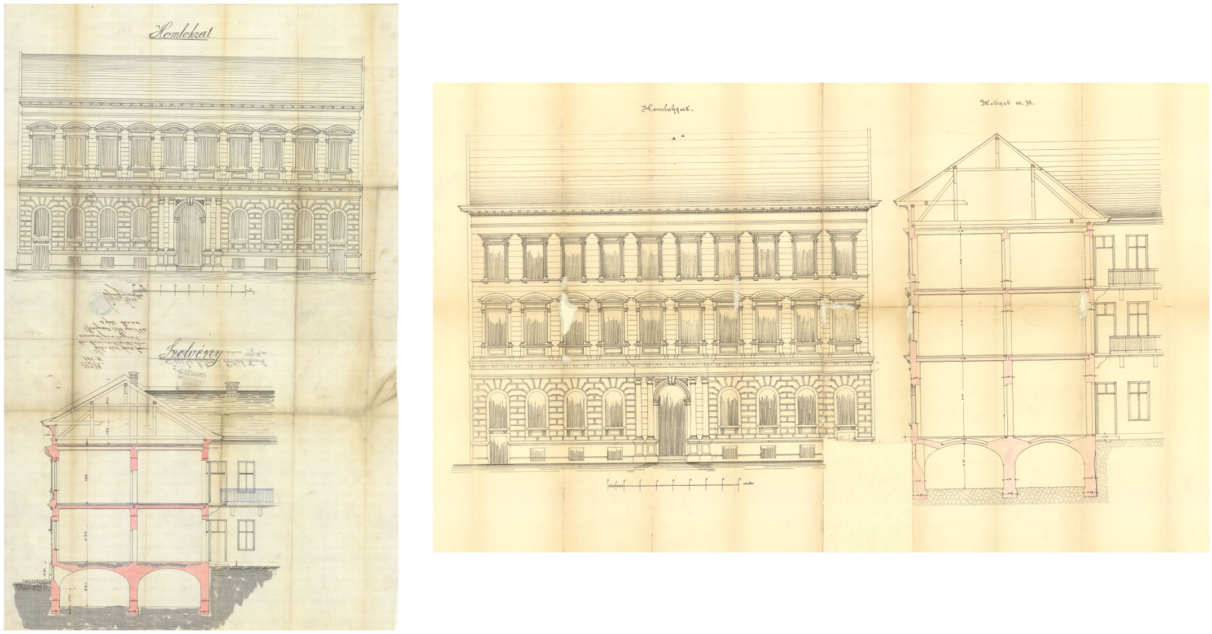


Figure 1. Illustration for two designed versions of the same building within three months. (**left**) Façade and section of the three-storey building (April 1886). (**right**) Façade and section of the four-storey building (July 1886) [22].

The 3D modelling of historical heritage (either from archival plans or from the survey mentioned above) is an important issue in higher education. There are international examples, whether it be a one-day educational project bringing together engineers from different backgrounds (but all with an HBIM background) to highlight the importance of collaboration [28] or photogrammetry education at different scales [29].

As part of the Digital Modeling of Historical Buildings elective course at Obuda University, Ybl Miklos Faculty of Architecture and Civil Engineering (Hungary), architecture students were tasked with reconstructing historical buildings in the capital (Budapest) using only archive sources from the Budapest City Archives [30]. The project encompassed both existing, demolished, and never-built buildings.

While the educational aspects of the course provided valuable context, this paper concentrates on the methodological implications of archival-based 3D modeling. It presents an alternative approach for reconstructing built heritage in cases where the original structures no longer exist, but sufficient archival documentation—such as architectural plans, technical descriptions, and historical photographs—remains accessible. By identifying and classifying recurring types of uncertainty encountered during modeling, this study contributes to a clearer understanding of the limitations and interpretive nature of archival reconstructions. Furthermore, it proposes a structured paradata recording template to enhance transparency, reusability, and scholarly rigor in future digital heritage projects.

The remainder of this paper is structured as follows: Section 2 outlines selected archive-based case studies; Section 3 details the applied modeling procedures and accompanying guidelines; Section 4 discusses the typology of challenges identified during the pilot project; Section 5 introduces the proposed paradata framework; and finally, Section 6 provides concluding reflections and recommendations for future work.

2. Related Works—Archival-Based 3D Reconstructions

The 3D reconstruction of historic buildings from archival sources has become an increasingly common practice in digital heritage research. While the previously mentioned advanced methods, such as terrestrial laser scanning (TLS), photogrammetry, and UAV-based surveying, dominate the recording of existing built heritage, archival-based modeling plays a crucial role when dealing with structures that no longer exist, are partially preserved, or have never existed. This section provides an overview of key international and Hungarian projects that have primarily utilized archival drawings, photographs, and written documentation to reconstruct historical buildings digitally. Rather than presenting these examples as a simple catalogue, the following section focuses specifically on two recurring issues: (1) how each project handled uncertainty caused by missing or contradictory source material, and (2) whether any form of paradata or interpretive documentation was included to make reconstruction decisions transparent.

2.1. International Case Studies

Warsaw (Poland)—In a study published in Applied Sciences, researchers reconstructed non-existent historical buildings in Warsaw by integrating multiple sources, including archival architectural drawings and photographs, terrestrial and aerial photographs, historical maps, and results from tachymetric measurements [16]. The resulting 3D models reflect not only the physical appearance but also the spatial relationship of the vanished buildings, enabling new forms of urban analysis and memory preservation:

- Uncertainty handling: The project dealt with data inconsistency through cross-referencing multiple source types. However, uncertainty remained implicit, as the final visualisation does not reveal where interpretive reconstruction began.
- Paradata use: No explicit paradata or metadata annotation was implemented, meaning interpretive decisions are embedded in the model but not made visible to future users.

Kinburn Spit (Ukraine)—Historical maps, archival plans, and contemporary spatial data (digital terrain models—DTM) were used to create a 3D reconstruction of a fortress that no longer exists. This was supplemented by drone surveys and on-site inspections (a small portion of the fort's ruins are still visible, which helped with spatial positioning) [18]:

- Uncertainty handling: Missing walls and fragmented plans were resolved through georeferencing and interpolation between archival and physical survey data, creating a hybrid reconstruction method.
- Paradata use: The workflow implies interpretive steps, but these are not made explicit within the model or through metadata, indicating an absence of formal paradata documentation.

Rome (Italy)—Although not explicitly based on archival plans, but historical drawings and remains, the largest project of the UCLA Cultural Virtual Reality Laboratory (CVRLab) was the digital model of the partially existing Roman Forum within the Rome Reborn project. The project's primary objective, beyond visualization, was urban simulation, specifically the reconstruction of the urban fabric. During the modeling process, authors recorded which time period the model reflects, as well as what was omitted during modeling (furniture, murals, sculptures). They point out that the model may also be suitable for studies

in urban history or architectural history. It is worth noting that a scientific committee was established to validate the model, whose task was to provide support, supervision, and expert review of the work [31]:

- Uncertainty handling: Contradictory archaeological and historical records were resolved via expert arbitration rather than automated inference.
- Paradata use: This example stands out for explicitly documenting modeling assumptions, temporal states, and exclusions, functioning as an early structured paradata system.

Greece—Archival survey plans (believed to be lost), as well as exterior and interior photographs, were used for the 3D reconstruction of synagogues in Greece. There are also buildings for which not only virtual models but also laser-cut models were created based on the plans. Archival maps were also used to create the models (to locate the footprint). The author's research highlights the inconsistency of archival sources and that gaps can be filled by examining typologically similar sites or buildings [6]:

- Uncertainty handling: The author acknowledges the limitations of the source material and resolves missing geometry using typological analogy—comparing similar buildings to infer absent details. This creates a controlled interpretive strategy rather than free-form speculation.
- Paradata use: Although not called "paradata," the project communicates interpretive assumptions textually in its presentation, making the reasoning behind the reconstruction partially visible to the audience—an approach close to narrative paradata.

Cicogna (Italy)—A study published in Journal of Cultural Heritage outlines a methodological framework for the digital reconstruction of Palladio's unbuilt Villa Thiene at Cicogna, in which archival drawings, survey data, and proportional rules are systematically integrated. Through the application of shape grammar and semantic organization, a historically informed 3D model is produced, demonstrating how virtual reconstruction can operate as both an instrument of architectural analysis and a vehicle for cultural heritage dissemination [5]:

- Uncertainty handling: Rather than freely inventing missing geometry, the authors used Palladian proportion theory as a formal interpretive method, reducing arbitrary assumptions.
- Paradata use: While no paradata table was produced, the proportional reconstruction logic itself serves as an embedded interpretive framework, making the decision logic academically traceable.

Apollonio et al. analyze 3D reconstructions of architectural projects that have survived only in blueprints (e.g., Andrea Palladio's buildings). In these cases, the drawings provide the basis, but the authors raise issues related to general reconstruction criteria, such as uncertainty and accuracy. The authors emphasize that other types of sources—such as pictorial representations, historical documents, and methods of deduction and analogy—must also be included in 3D model building, as these carry varying degrees of accuracy and uncertainty [32]:

- Uncertainty handling: The Level of Reliability (LoR) framework directly addressed the issue of incomplete archival sources by encouraging explicit classification of each modeled element's evidence base.
- Paradata use: LoR is one of the rare examples of a formalised paradata system, where interpretive uncertainty is not only acknowledged but encoded into the model structure and made visible to the viewer through colour-coded representation.

Ahtik et al. reconstruct Plečnik's unrealized monument to Jan Žižka by digitally modeling it from historical sketches, plans, and a single photograph of a lost wooden model,

followed by 3D printing using SLA and FDM technologies. The study further evaluates the reconstructed model's effectiveness in conveying architectural and sculptural style through gallery-based visitor testing using semantic differential methods, demonstrating that the architectural reconstruction enhanced the exhibition experience [7]:

- Uncertainty handling: The workflow incorporated comparative source analysis but did not establish a standardised logic for marking uncertainty, relying instead on implicit modelling judgement.
- Paradata use: No explicit paradata or metadata layer was implemented, and interpretive choices remain embedded in the model without external documentation—illustrating precisely the methodological gap that motivates the present paper.

2.2. Hungarian Case Studies

Hungarian practice also offers relevant precedents, although scholarly documentation is somewhat less comprehensive. Nevertheless, several high-profile projects demonstrate a growing institutional and academic engagement with archival-based reconstruction.

Visegrád Franciscan Friary—A digital reconstruction of the medieval friary at Visegrád was created using archaeological remains (surveyed by photogrammetry and TLS) and historical plans to generate 3D models of several building phases. In the modelling, following a kind of paradata approach, the authors took care to distinguish in the textured model between the elements physically discovered on site and the (quasi-presumed) elements modelled based on these and expert knowledge [33]. Though archaeological in orientation, it showcases the layered use of data in architectural heritage work:

- Uncertainty handling: Missing and fragmentary information was compensated through archaeological cross-referencing and architectural analogy, rather than documented inference protocols.
- Paradata use: No explicit paradata or decision-recording mechanism accompanied the reconstruction.

Budavári Projects—As part of the ongoing National Hauszmann Program (a reconstruction program in the Buda Castle, Budapest), two significant lost buildings are being rebuilt: the József Archduke Palace (demolished in 1968) and the Red Cross Headquarters (demolished in 1946). Both rely heavily on archival plans and historic photographs [34]. Bodó highlighted that an interesting challenge in the reconstruction process is interpreting colours based on archival photographs. For instance, in the case of the Red Cross Headquarters, only black-and-white images of the original stained glass windows have survived, making it difficult to determine their original colours with certainty [35,36]. The Main Gate of the Buda Castle (see Figure 2) was also reconstructed based on archival photographs (from contemporary journals) and original blueprints and samples preserved in the Hungarian Museum of Applied Arts [37]:

- Uncertainty handling: Colour, material texture, and ornamentation decisions had to be inferred from black-and-white photographs, resulting in aesthetic choices based on probability rather than documented evidence.
- Paradata use: While internal documentation protocols may exist within the Hauszmann reconstruction programme, no publicly accessible paradata or metadata layer accompanies the released visual material, meaning that interpretive decisions remain opaque to external users.

St. Stephen's Hall—although primarily an interior design project, the reconstruction of St. Stephen's Hall in the Buda Castle (also part of The National Hauszmann Program)—likely destroyed by fire during World War II—offers a noteworthy example. In addition to surviving elements such as curtains, wall textiles, and pyrogranite decorations, features

like the fireplace and door wings were reconstructed based on archival drawings at a 1:1 scale. Historical elevation drawings, ceramic detail sketches, and archival photographs of the original space provided further insight into the process. However, even the archival plans required critical reassessment and correction using historical photographs to ensure fidelity to the original design [20,21]. This project also raised the issue of colour-correct reconstruction: the colour scheme was based on the designer's other original work, test pieces, surviving textile fragments, and a salvaged curtain [39]:

- Uncertainty handling: The presence of physical fragments allowed partial validation of archival drawings, but inconsistencies between drawings and material remains forced interpretive resolution by experts.
- Paradata use: Although the reconstruction process was guided by expert input and fragmentary physical evidence, no dedicated paradata structure is published alongside the visual outcome, and it remains unclear whether interpretive decisions were systematically recorded.



Figure 2. The Main Gate of the Buda Castle (destroyed during World War II) [38].

2.3. Synthesis

Taken together, the international and Hungarian archival-based reconstruction projects reviewed above demonstrate recurring patterns in how uncertainty is managed when source material is fragmentary or contradictory. Some projects, such as Rome Reborn or the Villa Thiene reconstruction, attempted to anchor interpretive decisions in formalised frameworks (expert committees, proportion systems). In contrast, others relied on multi-source triangulation without making the interpretive process explicit to end users. In the Hungarian context, large-scale initiatives like the Hauszmann Program and smaller academic reconstructions equally reveal that archival-based modelling frequently involves undocumented decisions about colour, geometry, or missing façades:

- In terms of uncertainty handling, most projects compensate for gaps through a mixture of analogy, expert judgement, or cross-referencing. Nevertheless, these strategies are rarely exposed as part of the model itself.

- In terms of paradata use, only a few examples provide structured documentation of interpretive steps, and even when such information exists, it is typically embedded in explanatory texts rather than encoded as metadata or visual cues in the model.

This comparison reveals a methodological gap: while uncertainty is widely acknowledged, it is not consistently formalised or made machine-readable for reuse, validation, or teaching. This is particularly evident in educational or public-facing projects, where the final visual output presents a seamless reconstruction that may conceal interpretive work.

By highlighting this gap, the synthesis of case studies establishes the rationale for the lightweight paradata approach proposed in this paper: rather than introducing a complex HBIM ontology or speculative IFC schema prematurely, a decision-level paradata log offers a pragmatic and scalable solution that can be adopted in both institutional and pedagogical contexts. A summary of the studies detailed above (type of sources used, purpose of modeling, challenges) can be found in Table 1.

Table 1. Summary of selected case studies of historical building reconstruction, mainly based on archival documentation.

Project (Location)	Type of Sources	Modeling and Visualization Tools	Purpose	Main Challenge During Modeling	Ref.
Warsaw (Poland)	historical maps, terrestrial and aerial photographs, architectural blueprints, spatial data, and results from tachymetric measurements	CityEngine, GIMP, SketchUp (for 3D printing)	visualization	quality and completeness of archival materials	[16]
Kilburun Fortress (Ukraine)	archive maps, archive plans and survey plans, DTM, drone survey	AutoCAD, SketchUp, Twinmotion	visualization	find the exact location	[18]
Forum Romanum (Italy)	archeological remains, archive documentation, site survey	MultiGen Creator, Lightscape	visualization, urban simulation	lack of sources	[31]
Synagogues (Greece)	survey plans, archive photos	unspecified	visualization, small-scale laser-cut physical model	combine different sources, a lack of drawings	[6]
Cicogna (Italy)	archival drawings, on-site survey, proportional rules	unspecified	historical analysis, architectural interpretation	missing parts of the design, proportional accuracy	[5]
different locations	archive plans	unspecified	visualization	uncertainty and accuracy of archived materials	[32]
Prague (Czech Republic)	archive sketches, plans, and photos	unspecified	historical reconstruction, exhibition enhancement	limited sources, interpretive reconstruction of details	[7]
Franciscan Friary (Hungary)	archeological remains (walls), site survey	Archiline XP, Archicad	phase-based virtual model	Multi-phase historical evolution	[33]
József Archduke Palace (Hungary)	archival drawings, archive photos, remains structures (foundation)	unspecified	full-scale physical reconstruction	-	[34]
Red Cross Headquarters (Hungary)	archival drawings, archive photos, and remains of structures (basement walls)	unspecified	full-scale physical reconstruction	authentic, colour-correct reconstruction	[35,36]
Main Gate of Buda Castle (Hungary)	archival photos, drawings, samples	unspecified	full-scale physical reconstruction	-	[37,38]
St. Stephen's Hall (Hungary)	archival drawings, archive photos, and remains of interior	unspecified	full-scale physical reconstruction	not constructed exactly as planned (validated by photos)	[20,21,39]

3. Materials and Methods

The present study is based on a pilot educational project conducted within the framework of the elective course Digital Modelling of Historic Buildings offered at Obuda University. The primary aim of the course was to experiment with archival-based 3D reconstruction methods by involving students in modeling historical buildings, mainly from archival sources. The project was carried out in collaboration with the Budapest City Archives [40], which provided digitized documentation of selected buildings.

3.1. Modelling Workflow Overview

A standardized digital modeling workflow developed within a university course, which is tailored to generate Level of Detail 3 (LOD 3) models using Graphisoft Archicad. Given that the primary purpose of the models was visualization, the decision was made to create the most detailed (LOD 3.3—see Figure 3) models, as classified by Biljecki et al. [41]. In terms of modeling software, students used Graphisoft Archicad, which is used by approximately three-quarters of architects in Hungary [42]. Students also learn how to use it during their BSc degree program in architecture at Obuda University. The aim was to recreate the building envelope and decorative elements of selected historical buildings that no longer exist, or exist in a significantly altered form, based solely on historical plans, photos, and maps.

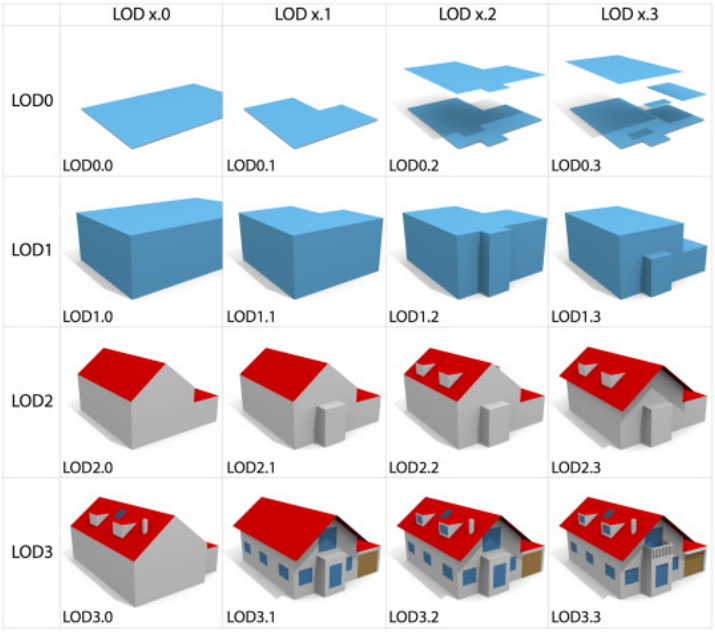


Figure 3. LODs for residential buildings by Biljecki et al. (2016) [41].

The models were created by architecture students, with the instructor providing methodological guidance and oversight. In each case, the archival architectural documentation served as the primary source, with no laser scanning or photogrammetric survey data used. This distinguishes the workflow from more common heritage recording approaches that rely on on-site capture of existing structures. In addition to historical sources, students are encouraged to use contemporary digital sources (such as satellite imagery, online street views, and aerial photographs) to understand the urban context and topographic conditions better. For existing buildings, on-site visits are explicitly required: students are expected to observe the structure in person, take reference photographs, and compare physical conditions with archival documentation to enhance both accuracy and interpretation.

The focus of this study is on Budapest's historical tenement houses, which represent a central part of the city's architectural heritage (see Figure 4). The construction of these multi-unit, courtyard-style buildings reached its peak around the turn of the 19th and 20th centuries, when thousands of flats were built in a short time to satisfy the growing demand for rental housing. This architectural legacy stands as a testament to Hungary's era of prosperity, and its significance is underscored by the 3D reconstructions created within the project [43,44].



Figure 4. Downtown (District VII) of Budapest (photo by Dorka SZAKSZ).

3.2. Step-by-Step Modelling Procedure

To support the modeling process, students are provided with a detailed, step-by-step guideline. This guide begins with instructions on how to interpret and analyze archival materials and continues through the modeling procedure, including recommended tools, modeling conventions, and Level of Detail. It concludes with guidelines for finalizing and exporting the model in standardized formats suitable for archiving or presentation purposes.

The following section presents and discusses the main steps of this workflow in detail. While designed for a university course, this workflow provides a transferable framework for archival-based modelling projects in broader heritage contexts.

1. Familiarisation with the sources

Each student is assigned a building selected at the instructor's discretion. Only buildings with sufficient archival documentation for 3D modeling are considered for assignment, and the necessary materials are pre-selected from archival sources by the instructor in advance. Students identify the building based on its current cadastral number.

As a first step, they analyze the provided documentation (see Figure 5) and locate the building within the urban fabric using the Budapest Time Machine [45].

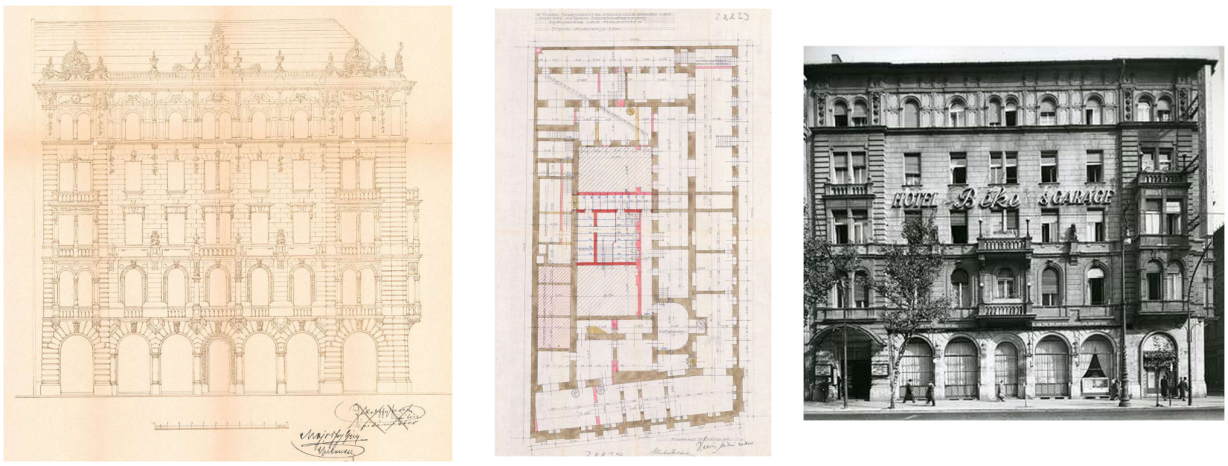


Figure 5. Example of archive sources of "Hotel Béke". From left to right: Main façade, Floor plan of the basement, Archival photo of the building [46,47].

At the end of this initial analysis phase, they are expected to answer the following key questions:

- Is all the documentation necessary for modeling available?
- Is the documentation coherent and consistent?
- If multiple design versions are included, is there one that is fully documented and therefore modelable?
- If several versions are modelable, which one will be selected for reconstruction?
- Are there any additional observations or concerns regarding the provided materials?

2. Model preparation

The key considerations related to the creation of the models are as follows:

- Students must follow a uniform technical environment, utilizing a shared, pre-set Archicad template file (maintained by the instructor and provided to students in every semester) to ensure consistency across all models.
- The template file includes the cadastral base map of the site, into which the 3D modeling is carried out.
- Based on the building and structure dimensions provided in the archival drawings, the first step is to create a basic model that includes the building envelope (walls, slabs, roofs) and the openings (see Figure 6). This model corresponds to approximately LOD 3.1–3.2 [41].
- In the next phase, students construct simplified 3D representations of the architectural ornaments.
- In the final modeling stage, these decorative elements are placed onto the façades of the building (see Figure 6).

3. Export for Archiving

Final models were exported in Wavefront (.OBJ) and Archicad archive plan (.PLA) format using an export protocol. After verification by the instructor, the models are transferred to the Budapest City Archives for archiving and future use. Based on a discussion with the Archives and their digitalization expert partners, the deliverables for this pilot were only the native Archicad archive (.PLA) and the Wavefront mesh (.OBJ); consequently, IFC export was not considered at this stage. The .OBJ choice directly reflects platform compatibility with the Budapest Time Machine [45], while the .PLA preserves the editable source model for potential reuse by the Archives.

The outcomes and digital products generated in such projects possess the potential for reuse and repurposing, which underscores the growing need to develop structured roadmaps for their systematic integration into archival infrastructures. Such measures are essential to guarantee long-term accessibility and reusability for a broad spectrum of stakeholders. This notion of Data Circulation (see Figure 7) embodies a contemporary paradigm, reflecting how archival resources can be enriched and mobilized in ways that respond to the challenges and opportunities of the digital era [40].

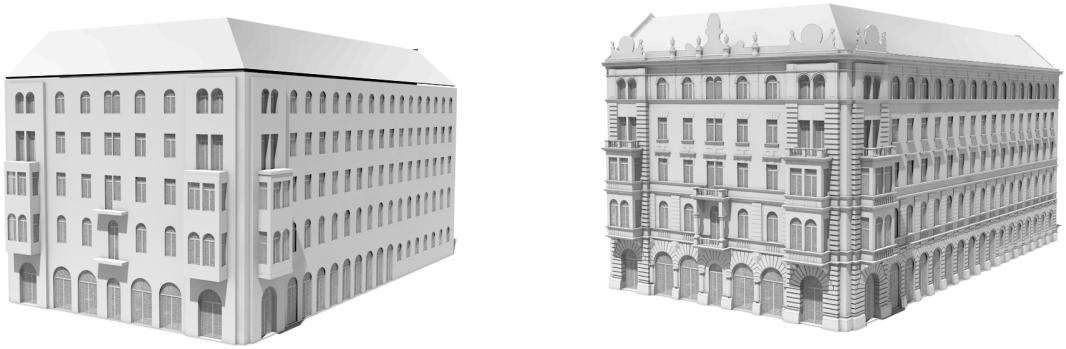


Figure 6. Main steps in the modeling process, demonstrating the transition from envelope-only geometry to detailed, ornamented façades. (**left**) Building envelope. (**right**) Detailed model—model by: László BÍRÓ (Óbuda University, 2020), included with permission.

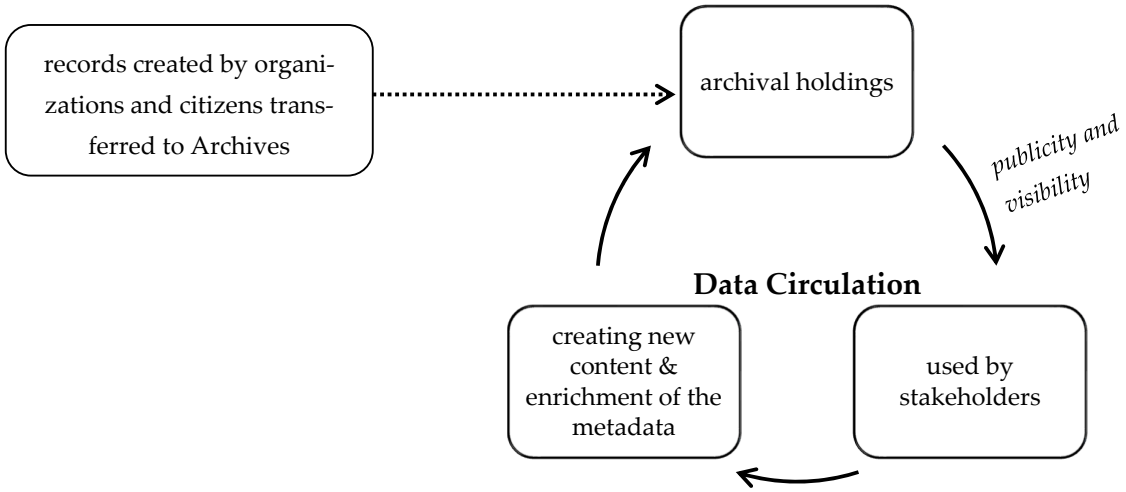


Figure 7. The phenomenon of Data Circulation (figure by the author based on Budapest City Archives) [40].

3.3. Modelling Guidelines and Principles

To ensure methodological consistency across the models created by different students, the following principles were adopted:

- Cadastral map: Modeling was carried out using the official state cadastral map from the 2020s, as property boundaries in this part of Budapest have remained essentially unchanged since the 1870s–1890s. This continuity is due to the work of the Capital Public Works Council, founded in 1870, which laid the foundations for modern urban planning in both Pest and Buda. The Council's efforts established the structural framework upon which the city's present-day urban fabric is still based, enabling long-term consistency in cadastral organization [48].
- Adjustments: If necessary, students should make minor adjustments to the building plans based on the provided cadastral map. This is important because it ensures that

there will be no overlaps or gaps between the models during subsequent street view visualization. In most cases, aligning buildings with the plot is not a problem. The deviation is less than 50 centimeters at most. In extreme cases, the difference between the cadastral map and the ground floor plan has been as much as 1.5 meters. In such cases, a decision is made on a case-by-case basis, with the instructor determining which geometry should be used for modeling.

- Archive documentation-driven modelling: only elements supported by archival docs were modelled. Where documentation is missing (e.g., courtyard façades), simplified geometry (only openings) was used, usually without ornamentation. Therefore, no speculative geometry is used: in cases of missing information, model elements were omitted without creative reconstruction. Based on this principle, the main façades are typically fully decorated, while the courtyard façades are often left without decorations (see Figure 8). Only the suspended corridor and a stylized railing are built in the courtyard.

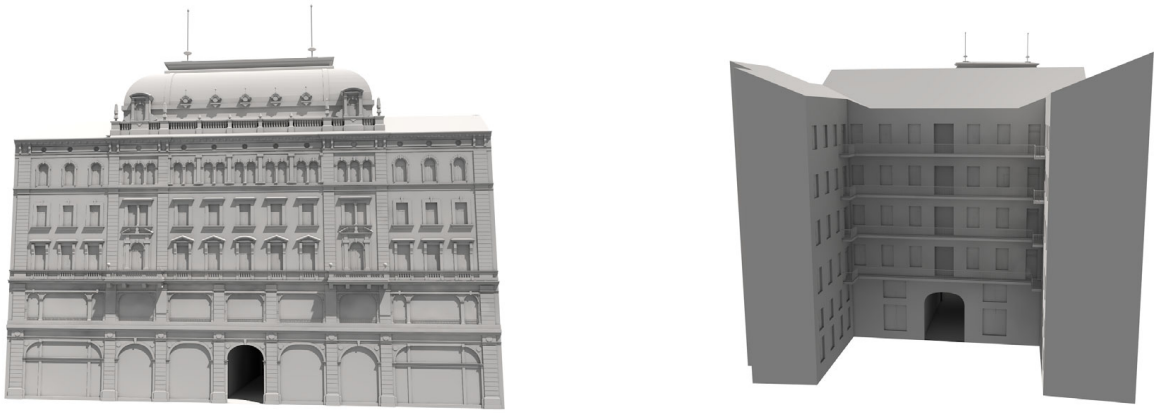


Figure 8. Ornamentations on the façades driven by archive documentation (**left**) Fully ornamented main façade (**right**) Courtyard façades without ornamentation—model by Anna HARANGI (Óbuda University, 2020), included with permission.

- Building envelope: Only the building envelope and ornaments are modeled; internal structures are not. This is because the primary purpose of the models is external visualization.
- Simplification: During modeling, students employ the so-called main line simplification method when creating façade decorations, ensuring that model elements are not detailed in full, but rather only with their most characteristic and important lines (see Figure 9).

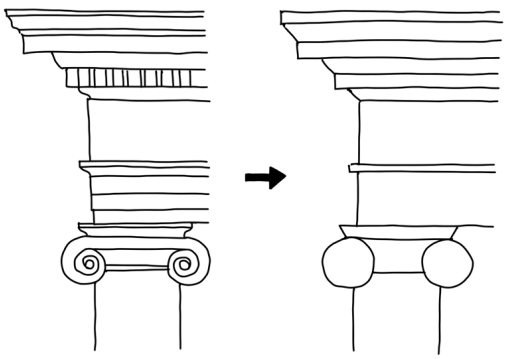


Figure 9. Example of main line simplification (author's illustration).

Highly detailed motifs (e.g., Art Nouveau plant or human forms), due to the complexity of modeling (Archicad is not optimized for this), and the excessive number of polygons, are omitted or greatly simplified.

- Interpretive Decision-Making: When multiple design versions existed, the most completely documented version was selected. Students were encouraged to annotate interpretive choices where applicable.

These modelling conventions ensured that the resulting digital objects were not only internally consistent but also traceable to their historical source materials.

Due to the specific circumstances of this pilot project—namely, that *Digital Modeling of Historic Buildings* is an elective course and students work under time constraints—paradata is generally not documented during the modeling process and is therefore not provided with the individual models submitted to Archives. However, the overall methodology and the main modeling principles are available, effectively providing a form of "general paradata." Addressing the lack of model-specific documentation will require further development of the collaboration with the Archives.

In projects where existing buildings have undergone significant renovations and the goal is to represent the current state as accurately as possible, the archival-first workflow described above can be extended into a hybrid pipeline: Terrestrial Laser Scanning or photogrammetry captures the as-is geometry, while archival plans, photographs, maps, and written documents inform the reconstruction of altered or missing parts. HBIM environments can then serve as integrative containers to cross-reference measured data and historical evidence, and to record paradata about what is empirical, inferred, or hypothetical [49,50].

4. Challenges in Archival-Based 3D Modeling

The process of reconstructing historical buildings from archival sources within the framework of a university course presents a distinct set of challenges. These relate not only to the nature and availability of the documentation but also to the limitations of digital modeling tools and the learning curve of students involved in the reconstruction. In this section, the most significant challenges were grouped into thematic categories, each illustrated with practical examples from this pilot project, while drawing parallels with international case studies.

4.1. Incomplete or Inconsistent Archival Sources

Archival documentation is often fragmented or contradictory. While some buildings are richly documented with complete floor plans, sections, and elevations (and in several cases with plans for alterations or detailed plans), others may lack essential drawings. A common issue during the project is that many buildings lack sufficient (or any) documentation to be modeled. Students do not encounter this problem because the instructor pre-selects buildings that are suitable for modeling; from an educational perspective, pre-selection is an important part of the beginning of the semester.

However, concerning buildings suitable for modeling, a common issue is the absence of courtyard or rear elevations (see Figure 10), or confusing façades (see Figure 11), requiring students to model these façades based on section fragments or inferred logic.

Additionally, mismatches between different drawing sets (e.g., wall thicknesses or opening positions differing between floor plans and sections) required critical interpretation (see Figure 12). In the other case, the building appeared to extend beyond the plot boundary shown on the site plan, indicating either an error or a later design modification (see Figure 13).

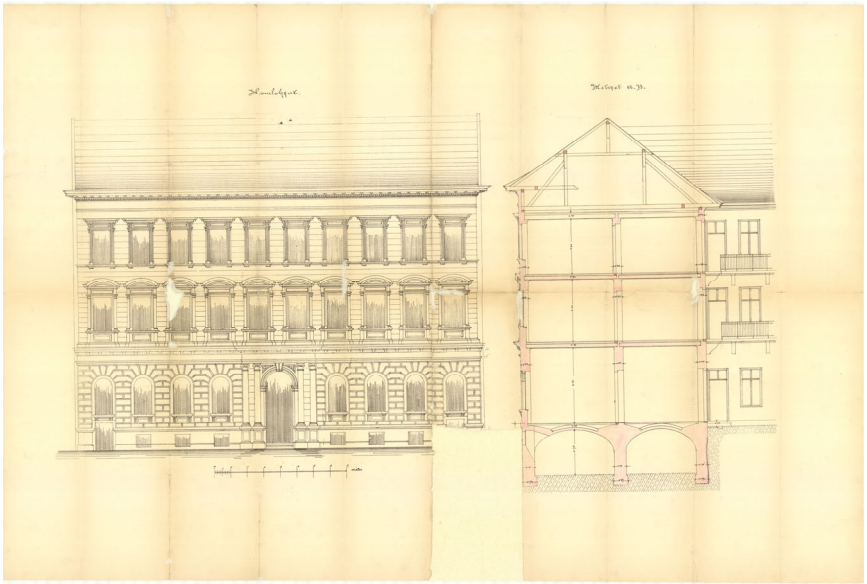


Figure 10. While the main façade is complete, the façade of the inner courtyard is only partial: based on one door and window, it is necessary to reconstruct the interior façade [22].

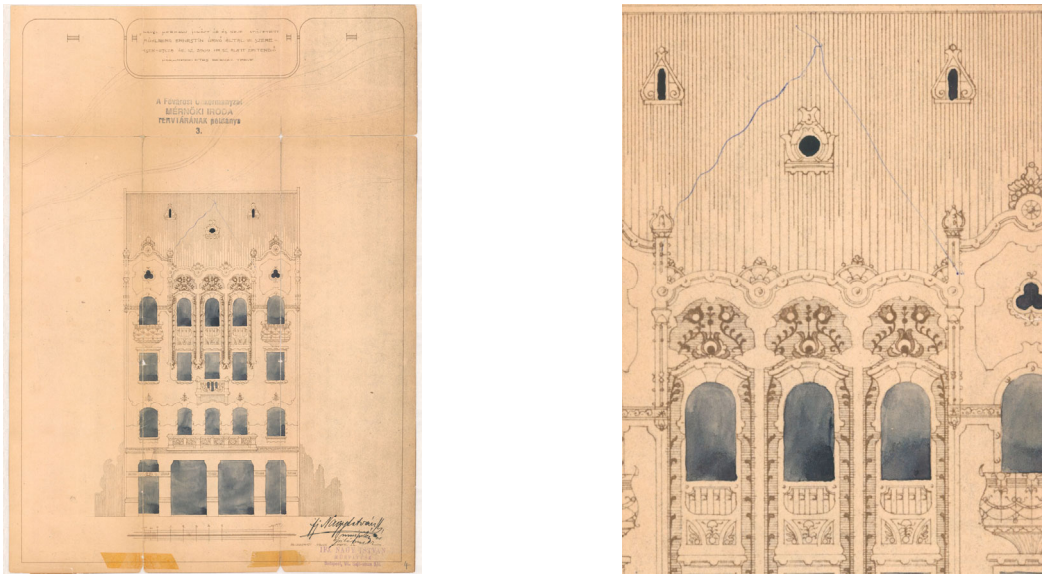


Figure 11. Example of a confusing façade (freehand corrections on the drawing) and missing information regarding the window details (frames, divisions) [51].

During the modeling of the Basilica Aemilia, Frischer [31] also mentions the problem of incomplete documentation. In that case, the Scientific Committee of the project was a great help in dealing with the gaps. Messinas also mentions the difficulty of reconstructing Greek synagogues due to the numerous inconsistent and incomplete sources available [6].

To address such challenges, some projects have developed "Level of Reliability" (LoR) [53] or "Level of Existence" (LoE) [47] frameworks that visualize the confidence level of model elements. The present pilot project did not utilize such metadata encoding; however, this highlights potential methodological improvements for future discussion, as outlined in Section 5. In addition, a quantitative review of the student works indicated that approximately 75% of the reconstructed buildings lacked at least one façade drawing, 20% contained contradictions between plans and sections, and 10–15% required stylistic assumptions about ornamentation. This demonstrates that uncertainty is not marginal but rather intrinsic to archival-based modelling.

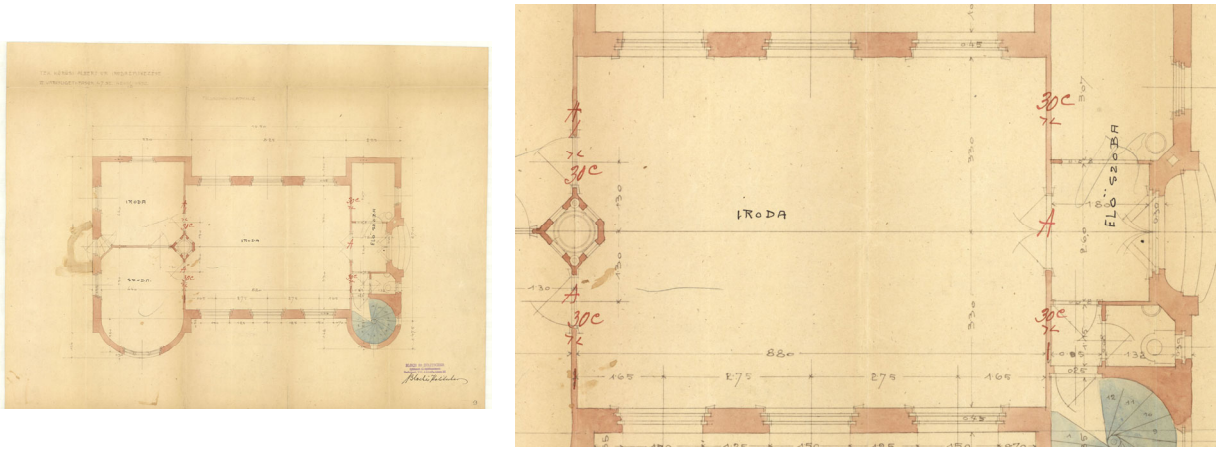


Figure 12. Example of a contradictory floor plan: wall thicknesses rewritten by hand, walls crossed out, rooms merged [52].

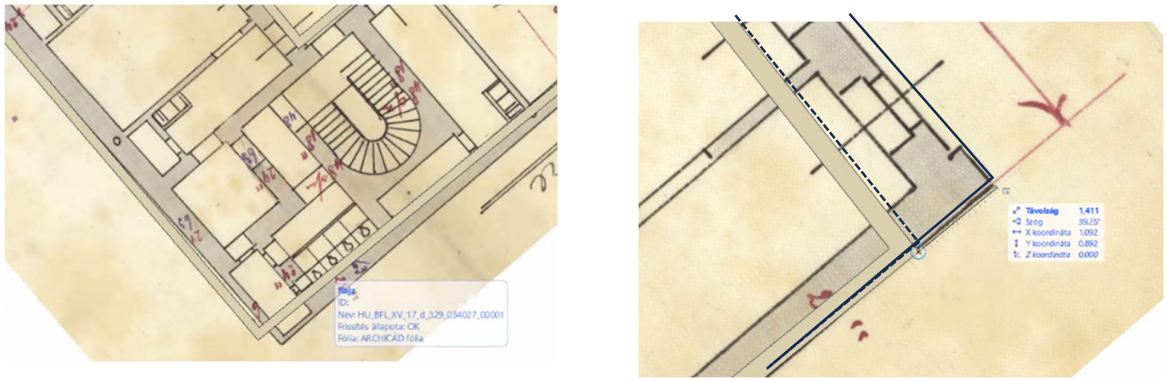


Figure 13. Example of the problem of fitting to the plot (dashed line indicates the plot boundary according to the official land register, solid line indicates the plot boundary according to the building plans): general fitting on the **left side** (<30 cm); exceptional fitting on the **right side** (~1.5 m).

To make these uncertainties more transparent, several international projects have experimented with false-colour or layered visualisation methods, where model elements are colour-coded according to their degree of certainty (e.g., green = documented, yellow = inferred, red = hypothetical). Such practices could also be applied in the present framework to distinguish evidence-based from interpretive content clearly and intuitively [32,54].

4.2. Multiple Archived Versions

An important situation—though not strictly a challenge—is when archival sources contain multiple design versions of the same building. In such cases, the first step is to assess whether each documented version is complete enough to support accurate modeling. If multiple alternatives are equally well-documented, the decision about which version to model is made in consultation with the instructor. Typically, the earliest version is selected to represent the original design intent best. However, from a pedagogical standpoint, instructor often allows students to choose the version they find most engaging, which enhances motivation and encourages critical evaluation of sources (two design versions in one archival package: see Figure 1).

In connection with the documentation of the multiple planned versions or the final modeled version, Frischer et al. also recorded the modeled state (year) as metadata/paradata during the modeling of the Forum Romanum [31]. In future projects, adopting a similar protocol could enhance clarity: explicitly recording which design

version was modelled and why would allow researchers to trace interpretive decisions more systematically.

4.3. Technical Limitations

The modeling of architectural ornamentation posed recurring technical difficulties. Archicad's native toolset is well-suited for simple elements (such as walls, slabs, roofs, and openings) and regular geometry. However, it has limitations when it comes to curved, sculptural, or non-orthogonal features, because Archicad is not based on NURBS geometry but on polygonal mesh representations. In particular,

- Double-curved surfaces (e.g., domes or vaults) could not be created using standard modeling tools. This requires the use of Shell, Morph, or Mesh tools, which are generally more difficult for students to use.
- Floral or human motifs, typical of, e.g., Art Nouveau architecture, can only be approximated using the Morph tool, which is difficult to edit later and results in a large number of polygons, making the model difficult to handle (see Figure 14).

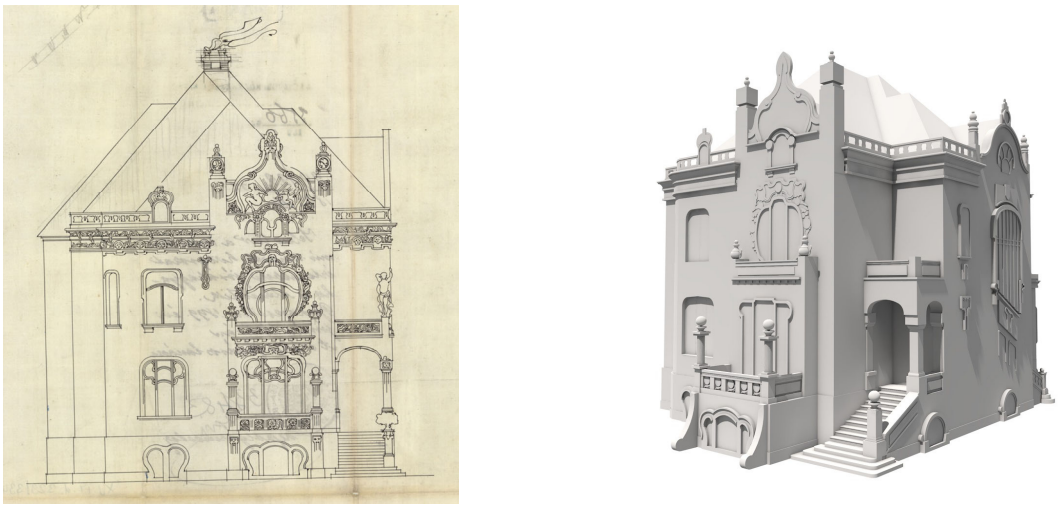


Figure 14. Although the façade is richly decorated with organic elements (plant motifs and human figures), some of these had to be omitted due to technical limitations. (**left**) Planned façade [52]. (**right**) Detailed model—model by Réka SZABÓ (Óbuda University, 2025), included with permission.

In the above cases, when a very complex, parametric, or NURBS-based surface needs to be created, it can be modeled in programs such as Rhino, 3ds Max, or Blender, and then imported into Archicad in .obj or .skp format. After importing, it can be converted to a GDL object or Morph so that it can be further edited.

The lesson to be learned is that the use of a single modeling platform—Archicad—ensured consistency, but also limited flexibility.

López et al. (2018) report a similar difficulty in their study [49], stating that the virtual reconstruction of cultural and historical heritage in high detail has highlighted certain limitations inherent to BIM platforms. These include the absence of dedicated parametric object libraries for historical elements, as well as insufficient functionalities for handling complex, irregular, and uncertain geometries. Such findings confirm that the challenges observed in the present pilot are not isolated to educational settings, but represent broader methodological gaps in current BIM/HBIM platforms.

4.4. Educational Constraints

The course was offered as an elective subject for full-time and distance-learning students; therefore, student motivation and engagement varied. Many participants (especially

in the distance learning group) underestimated the complexity of the task. They were also less inclined to ask questions between consultations, despite repeated encouragement. This often led to

- Late discovery of fundamental modeling errors (e.g., wrong scaling, wrong building location, mix of different versions);
- Wasted effort due to incorrect assumptions;
- High dropout or failure rates (approximately 25% in full-time and 50% in distance-learning groups).

The temporal structure of the course also played a role. Students typically worked in weekly or biweekly cycles, with limited time for iterative corrections and refinements. This suggests that an intensive workshop model—where participants work full-time over a single week—might yield better learning outcomes and more coherent models. According to the study conducted at Victoria University [55] on the implementation of the intensive block model, the results demonstrate significant improvements in grades and pass rates, alongside positive student perceptions of this workshop-based approach. Adeyeye et al. (2011) also found that intensive teaching block weeks in design disciplines significantly enhanced students' ability to learn and apply design knowledge while also fostering key soft skills: supporting the view that block-based instruction can be more effective than traditional semester-length delivery [56].

In light of these findings, it is evident that the educational framework strongly influences not only the quality of the resulting models but also the students' capacity to engage with uncertainty critically. Embedding paradata recording exercises into the course could simultaneously improve learning outcomes and contribute to methodological standardisation.

5. Paradata and Documentation Proposal

The challenges discussed above show that archival-based 3D reconstruction is as much an interpretive process as it is a geometric one. Decisions regarding missing façades, contradictory plans, or stylistic detailing have a significant impact on the resulting model. When such choices remain undocumented, future users—be they researchers, architectural history experts, or educators—have no way to assess the reliability or rationale behind the geometry.

To address this, the authors propose the use of paradata—a structured record of modeling decisions, sources used, Level of Certainty, and interpretation logic. While paradata has been widely discussed in the field of virtual archaeology, it remains underdeveloped in building-scale, BIM-based workflows. In particular, existing approaches such as the Level of Reliability [32] or stratigraphic paradata [54] demonstrate that uncertainty can be encoded and visualised in ways that are accessible both to experts and non-experts. Adapting these principles to building-scale projects is therefore a logical next step.

5.1. Decision-Level Documentation: A Practical Paradata Table

In educational settings, tracking metadata for every single model element (e.g., walls, roofs, windows, building decorations) is not feasible. Instead, authors recommend maintaining a decision-level Paradata Log that focuses only on elements with interpretive complexity or non-standard solutions. This approach has the advantage of being:

- Lightweight;
- Easy to complete during modelling,;
- Useful as a later metadata supplement for archival systems.

The authors propose the following paradata table format (see Table 2), based on entries collected in during the pilot project.

Table 2. Proposed Paradata Log for documenting interpretive decisions, enabling transparency and reproducibility in archival-based modelling.

Model Part/Element	Issue/Cause of Uncertainty	Source of Modeling	Decision Taken	Interpretation	Notes
Façade of the courtyard	Missing courtyard elevation	Floor plans, sections	Modeled without decorative elements	Positions, geometric properties from floor plans	Typical approach within the course
Façade of the side street	Missing elevation	Floor plans, other elevations	Modeled based on the main façade	Positions, geometric properties from floor plans	Typical approach within the course
Window mullions	Lack of details	No source (unclear in the drawings)	Modeled without mullions	Simplified window with primary geometries	
Multiple design versions	Necessary to choose a version due to consequential modeling	Different documentation for different versions	1st version is modeled	Complete model for the 1st version	
Roof	Geometric contradiction between the floor plan and the façade	Floor plan, aerial view (existing status)	Follow the geometry given by the floor plan	Complete model	Verified by the instructor

The rows in the table can be modified depending on the decisions made for individual buildings. The advantage of this method is that the table can be created using any spreadsheet editor (e.g., Microsoft Excel or Google Sheets) and ideally maintained in parallel with the modeling process. It also serves as a helpful teaching tool, making decision-making processes explicit. From an archival perspective, the paradata table can be stored alongside the model as part of a Submission Information Package (SIP). In classroom application, the act of filling the table also helps students to critically reflect on uncertainty, turning paradata into both a documentation instrument and a pedagogical device.

5.2. Proposed Structure for Paradata Integration in IFC Models

To ensure transparency and traceability in archival-based 3D reconstructions, the structured recording of paradata could be integrated into the 3D model. Given the hierarchical nature of the Industry Foundation Classes (IFC) schema [57,58], different types of paradata can be meaningfully distributed across distinct levels of the model.

At the project level (IfcProject), overarching metadata should be recorded. This includes general information such as the types of archival sources used (e.g., archive plans, historical photographs, cadastral maps), their provenance (e.g., city archives, online databases), the purpose of the reconstruction (e.g., educational or research-oriented), and in case of educational projects the academic context (e.g., name of creator (student), semester, name of instructor). A dedicated *Pset_ProjectParadata* property set could house this data, providing clarity for future reuse or scholarly interpretation.

At the building level ("construction work that has the provision of shelter for its occupants or contents as one of its main purposes and is normally designed to stand permanently in one place"—IfcBuilding [58]), context-specific paradata can be recorded. These include the documentation completeness for each version of the building, justification

for choosing one design phase over another (in cases where multiple versions exist), and known limitations in the available documentation—such as missing internal courtyard elevations or absent rear façade drawings. These decisions often reflect the trade-offs between historical fidelity and feasibility and could be stored in a *Pset_BuildingParadata*.

The element level ("major functional part of the building"—IfcBuildingElement: IfcWall, IfcWindow, IfcColumn [58]) is particularly suitable for recording granular uncertainty information. For example, each modeled object may carry a custom *Pset_ElementParadata* property set that includes attributes such as the Level of Certainty (exact, inferred, or hypothetical), modeling method, or special, important notes related to the model elements by the modeler. (In the case of the present study, all elements would be assigned the "exact" property, but in other projects, the other properties may also be relevant.)

In cases where all model elements are derived from the same consistent source set, it may not be necessary to repeat this metadata per element; project-level attribution may suffice. However, when interpretative decisions vary between elements, per-element documentation becomes essential.

This structured approach supports FAIR data principles (Findable, Accessible, Interoperable, Reusable) and strengthens the scientific value of virtual reconstructions by distinguishing empirical data from informed conjecture. While the IFC schema does not yet provide standard property sets for paradata, the proposed method aligns with recommendations in digital heritage literature [24]. It could be implemented through custom IFC property sets.

Authors recommend a lightweight `PSET_PARADATA` with fields such as those outlined in Table 3.

Table 3. Proposed fields of Pset_Paradata by Ifc Levels.

Ifc Level	Field	Purpose	Example
Project	`SourceType`	Identifies the sources of the project	Original plans Original written docs Historical photos Historic paintings Streetview
	`ModelPurpose`	Identifies the primary goal of the project	Pilot project for visualization and archiving
	`ModelledBy`	Traceability and copyright	Peter FEJES (Semester 2024/2025/2)
	`Instructor`	Traceability	Andras HORKAI
Building	`ModelVersion`	Which version was selected and why	Model based on the 1896 plans
	`SourceNote`	Comments on sources	Missing courtyard façade Contradiction between the floor plan and the elevation
Element	`LevelOfCertanitiy`	Define the Level of Certainty	Exact (based on archival documentation) Inferred (based on archival documentation) Hypothetical (based on contemporary buildings or expert opinion)
	`ModelingMethod`	Indicates technical approach	Morph tool, Profile
	`ParadataNote (optional)`	Records reasoning behind creative assumptions	The geometry of the balustrade is estimated from other contemporary buildings

Although this functionality was not implemented in the current pilot project, the proposed paradata fields can serve as a basis for future IFC-based documentation strategies. Embedding such paradata at multiple scales (project, building, element) would not only facilitate archival reuse but also foster methodological comparability across projects internationally.

6. Conclusions

This paper explores the specific challenges and interpretive decisions involved in the 3D reconstruction of historical buildings based on archival drawings. Unlike laser scanning or photogrammetric approaches, archival-based modelling often deals with absent or inconsistent data, requiring both architectural knowledge and creative judgement. Through a pilot project involving university students, a range of uncertainty types was identified, including missing drawings and inconsistent plans, as well as subjective interpretations of ornamentation and layout.

To address these issues, this paper proposes a lightweight paradata documentation schema suitable for both educational and archival use. While IFC-based metadata remains a promising long-term standard, spreadsheet-based reporting at the decision level proved to be a more feasible solution during the modelling process. The proposed framework aligns with FAIR data principles, enhancing the findability, accessibility, and reusability of 3D heritage models. By introducing categories such as Level of Certainty, the framework also connects with international best practices. It provides a bridge between scholarly conventions in virtual architecture and building-scale BIM applications.

Experience from this pilot project confirms that archival-based 3D reconstruction is not only a valuable historical research method, but is also a highly effective pedagogical tool. It fosters critical thinking, source evaluation, and digital literacy in the fields of architecture and engineering education. The explicit use of paradata in the classroom setting demonstrated that documenting interpretive decisions can enhance student awareness of uncertainty and methodological rigour. Future research could explore the integration of automated paradata into BIM workflows and develop shared standards for documenting interpretation across heritage modeling initiatives.

Overall, the proposed lightweight paradata framework is not only applicable to educational settings, but can also be adopted by heritage institutions and research projects internationally, thereby contributing to the broader discourse on transparency and reproducibility in virtual heritage. Rather than treating paradata as an optional annotation layer, this paper argues that lightweight, decision-level transparency should become a baseline expectation for archival-based digital reconstruction. In this sense, the proposed framework does not simply document interpretation retrospectively. However, it establishes a reusable methodological standard that can guide future projects towards greater accountability, scholarly credibility, and educational value.

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Data Availability Statement: The 3D models created within the pilot project are preserved at the Budapest City Archives as part of their digital collection. While the models are not publicly available via an open online repository, they can be consulted on-site or accessed upon request through the Archives' research services, in accordance with their access policy. No additional proprietary or restricted datasets were generated in this study.

Conflicts of Interest: The author declares no conflicts of interest.

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