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HBIM in the digital reconstruction of historic buildings based on point clouds – a case study of the manor house in Nużewo, Poland

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Abstract:
Heritage Building Information Modeling (HBIM) is becoming essential for documenting wooden architecture at risk of disappearance. This article proposes a comprehensive scan-to-HBIM workflow, demonstrated through the digital reconstruction of a deteriorated late-19th-century manor veranda in Nużewo, Poland. By integrating high-density Terrestrial Laser Scanning (TLS) point clouds with archival photographic evidence, the study addresses the challenge of modeling geometry that is partially lost or deformed due to significant material weathering. Central to this approach is the application of the Level of Information Need concept, which prioritizes informational value. The methodology semantically enriches the model with evidence-based metadata, explicitly defining the data source and uncertainty for each component. This ensures transparency of the reconstruction process, clearly distinguishing between the surveyed reality and hypothetical restoration based on historical records. The resulting IFC-compliant model validates the utility of HBIM not only for spatial archiving but also for supporting conservation decisions and interoperable data exchange. While identifying the limitations of current BIM tools regarding the complexity of irregular structures, the study presents a reproducible framework for documenting and digitally reconstructing at-risk wooden architecture, advocating for open standards that transform fragile physical evidence into an enduring digital legacy.

Keywords:
HBIM, laser scanning, scan to BIM, heritage conservation, digital reconstruction

1. Introduction

The phenomenon of entropy in monuments, associated with the natural process of material degradation, weathering, climate change, the passage of time, and human interference, is irreversible and inevitable [1]. As a result, objects recognized as monuments due to their historical, artistic, or scientific value face the risk of partial or complete loss over time. To address these challenges, a three-dimensional record of an object in the form of a point cloud, obtained through laser scanning or photogrammetry, becomes a key documentation tool [2].

A point cloud is a record of a "moment in time" for objects at risk of destruction. It records not only the spatial structure of a building but also its defects, deformations, discolorations, and elements analogous to missing ones, which may indicate the original form of the object. This data, supplemented with archival photographic documentation and descriptions, allows for further research on the object even when it no longer exists. The availability of point clouds also enhances the possibility of developing digital reconstructions. Using BIM (Building Information Modeling) in this process allows not only for the reconstruction of geometry but also for semantic and non-graphical enrichment, which supports the analysis of archival materials and research on the object.

HBIM (Heritage Building Information Modeling), as a subset of BIM, is an interdisciplinary science combining issues from fields such as architecture, heritage protection and conservation, and photogrammetry. An HBIM model is a digital representation of a building that stores data and information about a cultural heritage object. Image-based digitization techniques are considered cost-effective, highly flexible, and efficient in creating high-quality textured 3D models. Such hybrid scanning can be imported into BIM environments [3]. Creating highly accurate HBIM models typically requires the use of several reality capture tools, such as terrestrial laser scanning, photogrammetry, unmanned aerial vehicles (UAVs), etc.

The creation of an HBIM model typically involves several stages, with a basic division of the collection of source materials (including both historical documentation and point cloud data), preparing the point cloud for a BIM environment (including possible manual or automated segmentation and classification), referencing the point cloud, model and components creation, and semantic enrichment [4]. While the case study presented in this article adheres to this general workflow, point cloud segmentation and classification were not performed, as point cloud data were unavailable for certain elements (e.g., the roof), and the scope of the work was limited to a relatively small fragment of the object.

The literature review to date indicates that there are many literature studies, but significantly fewer case studies on the use of laser scanning for HBIM. The process of acquisition, extraction, and modeling can bring several benefits. During practical work, advantages, disadvantages, opportunities, and threats can be identified.

It is crucial to emphasize the significance of residential wooden buildings, given their declining representation in the Polish register of monuments [5]. This group is vulnerable to progressive destruction due to the physical characteristics of the material, the need for increased maintenance, exposure to fire and moisture, as well as shortcomings in adapting to current residential requirements. This type of architecture is particularly associated with local architectural heritage, which is being displaced by other construction methods. Digital documentation of such buildings, which bear witness to generations of craftsmanship, is of particular importance from a social perspective.

Therefore, this study evaluates the potential of HBIM technology for reconstructing historic wooden buildings by integrating point cloud data with archival documentation. Beyond assessing geometric reproduction capabilities, the analysis focuses on the practical workflow of creating digital reconstruction, while highlighting specific functional limitations imposed by standard BIM software.

2. Materials and methods

2.1. Description of the object

The manor house in Nużewo is located in Poland, in the Mazowieckie Province, in the Ciechanów County, in the municipality of Ciechanów (Fig. 1). The building was constructed in the fourth quarter of the 19th century and was owned by Henryk Ponikowski. During World War II, it was seized by the Germans. After the war, the estate was divided, and the manor house was converted into a school, which operated until 1980. Since 1985, the structure has been used as a residential building. The architectural style refers to the wooden buildings of northern Mazovia from the second half of the 19th century.

It is a single-story wooden building with a usable attic and a partial basement. The foundations are made of erratic stones, on which machine-made bricks are laid [6]. The building consists of two parts, both with a rectangular floor plan: a lower part with an axially located veranda and a higher part.

Currently, the building is in poor condition. At the time of the site visit and measurements, i.e., April 27, 2021, it had no window frames, and the door frames were partially preserved. The walls of the veranda (reconstructed element) showed deformations, and the remains of its roof and one wing of the entrance door were preserved. The preserved boarding had numerous deformations and discolorations (Fig. 2).

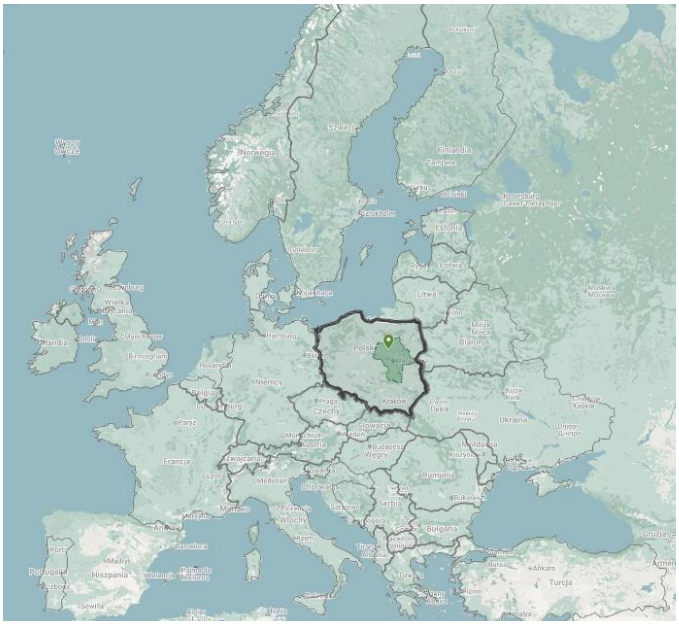

Fig. 1. Location map of Nużewo. Source: own study

Fig. 2. Photo of the manor house in Nużewo, 2021, Source: own collection

2.2. Existing documentation

Before the laser scanning was performed, the building was documented in the "Record Card of Architectural and Construction Monuments 305-A Manor House in Nużewo" [6] and the "Park Record of the Manor House in Nużewo" [7]. The heavily degraded veranda appears in black-and-white photographic documentation taken in 1983 and 1996 in three photographs, one of which shows a fragment, while the other two show the wider context of the building's facade. The description in the record card reads [6]:

- "Roofing made of galvanized sheet metal on battens, only above the veranda, is roofing felt."
- "In the veranda preceding the main entrance, there are three- and six-pane windows."
- "An almost square veranda in front of the hallway."
- "The rectangular veranda on the axis of the larger part of the facade has a gable roof, significantly lower than the main one."
- "Facade - larger part 7-axis symmetrical, with an entrance opening on the axis, flanked by two narrow windows - this triad is located in the veranda."

The schematic plan available in the record card shows the dimensions as 3.74 x 3.44 m.

2.3. Measurement description

The measurements were taken for research related to the doctoral dissertation [8]. The survey was conducted on April 27, 2021, after a prior site visit. The scan covered the interior and exterior of the building, and all floors (basement, ground floor, and attic) (Fig. 3). Three Faro Focus S350 scanners were used to perform the measurement.

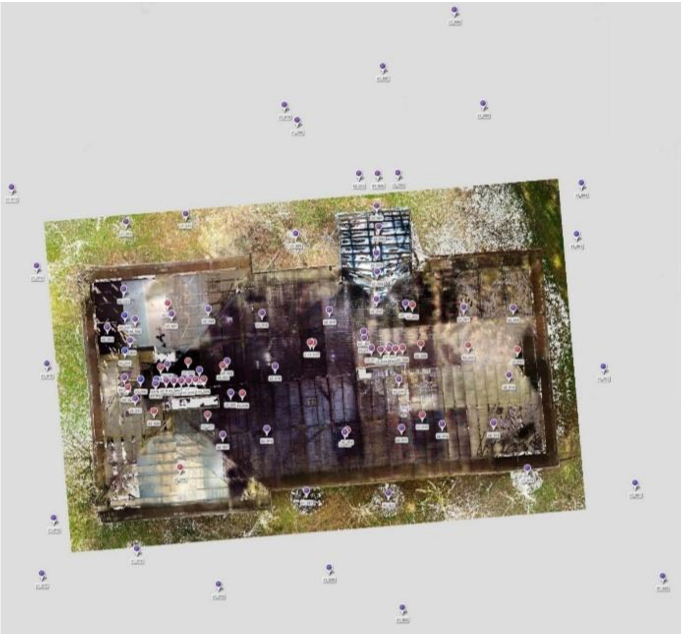

Fig. 3. Location of measurement points shown in the Faro WebShare online browser. Source: [8]

In total, 101 scans were captured over a duration of 4 hours and 10 minutes. This substantial number of scan locations was necessary to ensure comprehensive coverage of all building levels and elevations. The scan count was particularly high in the attic, where poor technical conditions and safety concerns dictated scanner placement. One ground-floor room could not be directly entered due to a collapsed ceiling; data for this area was acquired from the nearest safe location. Additionally, the windows were not fully captured in the scans due to obstruction by the boarding. It is worth noting that if the survey had focused solely on the veranda, the scan count and subsequent processing time would have been significantly reduced.

Post-processing was performed using Faro Scene software. Scan registration was performed using a target-less 'cloud-to-cloud' method and required 7 hours, including 1 hour of manual work. The alignment achieved a mean error of 2 mm. Further analysis in CloudCompare, using the Surface Density algorithm (r=0.05 m, Gaussian distribution), indicated a mean surface density of 175,858 pts/m² (approx. 2.4 mm spacing). This density is a critical factor for HBIM, as it determines the potential for geometric detailing and must be balanced against hardware and processing constraints.

While the current study did not employ additional quality control measures, their implementation would significantly enhance point cloud reliability. Furthermore, the absence of UAV-based scanning resulted in data gaps, particularly across the roof surface. Crucially, the survey was not georeferenced; adding this spatial reference would be particularly valuable for endangered structures, ensuring their exact location and potential subsurface remnants can be identified even if the building ceases to exist.

2.4. Creating an HBIM model

Prior to initiating the model development, it is essential to define the basic requirements. In the case of the contracting entity, these should be specified in the Exchange Information Requirements (EIR) document [9]. Based on this document, a BIM Execution Plan (BEP) is created. Both documents play a key role in BIM-based project delivery [10].

The HBIM model development process began with defining the Level of Information Need [11]. This required stating the prerequisites: the purpose, information delivery milestone, actor, and object, while adhering to the principle of providing the minimum information necessary to fulfill the objective [12]. This approach was adopted due to its capacity for flexible requirement definition and adaptation to the intended use. While detailed standards are widely applied to new construction projects, heritage architecture frequently deviates from these standardized assumptions. As a result, such standards may not be fully applicable to heritage buildings. The issue of expanding the classification to include aspects specific to historical objects is increasingly being raised in specialist circles [13,14].

To address the specificities of heritage documentation, the literature explores multiple aspects, such as: Level of Reliability (LOR) [15], Level of Accuracy [16], Level of Knowledge [17]. In HBIM, the classic approach of progressively upgrading geometric detail is effectively reversed through reverse engineering, as the process begins with highly detailed information derived from point clouds. Consequently, the literature proposes "downgrading approaches to Levels of Geometry (LoG)" [18].

Validation of HBIM models against point clouds is typically a crucial step. In this reconstruction, however, the object is modeled in its hypothetical original state, whereas the point cloud captures the current condition, which is deformed and incomplete. Consequently, a direct comparison would primarily highlight missing information and geometric distortions in the point cloud.

In terms of Level of Information Need, the purpose was a digital reconstruction of the veranda for research objectives to investigate its probable historical appearance, with the results presented graphically and accompanied by an assessment of information reliability. There are two expected actors: the information receiver (the community involved in architectural research) and the information provider (the architect). The objects are walls, doors, windows, roof, beams, and floors of the veranda. Considering the defined scope of the model's purpose, the rest of the building and its context were excluded from modeling.

The stated purpose reflects the specific use in the case study; however, HBIM models can serve a wide range of applications, including scientific research, task automation (e.g., automated verification of model geometry accuracy against point clouds [18]), facility management (maintenance and conservation work), and dissemination through new technologies such as virtual and augmented reality or Common Data Environment [12].

To satisfy the geometric requirements defined within the Level of Information Need framework, Level of Development (LOD) 300 [19] was adopted. This provides precise element geometry, including dimensions, positions, and orientations. In the case of historic buildings and those in poor technical condition, it is also crucial to consider the accuracy of mapping deviations from the actual geometry of the building (example of deformations – Fig. 4). For the purpose stated in Level of Information Need, it was decided that the model reflects the hypothetical condition of the veranda after completion of construction; therefore, horizontal and vertical deviations resulting from the deformation of the object were omitted.

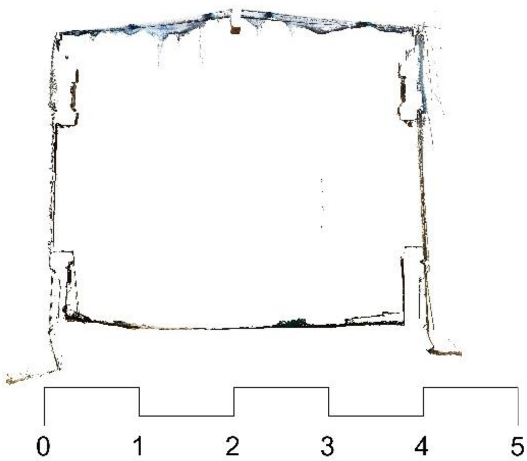

Fig. 4. Cross-section of the point cloud with visible deformations of the veranda walls. Source: own study

To fulfill the objectives defined in the Level of Information Need, specific requirements for the model's information layer were established. It was determined that the parameter defining the uncertainty of representation (Ifc_StopienPewnosci Odwzorowania), is required for all objects stated in the Level of Information Need. Additionally, simplified material attributes were assigned to elements to facilitate schematic visualization within the native BIM environment. The importance of citing sources in reconstruction work is emphasized in the literature due to its key role in critically referencing and validating the presented materials [15]. The concept of transparency first emerged in archaeology, which also employs digital representation. The creation of HBIM models often requires filling information gaps, due to the absence or unavailability of data [12] with direct and indirect information sources [15]. To convey the uncertainty information, 3D graphics [12] with assigned visual coding are used [20]. Beyond the parameters discussed above, HBIM models can incorporate information related to the state of preservation, the date of creation, and the representation of different transformation phases of the heritage building [21], URL links connecting with external sources [12] like drawings, sketches, and pictures. While the geometric model may remain unchanged, its informational layer can be progressively expanded as new data and historical sources emerge.

The model was exported to the Industry Foundation Classes (IFC 2x3) format to ensure cross-platform interoperability and long-term data accessibility. This is an open standard for data exchange in building information modeling, which allows models to be shared across multiple industries and programs. There are also free viewers available on the market that allow you to view models and analyze their assigned parameters, such as BIMvision [22] and BIMcollab Zoom [23]. It is worth emphasizing that HBIM models can be distributed in their native format and support the export of 2D documentation (including PDF, DWG, and JPG), which are still widely used standards, and enhance accessibility for a broader range of users.

Figure 5 shows a diagram of the process of creating and analyzing the model discussed in the article, specifying the software used.

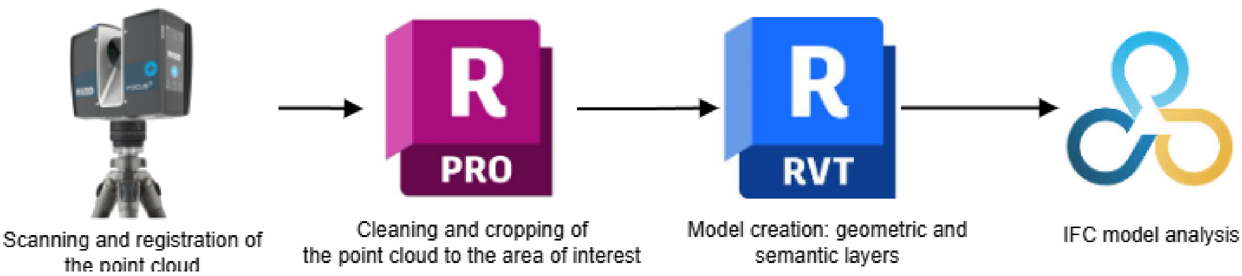

Fig. 5. Diagram of the process, specifying the software used. Source: own study

2.5. Preparation of the point cloud

The complex point cloud was imported in RCS format into Autodesk ReCap [24]. Next, two point cloud trims were performed, resulting in two separate files covering the veranda area and a single door leaf found in the basement during the measurements. There was suspicion that the door came from the veranda and could be used to supplement the front door. However, this assumption proved to be incorrect, as an attempt to match the point cloud fragment of the basement door with the preserved veranda door leaf failed (the door leaf and hinge locations did not match), and the use of this approach was subsequently abandoned. Point cloud modifications were performed using Autodesk ReCap, which enables integration with Revit. Nevertheless, open-source alternatives, such as CloudCompare [25], can also be employed for point cloud modifications.

2.6. Development of the HBIM model

Modeling began by linking a section of the point cloud to the project file. The project orientation was adjusted to align True North and the point cloud rotation. Next, the levels were defined to serve as base constraints for the elements, such as walls and roof structure. The height of the cutting plane for the projection was also adjusted and set at 100 cm. During modeling, a series of working point cloud excerpts were made to verify the dimensions of the elements.

The modeling process began with the definition of wall types. Due to significant structural deformations, particularly evident on the western elevation, determining a definitive wall thickness proved challenging. Consequently, a standardized thickness of 20 cm was adopted, based on an average of multiple measurements taken across the veranda. As wall type parameters define the internal structure of the partition, it is crucial in HBIM to ensure that these attributes are grounded in verified in situ data. The height of the bricks at the foundation, the horizontal formwork covering the foundation, and the wall itself were determined based on measurements taken on a point cloud. The dimensions of the profiles and the heights of the slats were also determined on this basis.

In the next stages, families of window and door joinery were created. The basis for creating a three-dimensional representation of the door geometry was the preserved door frame and one of the door leaves. In these places, the dimensions of the geometry could be based on the point cloud. The non-existent door leaf was reconstructed based on the existing counterpart. Transom dimensions were derived from adjacent preserved frame fragments, while the position of the vertical muntin was established using archival photographic documentation.

The window joinery was digitally reconstructed using a hybrid approach. Decorative mullions were derived from the point cloud of an analogous element (an exposed window on the first-floor front façade), while the glazing layout (three- and six-pane divisions) was established solely based on photographic documentation. Photographs from 1996 show that the original window frames were probably only preserved in the walls of the veranda, while the rest of the windows were replaced. The visible roof structure and decorative finishes were modeled using a combination of photographic documentation and preserved analogous elements captured in the point cloud.

Modeling historic buildings necessitates the creation of bespoke component libraries, given the scarcity of standard historical elements in existing software repositories. Furthermore, due to the low repeatability of architectural details – both between different structures and within a single object – components must often be modeled independently to suit specific project requirements. This increases the time required to create models of historical objects and requires a team with higher qualifications.

The development of BIM components prioritized structural logic and parametric adaptability. Parametric modeling refers to a process where geometric shapes and associated alphanumeric information are derived from a set of predefined rules and constraints [12]. It enhances the reusability of families in other projects, accommodates dimensional variations between instances (e.g., window frames) [26], and allows for easier updates when new information arises. An example of a parametric door component is pictured in Fig. 7. To manage geometric complexity, nested families were frequently employed. In the used Revit software version, it was not possible to embed a point cloud directly in the component creation environment. This forced the element, for example, a profile, to be outlined in the project environment and then transferred by copying it to the family environment.

Finally, the model was completed with the roof structure. Since the physical element had collapsed prior to the survey, the height of its junction with the main roof slope was reconstructed based on archival photographic documentation, where this connection remained visible. The relationship between the elements is shown in Fig. 6.

The model was exported to IFC version IFC 2x3 Coordination View 2.0 from Revit using a text file with a structure specified by the software manufacturer, which mapped the parameters used in the program to the parameter values available in the IFC model (Fig. 8).

Fig. 6. Relationships of the elements in the veranda model, Source: own study

Fig. 7. A parametric door family with geometry constrained to reference planes, controlled by parameters, Source: own study

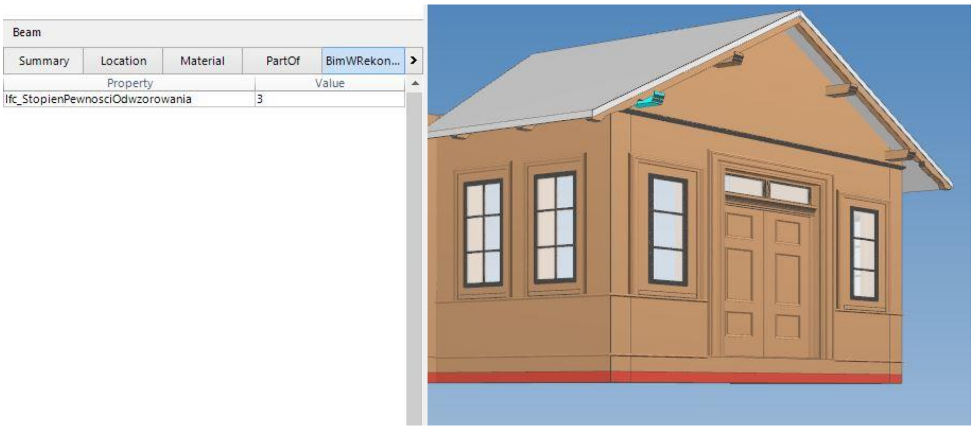

Fig. 8. View of the model in IFC format in the BIMcollab Zoom environment, showing the value of the exported parameter. Source: own study

3. Results

The result was a three-dimensional model of the digital reconstruction of the veranda, including elements such as walls, windows, and door frames, roof, beams, and cornices (Fig. 9, Fig. 10). Such a model can be used to disseminate knowledge about the historic building or for 3D visualization. It also makes it possible to create further studies, such as projections and cross-sections.

Although a point cloud is the most accurate possible record of an existing object, it often does not cover all its parts - and certainly cannot reflect what no longer exists. Therefore, it may be advantageous to obtain information from the point cloud where the given range has been captured.

The model was supplemented with an information layer related to the data source for creating the model, as shown in Fig. 9. These were:

- Point cloud – an element created on the basis of a point cloud, the representation with the lowest uncertainty,
- Photograph of a given location and relation to elements included in the point cloud – possibility to verify the dimensions and appearance of a given element (appearance limited by the quality of the photo),
- Photograph of a given location and point cloud of a similar element,
- Photograph of a given place – highest uncertainty.

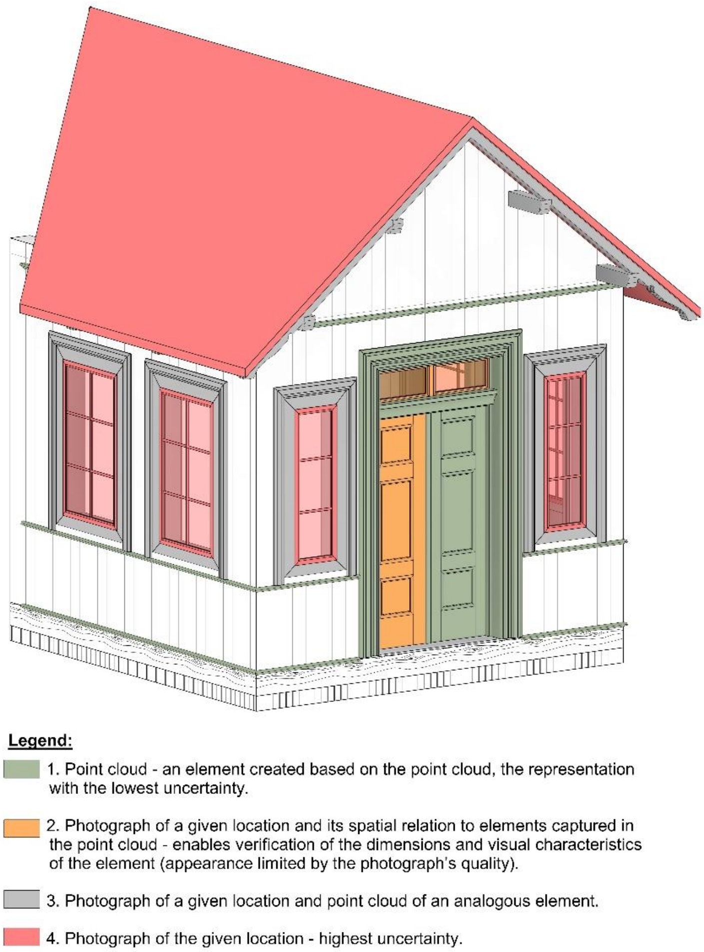

Fig. 9. Graphical representation of uncertainty associated with the source of information for the dimensions and form of the element. Source: own study

Fig. 10. From top: View of point cloud, point cloud and model, model with color coding of materials. Source: own study

The assignment of parameter values is presented in graphical form, thanks to the filtering of values and the assignment of color codes based on them. The lower the uncertainty, the higher the information reliability. The scale was tailored specifically for this study to reflect the characteristics of the available source materials. However, it should be noted that the information source is also addressed within the Level of Knowledge (LK) standards, which also encompass categories such as 2D surveys and original documentation [17].

The presented workflow exhibits both advantages and limitations. Among its benefits is the ability to generate geometry based on highly accurate data. By modeling information from other, better-preserved fragments of the point cloud, it was possible to reconstruct details that were missing within the portion of the object under study, which was a valuable workflow input. Attention should also be paid to the high labor intensity of the process, as numerous details are unique, limiting the applicability of publicly available libraries. Furthermore, the creation of the model requires handling large datasets (point clouds), which imposes substantial hardware requirements to ensure smooth processing.

4. Conclusion

The research confirms that the integration of laser scanning technology with building information modeling (BIM), particularly in the form of HBIM, is an effective tool for documenting and reconstructing historic buildings. The digital reconstruction of the veranda of the manor house in Nużewo proves that the "scan to BIM" process not only enables faithful reproduction of the geometry but also supplements the model with an information layer related to the uncertainty of the reproduction of elements. In practical terms, this HBIM layer is operationalized through a defined Level of Information Need (incl. intentional LOD selection for geometry representation) and the assignment of evidence/uncertainty metadata to elements, with the model exported to IFC to preserve interoperability and long-term accessibility. This approach allows for the unambiguous identification of data sources – from point clouds, through photographic documentation, to archival materials – and thus increases the scientific and conservation value of the study.

The limitations indicated, related, among other things, to the need to create libraries of elements characteristic of historical objects and the lack of adaptation of current classification systems to the specificity of monuments, prove the need for further development of HBIM tools. From the data-acquisition perspective, the case study also highlights that additional point-cloud quality control, completeness (e.g., roof gaps), and georeferencing would further increase the reliability and reusability of HBIM outputs, especially for buildings at risk of disappearance. The reconstruction of complex wooden geometries remains resource-intensive, underscoring the need for automated segmentation tools specifically designed for heritage applications. It is necessary to expand existing standards with categories and parameters specific to architectural heritage, which will enable a more complete and precise representation of actual historical objects.

The results obtained also show that digital models can serve not only as documentation of the condition of a building but also as a basis for future conservation, educational, and promotional activities. In the context of the growing threat of loss of monuments, especially wooden residential architecture, the development of such digital reconstructions should be treated as an important element of cultural heritage protection. Future work should therefore focus on harmonizing heritage-specific classification/parameters and evidence-ranking conventions in HBIM, so that reconstructions from different sites can be compared, validated, and reused across conservation workflows and openBIM exchanges.

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