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# SCAN-TO-BIM method and analysis of measurement accuracy on the example of a historic church

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**Abstract**

Building information modeling (BIM) data for existing buildings based on scans and point clouds acquired from terrestrial laser scanning (TLS) is the basis of the Scan-to-BIM methodology and is becoming common practice. However, work on the accuracy of the resulting model is still desired. The article discusses the possibility of developing a BIM model of a historical building, based on data obtained by terrestrial laser scanning. The subject of the study was the church in Posada Rybotycka (Poland). The mapping reliability studies included PointCab and ReCap point cloud processing, 3D modeling of the object using Revit software, and analysis of the accuracy of distance measurements made by TLS with data obtained from measurements made with traditional methods: total station and laser rangefinder. Based on the conducted research, the possibility of using the BIM with TLS data in the process of reconstructing the geometry of a historic building was evaluated. The results of the study showed that the convergence of the 3D model geometry with the actual course of the structure depends on the development methodology, i.e. the accuracy of 3D data acquisition, the registration process, the filtering procedure, or the parametric structural modeling method used.

**Keywords:** terrestrial laser scanning, Scan-to-BIM, historical church, architectural survey, geometry modeling, accuracy analysis

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# 1 Introduction

An essential task related to the management of historic objects including monitoring their state of preservation or planning activities for their conservation and ongoing maintenance, is the development of a reliable 3D model (Aricò and Brutto. 2022; Rocha et al., 2020). Currently, this problem can be solved by using non-contact measurement methods and Scan-to-BIM process/technology. These methods allow the creation of parametric models in a BIM (Building Informaton Modeling) environment, which are able to improve the geometric model under development. It should be noted that BIM technology also enables the integration of different types of data (Aricò and Brutto. 2022; Rocha et al., 2020). As you know, modeling historic buildings is often difficult and time-consuming, so non-contact measurement methods provide a solution to effectively implement HBIM (Hertitage Building Informaton Modeling) technology and overcome such problems (Skrzypczak and Leśniak, 2022, Leśniak et al., 2021). HBIM is a promising technology, but the assumptions, especially in terms of the measurement accuracy achieved, are insufficient.

In an attempt to expand this area of research, the first part of the article discusses the HBIM process based on an extensive literature review and highlights recent HBIM developments. In the second part, the results of a study on the application of the Scan-to-BIM approach to the measurement of an historical church in Posada Rybotycka (Podkarpacie, Poland) are presented. This activity was motivated, among other things, by the local administration's renewed interest in cultural heritage. Through the application of non-contact techniques and the use of a laser scanner, a 3D model was developed and the morphotypological style of the church was captured.

The primary goal of the research and analysis related to the technology used was to determine the measurement accuracy, while the next step was to obtain a parametric model that would best capture the specifics of the site. In order to carry out analyses regarding measurement accuracy, the results of TLS measurements were compared with laser total station and laser rangefinder measurements. It is assumed that the results of the planned study will provide information on the accuracy of measurements of the analyzed church building and identify weaknesses in the work on modeling the selected object using Scan-to-BIM methodology.

# 2 HBIM modeling of cultural heritage buildings

HBIM is a very useful and effective methodology for the management of historic/cultural heritage sites (Obolewicz and Baryłka, 2021; Obolewicz and Baryłka, 2023), as it provides a documentary basis for further analysis and project development of current and future maintenance, preservation or renovation activities (Rocha et al., 2020, Skrzypczak et al., 2023). The developed models of historical objects should include accurate structural features and information about their transformations and renovations that have taken place.

## 2.1 SCAN-TO-BIM

The term Scan-to-BIM refers to a set of works that integrate and regulate the process of measurement, modeling and information management, and make it possible to obtain a digital information system associated with geometric documentation, processing and data collection into an intelligent model built from semantic information (Volk et al., 2014; Rocha et al., 2020). The various stages of work may include:

- capturing geospatial data using digital technologies such as terrestrial laser scanning (TLS), airborne laser scanning, photogrammetry, and tachnimetry;
- creating a point cloud from raw data;
- importing and customizing point clouds into the BIM environment for manual or semi-automatic recognition;
- manual or semi-automatic generation of parametric components with attached information;
- modeling of other custom components.

The Scan-to-BIM process encompasses all decisions made in data collection, design development activities and modeling choices. When developing a Scan-to-BIM project, a high level of rigor must be imposed from the outset at every stage of integrating the information being acquired.

Archival research on the site under consideration and research on traditional techniques and materials should be conducted prior to on-site surveys. These initial phases can be tested and verified against data collected using TLS and photogrammetry techniques, which are widely used in the second stage of the work. In fact, the current state of the historic building is studied with the highest accuracy in a less time-consuming and most efficient, non-invasive way. The acquired point cloud represents the acquired surface of the entire building and contains registration information such as texture, color, architectural morphology and state of preservation (Sampaio et al., 2021). It is not recommended to construct HBIM models without first digitally reviewing the site. The amount of knowledge that can be obtained from the point cloud is indisputable, it is a reliable basis that can be imported into the BIM platform and used for modeling, bearing in mind that the accuracy and level of detail of the model depend on the acquired data (Chiabrando et al., 2017). It is therefore necessary to establish procedures for transforming this data into the HBIM environment and to know how these processes can be optimized (Moyano et al., 2021).

However, one should be aware that the HBIM process also has disadvantages. The parametric nature of BIM interferes with the precision of the resulting point cloud model. The inflexibility of the software tools results in a loss of accuracy and detail; the tolerable approximation does not allow for the inclusion of defects in, for example, elements with complex shapes, slightly deformed or differing from the ideal model as a result of construction techniques or structural damage (Aricò and Lo Brutto, 2022; Chmielewski and Kruszka, 2015; Chmielewski et al., 2021). HBIM is therefore the result of a compromise between the modeling techniques used and the actual model of the building object (Bruno and Roncella, 2018), and oversimplifications can render the model worthless. To determine the maximum fidelity of a 3D reconstruction, it is always necessary to develop a strategy. Therefore, before surveying, it is necessary to choose the definition of the level of detail (LoD), which in HBIM is different from the LoD assigned to the new construction model. In fact, in the BIM environment, LoD is closely related to the amount of graphic precision that should affect the entire model. In both HBIM and BIM, LoD includes only the geometric representation and not the information content of the modeled elements. This depends on the goals and future applications for which the model was created (Aricò and Lo Brutto, 2022).

In the case of the HBIM model, choosing an appropriate LoD is not easy, as it involves shaping architectural details in such a way that they are not remodeled or under-modeled compared to the real object. HBIM representation is a complex and resource-intensive process, and currently the most extensive segmentation and modeling method is still a manual approach. This approach is difficult and takes a lot of time, given that (Aricò and Lo Brutto, 2022):

- composite data should be compiled without inaccuracies and inconsistencies, and accidental data loss should be prevented;
- the size of point cloud files is huge;
- the process cannot be carried out with only one software, and interoperability of multiple programs for different purposes is an issue that can jeopardize the final result;
- all of this requires powerful machines, experienced designers and a lot of working time.

## 2.2 Ground-based measurement techniques

The use of non-invasive surveying tools and technologies, including ground-based surveying techniques, makes it possible to faithfully reproduce the actual geometry of objects (Wider and Gawronek, 2021; Piech et al., 2018, Kwinta and Gradka, 2021), and also makes it possible to use BIM technology to manage existing buildings (Baik, 2017). The guarantee of successful application of BIM technology is the proper selection of the measurement method. In engineering applications, two measurement methods dominate: contact and non-contact. Of course, the basis for the selection of a measurement method is the cost-effectiveness of its use (cost) and measurement time (Skrzypczak and Leśniak, 2023).

It should be noted that non-contact methods are considered one of the more accurate technologies for acquiring spatial data (Pitkänen et al., 2021). Spatial data acquisition therefore becomes fundamental to the quality and accuracy of the developed model (Alshawabkeh et al., 2021; Pitkänen et al., 2021) and the efficient application of BIM technology. According to scientific studies (Wider and Gawronek, 2021), the laser scanning method is considered one of the most accurate technologies for spatial data acquisition (Pitkänen et al., 2021). However, walls with non-uniform thickness, deviations and lack of perpendicularity are common in historic buildings. Non-orthogonal walls impair the HBIM workflow, and it is necessary to pay attention to this aspect to decide on the approach to be taken for modeling. The problem of faithfully reproducing an object in three-dimensional space inspired the authors to investigate the accuracy of distance measurements with TLS techniques. For this purpose, the object was laser scanned. Object-oriented parametric modeling was carried out on the basis of the facade's point clouds, and the modeling results were compared with data obtained from measurements with classical techniques: total station and laser rangefinder.

# 3 Case study

## 3.1 Research object

The church in Posada Rybotycka dates to 1341. It is one of the oldest defensive churches in Poland (Fig. 1).


South side

Northwest side

Eastern side

**Figure 1**. *View of the church*

The church dates to 1341. This stone church consists of three interconnected sections - towers. Each part is covered by a hipped roof. The church is a Gothic-Renaissance oriented building. Its exterior walls are plastered. The oldest is the Gothic chancel, built at the turn of the 14th and 15th centuries. The square nave dates to the 15th century. The youngest is the western part, built in the early 16th century. It includes a porch and a babiniec, as well as a former chapel for monks on the first floor. The church was a Basilian monastery temple until the end of the 18th century, and later served the local parish. The defense of the building was ensured not only by the thick walls and the loft gunnels, but also by its convenient location on a hill. The structure is also strengthened by massive buttresses covered with small canopies. After World War II, the building was taken over by the Polish Treasury. and then transferred to the ownership of the Fredropol Municipality. In 2010, the Property Commission transferred the church to the Archdiocese of Przemysl-Warsaw of the Greek Catholic Church. For many post-war years the building was permanently devastated and deteriorated, and was not repaired. It was not until the church was given to the National Museum of the Przemysl Region that restoration work was undertaken and completed in 1985 (Paszek, 2019).

## 3.2 Terrestrial laser scanning

The survey of the selected historic building using terrestrial laser scanning technology was performed in March 2022. The laser scanning covered the exterior and interior of the entire church and lasted two days. The field work included a total of 5 sites for scanning the building's exterior facade and more than 16 sites for scanning the interior (Fig. 2).

**Figure 2.** *TLS measurements: - indoor and outdoor measurements*

The measurement was made with a Faro Focus 3D 130 laser scanner. The measurement procedure at each station - the external position of the object - consisted of two successive scans. The first, performed at low resolution (the so-called preview scan), covered the full range of laser visibility and served to transfer the entire station environment to the Model's 3D space. Then, from the controller, the target scan range of the object was marked, and the actual scan was performed with the target resolution reduced to 2 mm/10 m. The interior of the object was scanned in full station panorama and at the target resolution. TLS data processing was performed in PointCab and included point cloud registration and manual filtering (Fig. 3-5).

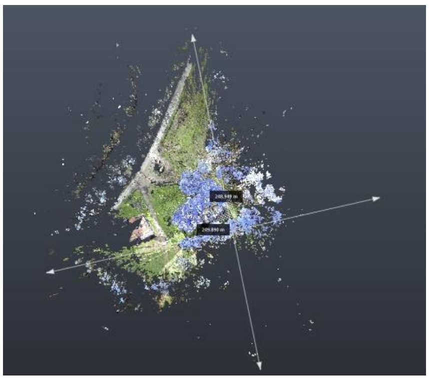
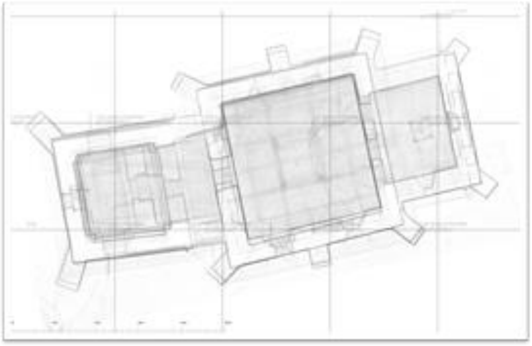


**Figure 3.** *View of the total scanning range, before processing the external part*

**Figure 4.** *View of a single scan taken between selected spaces*



*An overhead projection of the point cloud*

*Cross section through the point cloud*

**Figure 5.** *Example of projection and cross-section obtained in PointCab software*

After the filtering process, the object's point cloud was geometrically checked. After checking the geometric correctness of the 3D data, the point cloud was prepared for modeling and its export. The model of the church facade was developed in the Autodesk Revit software environment, commonly used for Building Information Modeling (Fig. 6 - 8).

*South elevation*

*North elevation*

**Figure 6.** *Views of selected elevations obtained with ReCap software*

1.

**Figure 7.** *The projection of the church at the level of the sanctuary +1.0m, obtained with ReCap software*

**Figure 8.** *Cross-section at aisle height without and after point cloud for better dimensioning effect* **-** *obtained with ReCap software*

**Figure 9.** *Detail of the vault of the nave, obtained with the ReCap sofware*

ReCap software enables dimensioning of the object, which avoids distortion of dimensions compared to drawings made in classical 2D technology (Fig. 10).

**Figure 10.** *Example of dimensioning done in ReCap software*

## 4 Analysis of the accuracy of the measurements taken

In order to check the accuracy of the laser scanner measurement, 14 points were measured between which distances were determined. It was assumed that the electronic total station measurement is an order of magnitude more accurate than the laser scanner measurement, so for the purpose of estimating the accuracy of the scanner, the classical measurements can be considered error-free. Both methods were used to determine the coordinates of reference points. Then the distances between these points were calculated based on the coordinates from the classical measurements and the scanner measurement.

The results were compared, and the calculated distances were summarized in several groups (distances from a site and between sites - appendix 1)

The value of the distance measurement deviation is obtained from the formula:

$$\left|\Delta d_{kj}\right| = \left|d_{kj}^{t} - d_{kj}^{s}\right|$$

where:

$\Delta d_{kj} -$ the absolute value of the deviation of the distance measurement between points $k$ and $j$,

$d_{kj}^{t} -$ distance obtained by the classical method,

$d_{kj}^{s} -$ distance obtained by terrestrial laser scanning.

The standard deviation, calculated from the formula, was used as a criterion to describe the accuracy of the laser scanner:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} \Delta d_{kj}^{\ 2}}{n}}$$

where:

$\sigma$- standard deviation,

n- number of measurements.

Appendix 1 and Appendix 2 summarize the distances obtained from the classic total station measurement and the laser rangefinder measurement, and determine the length deviation and relative error expressed in %. In the tables in the appendices, distances determined based on points measured from each site and distances between points determined from two different sites are separately tabulated. These distances are described in the table as "Combined scans."

Table 1 shows the standard deviations of all recorded measurements with respect to the distances analyzed. After analyzing the results, it can be seen that the mapping accuracy was not identical for all measurement data. The largest measurement error value obtained was 31 mm. It is worth noting that the obtained average mapping error was 7 mm. The standard deviations of measurements from individual measuring stands are much smaller than the standard deviation of all distances.

| **Measurements** | **Standard deviation [mm]** |
|---|---|
| measuring stand 1 | 6,95 |
| measuring stand 2 | 4,87 |
| measuring stand 4 | 2,88 |
| measuring stand 5 | 2,38 |
| Combined scans | 10,93 |
| Laser rangefinder measurement | 1,90 |

**Table 1.** *List of the standard deviation in each set of results*

## 5 Summary

The Scan-to-BIM approach is an inherent tool of the BIM process, which enables the transformation of data extracted from TSL surveys into an intelligently structured model that integrates structured multi-discipline data. In the BIM model, all data is linked to a digital information system. The model guarantees the management, acquisition and updating of geometric and non-geometric information of existing buildings. However, this methodology has some drawbacks when applied to historic, heritage buildings, especially at the parametric modeling stage. These buildings, due to their nature, always bring with them some problems, including the use of ready-made libraries of parametric BIM shaping. These objects are most often characterized by lack of verticality of edges, tapering, uneven or unorthogonal walls, barack flatness of walls, architectural details with unique shapes, irregular shape . windows or arches, etc. Currently, typical BIM libraries do not contain families adaptable to the specifics of historic buildings. Combining 3D data with complex geometric elements is sometimes difficult due to the lack of advanced modeling tools in BIM applications. Creating and implementing customized procedures and functions can solve these problems, but they are time-consuming solutions that affect the modeling process.

An interesting research attempt from a historical and methodological point of view is the church in Posada Rybotycka. 3D measurements and the creation of a parametric model were aimed at looking at the building's construction, conservation and possible restoration. Adopting a Scan-to-BIM methodological approach, attention was paid to minimizing steps regarding format changes during the process to prevent oversimplification and loss of information.

Based on the point cloud, a parametric model of the orthodox church was built to analyze the accuracy of the measurement methods used. Measurements made with the laser scanner coincided with the results of measurements made with two classical methods. The highest recorded error of the tested section distance was 37 mm, standard deviations of the results measured within single, unconnected scans ranged from 2.88 mm to 6.95 mm. Merging the scans together significantly degraded the accuracy of the final product, the standard deviation for this variant was as high as 10.93 mm. The developed model can be considered a starting point for future research.

HBIM can be used to supplement the knowledge of the condition of masonry walls, for Finite Element Method (FEM) analysis, and for more in-depth geometric analysis of major architectural elements, or to develop a detailed plan for maintenance and repair work. The process of scanning to BIM proved to be extremely effective in the case of the site under consideration. It allowed minimizing the time for field survey work, as well as, thanks to the use of BIM software for the 3D architectural reconstruction of the church, minimizing the time for office work related to the production of the applicable documentation including the architectural and construction design.

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Appendix 1 shows the distances obtained with the scanner and total station for each measuring stand, while Appendix 2 shows the distances measured with the laser rangefinder and the same distances obtained from the laser scanner measurement.

**Appendix 1.**

**Table A.1. Summary of distances obtained with the scanner and total station for each measuring stand**

| **Length of section [mm]** | | **Length deviation [mm]** | **Relative error [%]** |
|---|---|---|---|
| $d_{kj}^t$ | $d_{kj}^s$ | $\lvert\Delta d_{kj\rvert}$ | $\lvert\Delta d_{kj\rvert}$ |
| measuring stand 1 | | | |
| 2448 | 2459 | 11 | 0.45 |
| 3131 | 3137 | 6 | 0.19 |
| 2835 | 2837 | 2 | 0.07 |
| 3379 | 3371 | 8 | 0.24 |
| 8424 | 8418 | 6 | 0.07 |
| 996 | 993 | 3 | 0.30 |
| 3284 | 3289 | 5 | 0.15 |
| 3862 | 3861 | 1 | 0.03 |
| 9260 | 9262 | 2 | 0.02 |
| 3066 | 3064 | 2 | 0.07 |
| 3580 | 3567 | 13 | 0.36 |
| 8850 | 8852 | 2 | 0.02 |
| 601 | 596 | 5 | 0.83 |
| 5996 | 5998 | 2 | 0.03 |
| 5395 | 5410 | 15 | 0.28 |
| measuring stand 2 | | | |
| 2681 | 2677 | 4 | 0.15 |
| 4886 | 4881 | 5 | 0.10 |
| 5265 | 5259 | 6 | 0.11 |
| 6480 | 6475 | 5 | 0.08 |
| 3328 | 3324 | 4 | 0.12 |
| 3154 | 3147 | 7 | 0.22 |
| 2448 | 2445 | 3 | 0.12 |
| 3131 | 3128 | 3 | 0.10 |
| 5670 | 5668 | 2 | 0.04 |
| 3015 | 3019 | 4 | 0.13 |
| 4696 | 4700 | 4 | 0.09 |
| 996 | 990 | 6 | 0.60 |
| 4492 | 4490 | 2 | 0.04 |
| 3296 | 3302 | 6 | 0.18 |
| 5823 | 5829 | 6 | 0.10 |
| 3573 | 3575 | 2 | 0.06 |
| 3003 | 3011 | 8 | 0.27 |
| 5640 | 5647 | 7 | 0.12 |

| | | | |
|---|---|---|---|
| 3154 | 3154 | 0 | 0.00 |
| 4876 | 4883 | 7 | 0.14 |
| 2641 | 2641 | 0 | 0.00 |
| measuring stand 3 | | | |
| 996 | 995 | 1 | 0.10 |
| measuring stand 4 | | | |
| 10162 | 10156 | 6 | 0.06 |
| 10503 | 10499 | 4 | 0.04 |
| 10551 | 10548 | 3 | 0.03 |
| 8125 | 8124 | 1 | 0.01 |
| 2519 | 2519 | 0 | 0.00 |
| 4026 | 4025 | 1 | 0.02 |
| 5114 | 5110 | 4 | 0.08 |
| 1548 | 1548 | 0 | 0.00 |
| 3503 | 3503 | 0 | 0.00 |
| 2719 | 2717 | 2 | 0.07 |
| measuring stand 5 | | | |
| 1548 | 1548 | 0 | 0.00 |
| 3503 | 3502 | 1 | 0.03 |
| 2719 | 2715 | 4 | 0.15 |
| COMBINED SCANS | | | |
| 3093 | 3094 | 1 | 0.03 |
| 3227 | 3209 | 18 | 0.56 |
| 6685 | 6697 | 12 | 0.18 |
| 10474 | 10466 | 8 | 0.08 |
| 10155 | 10155 | 0 | 0.00 |
| 9813 | 9808 | 5 | 0.05 |
| 7138 | 7158 | 20 | 0.28 |
| 9004 | 9002 | 2 | 0.02 |
| 9904 | 9908 | 4 | 0.04 |
| 10314 | 10313 | 1 | 0.01 |
| 8295 | 8297 | 2 | 0.02 |
| 8043 | 8044 | 1 | 0.01 |
| 9041 | 9048 | 7 | 0.08 |
| 9538 | 9538 | 0 | 0.00 |
| 7666 | 7671 | 5 | 0.07 |
| 3391 | 3386 | 5 | 0.15 |
| 3321 | 3349 | 28 | 0.84 |
| 6719 | 6713 | 6 | 0.09 |
| 4558 | 4555 | 3 | 0.07 |
| 5502 | 5506 | 4 | 0.07 |
| 6162 | 6159 | 3 | 0.05 |
| 4833 | 4835 | 2 | 0.04 |
| 232 | 234 | 2 | 0.86 |
| 620 | 623 | 3 | 0.01 |
| 5961 | 5962 | 1 | 0.02 |
| 7354 | 7347 | 7 | 0.10 |
| 7494 | 7492 | 2 | 0.03 |
| 7549 | 7540 | 9 | 0.12 |
| 5213 | 5209 | 4 | 0.08 |
| 2579 | 2580 | 1 | 0.04 |

| | | | |
|---|---|---|---|
| 7585 | 7574 | 11 | 0.15 |
| 7693 | 7689 | 4 | 0.05 |
| 7717 | 7707 | 10 | 0.13 |
| 5342 | 5339 | 3 | 0.06 |
| 2077 | 2064 | 13 | 0.01 |
| 5395 | 5358 | 37 | 0.69 |
| 7281 | 7282 | 1 | 0.01 |
| 7231 | 7223 | 8 | 0.11 |
| 7183 | 7159 | 24 | 0.33 |
| 4758 | 4732 | 26 | 0.55 |
| 3733 | 3741 | 8 | 0.21 |
| 7947 | 7946 | 1 | 0.01 |
| 7209 | 7213 | 4 | 0.06 |
| 6717 | 6715 | 2 | 0.03 |
| 4014 | 4015 | 1 | 0.02 |
| 7562 | 7550 | 12 | 0.16 |
| 5730 | 5720 | 10 | 0.17 |
| 4542 | 4526 | 16 | 0.35 |
| 2457 | 2449 | 8 | 0.33 |

**Appendix 2.**

**Table A.2.** *Summary of distances obtained with the scanner and laser rangefinder*

| $d_{kj}^{t}$ | $d_{kj}^{s}$ | **Deviation [mm]** | **Relative error [%]** |
|---|---|---|---|
| 1799 | 1801 | 2 | 0.11 |
| 2323 | 2320 | 3 | 0.13 |
| 901 | 905 | 4 | 0.44 |
| 2345 | 2340 | 5 | 0.21 |
| 900 | 906 | 6 | 0.67 |
| 1298 | 1298 | 0 | 0.00 |
| 900 | 906 | 6 | 0.67 |
| 1303 | 1306 | 3 | 0.23 |