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Standardisation in 3D building modelling: Terrestrial and mobile laser scanning level of detail

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ABSTRACT

The investigation of the standardisation of 3D building modelling based on TLS (Terrestrial Laser Scanning) and MLS (Mobile Laser Scanning) point clouds aims at assessing the possibility of obtaining various levels of detail (LOD) in the context of performance, accuracy, and structure condition evaluation. The two point clouds represent a heritage church in Żmijowiska (Poland). TLS provides detailed data, supporting higher LOD essential for representing intricate architectural details and monitoring conditions by facilitating the detection of deformations, damage, and signs of material degradation. Although less accurate, MLS offers substantial speed, cost, and hardware availability benefits. Effective and affordable scanning makes this method useful for regular monitoring of building and infrastructure conditions. Moreover, MLS cloud information can be enhanced with auxiliary data, such as images taken with mobile devices (smartphone or camera), to improve model detail and promote better structural evaluation. The results suggest that MLS is more suitable when rapid and cost-effective visualisation and monitoring are important. On the other hand, TLS is advantageous for more detailed reconstructions where high-quality data is required to diagnose infrastructure condition and create high-fidelity digital models of cultural heritage. Therefore, the technology should be chosen depending on the required level of detail and available resources because each offers unique benefits for specific types of projects.

Keywords: TLS, MLS, 3D modelling, LOD, visualisation, high-definition building models, infrastructure monitoring.

INTRODUCTION

The level of detail of a 3D model is critical in building modelling. It defines the accuracy and volume of geometric and semantic information the model contains. Depending on the purpose of modelling, the degree of detail may be adapted to a diversity of conditions, from basic geometric models to high-precision models with the minutest architectural details, structural components, and finishes [1]. Model detail can be described through various categories, such as LOD, LOI (level of information), LOA (level of accuracy), LOG (level of geometry), and others. Each concerns a different aspect of the model. LOD is mostly about geometric complexity and representation of the object's architectural details, for example, capturing the intricate features of a historic facade, such as decorative elements or precise structural geometry. LOI refers to additional information, such as materials, dimensions, or historical data. LOA measures how precisely the object's physical dimensions are represented [2]. LOG is linked to the geometric accuracy of the model: how precisely the shape of the building is represented. Different projects may call for different standards and evaluations based on various degrees of detail depending on the research or practical purposes of the 3D model [3]. Additionally, heritage and complex buildings are often approached with sophisticated model generation protocols, such as GOG (Grade of Generation), which go beyond standard practices by specifying the degree of detail and accuracy required for irregular structural components, such as vaulting, columns, or non-typical walls. This approach is particularly relevant for heritage buildings, as it ensures that their unique and often intricate architectural elements are accurately represented and preserved in the generated models. [4]. In the case of complex buildings, degrees of detail are often combined or adapted to the needs. For example, LOG and LOA may be adapted to the highest degree of geometric accuracy to ensure the model's consistency with laser scanning data. The models can represent shapes as well as damage and structural deformations, which is relevant for conservation and preservation analyses. A high degree of detail and proper information stewardship facilitate more effective object monitoring and support restoration decision-making [4].

LOD describes the accuracy and degree of detail used to represent the building model in a three-dimensional space, directly impacting the model's quality and functionality. It allows for standardization in 3D modeling, ensuring consistency across projects and enabling the degree of detail in the building's representation to be tailored to the specific requirements of each project profile. The current LOD specification under the CityGML 2.0 standard involves five levels (LOD0–LOD4). Each level describes a different degree of detail, from the lowest (LOD0) for 2D building outlines to the most detailed (LOD4), covering the interior and exterior features of buildings. Admittedly, Biljecki et al. [5] criticise this classification as not always capable of separating different levels of detail well, which may cause miscommunication. Still, the selection of the right LOD in 3D models is, beyond any doubt, pivotal, considering that various types of LOD may significantly affect the reliability and accuracy of spatial analyses, such as building area or volume estimation or sunlight and shade exposure analysis. Incorrect LOD or disregard for certain geometric references may lead to erroneous results, putting analytical precision of spatial planning or real estate management at risk [6].

Utmost care for transparency and reliability of representation of historical features is a must for 3D modelling of architectural heritage. As-built models based on precise measurements and observations on site must precisely reflect reality to be useful in architecture conservation and research. The palette of different LODs empowers engineers to adapt the model's geometric and historical detail to the project requirements depending on the resources. In the case of heritage objects, it is important to include information about data sources and employed interpretations to help researchers understand modelling assumptions. After all, the reliability of the models is evaluated through the level of detail and quality, which determines their value as records of heritage. It also powers a more effective analysis of past construction techniques and materials [7, 8].

Several important factors guide the process of selecting the right LOD. They include the reliability and completeness of the data source from which the model is generated and the project objective. Budget, available technology, and time are also weighty aspects. Highly specialised and difficult projects, such as heritage documentation where the maximum precision, reliability, and accuracy of the representation are critical, may require a high LOD (LOD3 or 4) [9]. A high LOD facilitates the precise representation of complex architectural details of cultural heritage, such as ornaments, sculptures, and other unique elements [1, 10]. On the other hand, rapid engineering projects that prefer time effectiveness at a specific degree of detail may accept lower LODs, such as LOD2, which provides a general outline of the building without details [11]. Lower LODs may also be sufficient for urban visualisation or analysis, where the general building geometry matters [12].

The suitability of the data source for modelling at a specific LOD depends mainly on the data collection technology. TLS and mobile laser scanning (MLS) are the most popular and accurate technologies. Terrestrial laser scanning is very often employed to survey various objects as a valuable data source for 3D model building. It can acquire very high-resolution point clouds, which are extremely useful in drafting architectural documentation, especially concerning intricate architectural details [13]. The laser scanning process can quickly and precisely represent large interior and exterior surfaces [14]. One significant advantage of TLS is its ability to collect accurate data in difficult ambient conditions, which makes it invaluable for compiling cultural heritage documentation. In addition, TLS data can be used to generate 3D models with various LODs [15]. Still, TLS can be time-consuming and cost-intensive, which limits its usefulness in projects where time and budget are of the essence [16]. Hence, although MLS is less precise, it can provide data faster and at a lower cost [17]. Alternatives like photogrammetry and UAV data are used for mid-range LOD. Data from these sensors can be synchronised with and integrated into a laser-scanning point cloud to build comprehensive 3D models [18]. Handheld MLS are growing more popular thanks to lower costs and greater mobility than TLS. Mobile laser scanners can collect data in dynamic field conditions, in motion, and in places difficult to reach [19]. Ease and speed of use make MLS the perfect solution for projects where data must be collected quickly [20]. Comparisons of TLS and MLS regarding accuracy and suitability for 3D modelling for high LOD found in the literature clearly favour TLS over MLS [21, 22]. Nevertheless, (handheld) MLS is a rapid scanning technique that is more budget-friendly than TLS. It also can collect comprehensive data for 3D modelling and generating technical documentation [23–25]. Both technologies exhibit profits and disadvantages in different laboratory and field conditions regarding their metrological characteristics. Mitka et al. [26] demonstrated that although MLS offers lower accuracy, it may be more effective in dynamic and rapidly changing environments. Thanks to its mobility, MLS can collect data faster and over larger areas, which is particularly valuable in urban cartography or when scanning extensive territories. Still, MLS often requires more postprocessing to reach an LOD similar to TLS [27, 28].

The study aims to assess the impact of the type of data source on the quality, accuracy, and completeness of 3D building models in the context of LOD standardisation, focusing on TLS and MLS point clouds. TLS and MLS were selected for their distinct advantages in capturing data for 3D building models. TLS is recognized for its ability to capture highly accurate and detailed point clouds, making it particularly suitable for intricate architectural elements and heritage buildings. On the other hand, MLS offers faster data acquisition and greater coverage for large-scale environments, although typically at a lower resolution. These differences provide a basis for evaluating their respective impacts on LOD requirements and their suitability for various modeling contexts.

The article is divided into four principal parts. The introduction concerns the importance of standardising 3D building modelling, taking into account LODs and characteristics of data collected using MLS and TLS, using the literature. The second section details the research method, focusing on the characteristics and parameters of TLS and MLS, the data collection procedure, and the comparison of quality, accuracy, and economic efficiency of the two methods. The third part presents the results as a comparative analysis of TLS and MLS point clouds in terms of the quality, degree of detail, and completeness of the data regarding the requirements of different LODs of 3D building models. The last section offers a summary and conclusions regarding the usefulness of the technologies depending on accuracy and economy requirements, followed by recommendations for practical use in 3D building modelling.

SCOPE OF SURVEYS

Standardisation aims to optimise costs, eliminate errors, and unify services, objects, and processes so that they follow the same principles each time, guaranteeing effectiveness, repeatability, and high-quality outcomes. The process involves classification, unification, and typisation [29]. Therefore, the author selected an object with visible structural components and clearly identifiable construction materials to investigate the standardisation of laser scanner data collection for 3D modelling. Additionally, the object has a clear-cut detail of non-standard geometry, which facilitated a more precise analysis and modelling effectiveness evaluation.

The surveys were conducted at a heritage Greek Catholic Church of the Dormition in Żmijowiska, Podkarpackie Voivodeship, southern Poland (Fig. 1a). The eighteenth-century church is a wooden log structure with two distinct parts with a clear-cut and symmetrical shape of a nave and a babinets. The structure has been reinforced with columns and has corner notches typical of traditional log architecture with historical details preserved. The walls are made of coniferous logs of large diameter. The nave and babinets have a hip ridged roof with collar tie frame supporting wood shingles (Fig. 1b) [30, 31].

The study involved two scanning systems, MLS (Fig. 2a) and TLS (Fig. 2b). The MandEye handheld laser scanner features the Livox Mid-360 sensor. The Livox Mid-360 sensor operates at a laser wavelength of 905 nm and ensures eye safety as a Class 1 laser device in compliance with IEC 60825-1:2014. It provides a detection range of up to 40 m for objects with 10% reflectivity and up to 70 m at 80% reflectivity, covering a field of view of 360° horizontally and −7° to 52° vertically. The device boasts a high point rate of 200,000 points per second and a frame rate of 10 Hz, with a distance random error of up to 2 cm at 10 m and an angular random error of up to 0.15°. [32]. According to laboratory tests by Mitka et al.

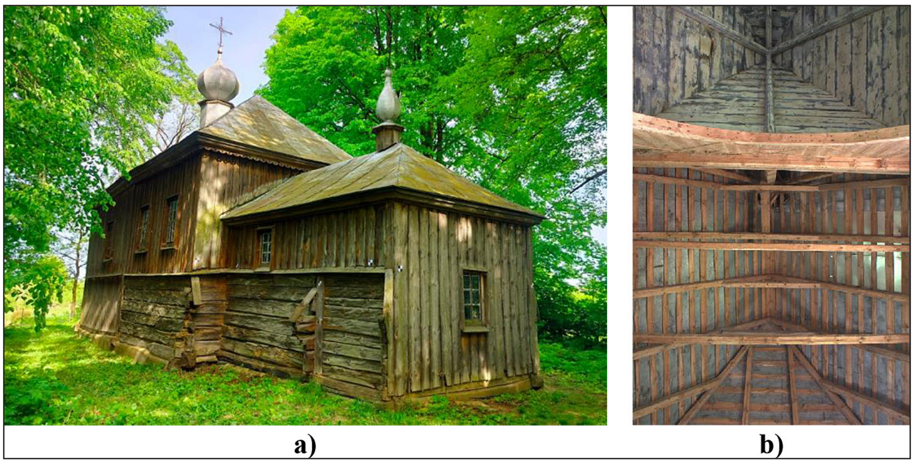


Figure 1. The surveyed object: the Church of the Dormition in Żmijowiska. (a) exterior, (b) interior, roof truss system

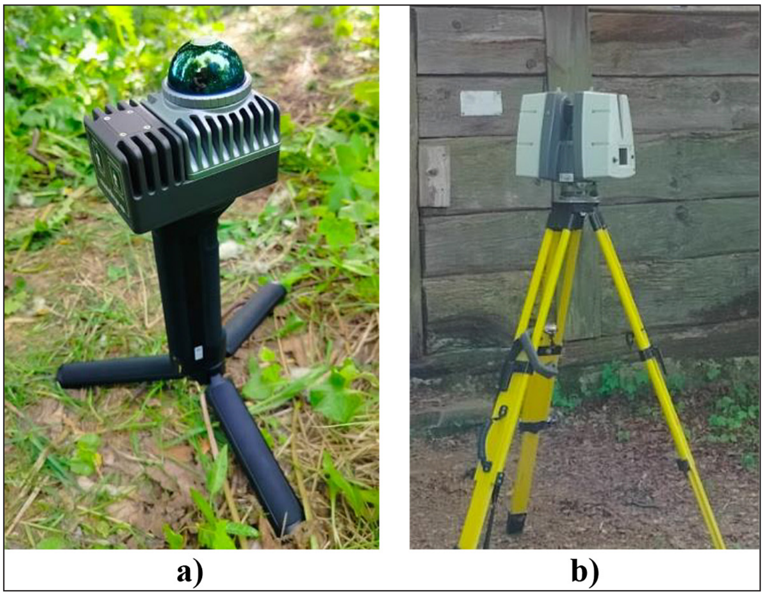


Figure 2. The laser scanners: (a) MLS: MandEye; (b) TLS: Leica ScanStation P4

[26], MandEye reached an accuracy for the average point cloud width of 0.015 m at 5 m and 0.024 m at 15 m in the static mode, with merely 0.2% of incorrect points, which were effectively filtered out. The geometric consistency with reference data was about 10 mm in the static mode and 15 mm in the dynamic mode. Still, target identification was limited in the dynamic mode due to higher noise levels.

The other instrument was the Leica ScanStation P40 terrestrial laser scanner. This advanced device offers exceptional precision and performance in diverse applications, such as topographic surveys, infrastructure surveys, and high-resolution scans. The scanner can register 3D data at up to one million points per second at a range of up to 270 m and a range accuracy of 1.2 mm + 10 ppm. The 3D position accuracy is 3 mm at 50 m. Thanks to the wide field of view, 360° horizontal and 290° vertical, it can scan its entire surroundings. The scanner minimises noise and offers exceptional data quality by using ultra-high-speed time-of-flight enhanced by Waveform Digitising (WFD) technology. It also features dual-axis compensation, which corrects the tilt in real-time with 1.5° accuracy [33]. The laser-scanning point clouds were post-processed in dedicated software. For the MandEye, it was https://github.com/JanuszBedkowski/mandeye_controller [34], and for TLS scans, the author employed Leica Cyclone 9.1. The process yielded a uniform and complete point cloud for the entire object (Fig. 3).

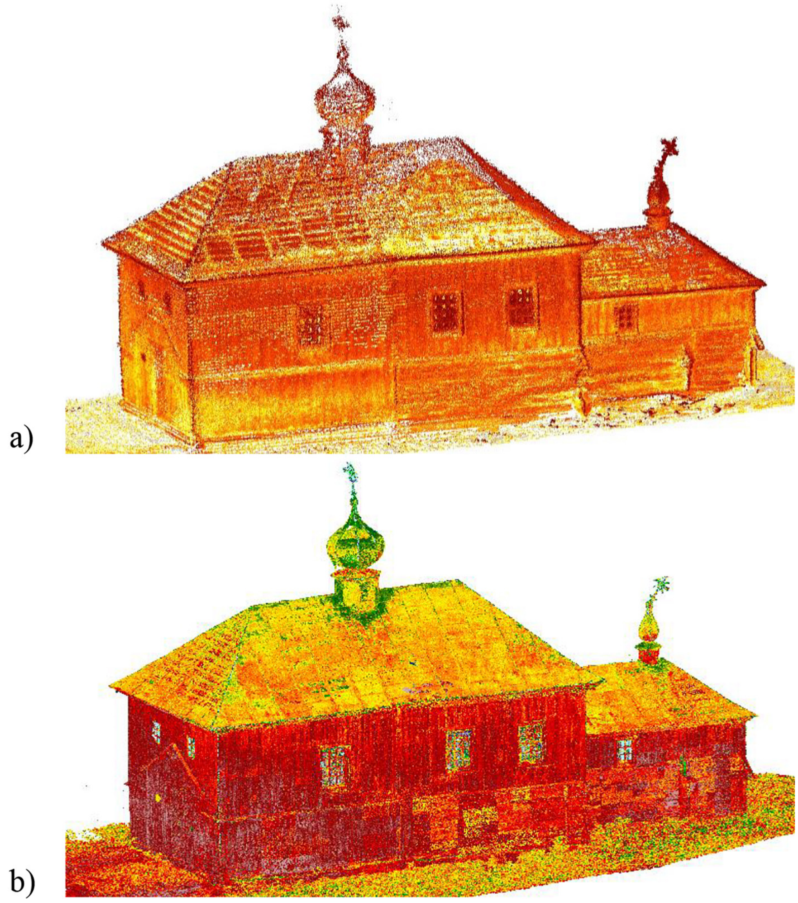


Figure 3. Point cloud from: (a) mobile (handheld) laser scanning, (b) terrestrial laser scanning

ANALYSIS OF TLS AND MLS DATA COMPATIBILITY

The analysis of TLS-MLS data compatibility consisted of comparing and evaluating the consistency of the spatial data from terrestrial and mobile laser scanning. Its purpose was to verify whether the data from both sources were consistent in geometry, accuracy, and object representation. The process included registering the point clouds in a common, uniform orientation, analysing geometric differences, and evaluating data density and quality. It is done with numerical methods like RMS and by comparing point-to-plane and point-to-point distances. The author employed the Iterative Closest Point (ICP) algorithm implemented in CloudCompare. The ICP algorithm aligns two 3D point clouds by iteratively identifying the closest points in the clouds and calculating a rigid transformation (rotation and translation) to minimise the distance between them. The process is repeated until the convergence or a minimum alignment error is reached [35]. The TLS and MLS point clouds were registered and aligned (Fig. 4). The comparative analysis of the TLS and MLS data is presented in sections illustrating information consistency and geometric and semantic alignment of the point clouds. The longitudinal and traverse sections (Fig. 5a, b) illustrate the juxtaposition of the MLS (red) and TLS (blue) point clouds. The author verified information consistency for the entire building by assessing point positioning in individual areas. The measurements were based on the cloud-to-cloud distance (Fig. 6).

IDENTIFICATION OF DETAILS AND 3D BUILDING MODELLING

The 3D modelling was done in MicroStation V8i (Connect Edition) and Solid modelling tools. The complete process was conducted independently for the TLS and MLS data. The details were identified at the suitable (maximum) LODs using the point clouds. The article presents detail modelling for TLS data (Figs 7, 8, 9) and the same areas for the MLS data (Figs 10, 11, and 12).

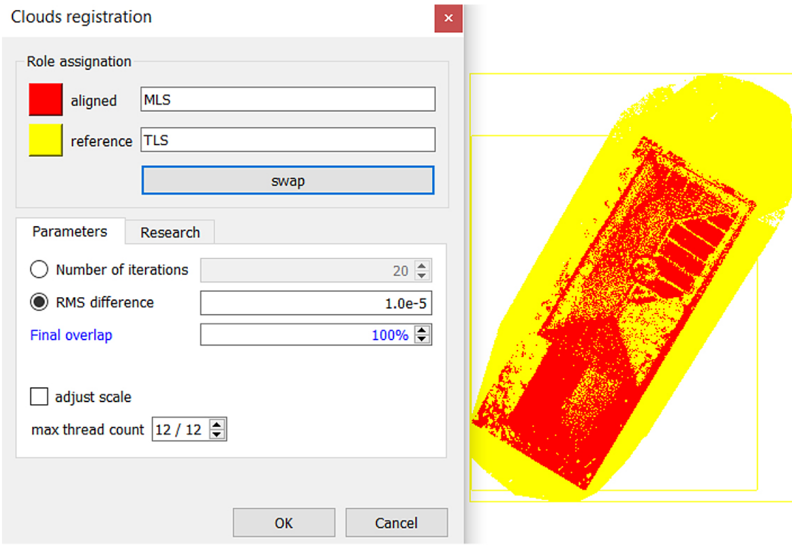
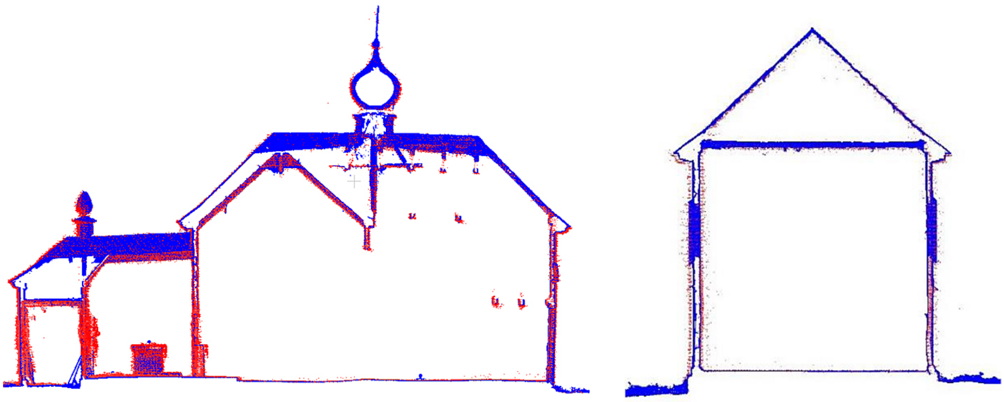
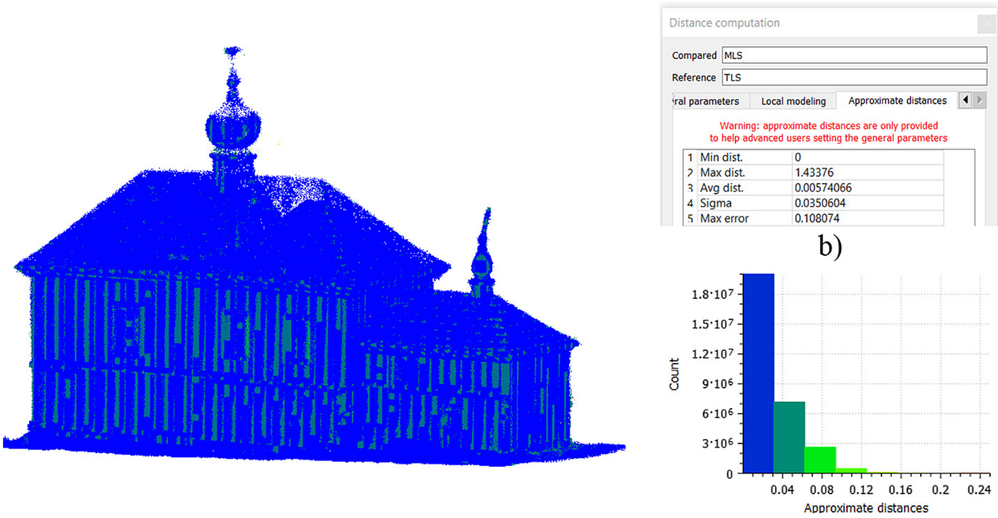


Figure 4. Iterative closest point: TLS/MLS



a) b)

Figure 5. Consistency analysis between TLS (blue) and MLS (red) data. Juxtaposition and sections across point clouds: (a) longitudinal section, (b) traverse section



a) b) c)

Figure 6. Consistency analysis of TLS and MLS data: (a) consistency visualisation, (b) analytical evaluation, (c) consistency histogram

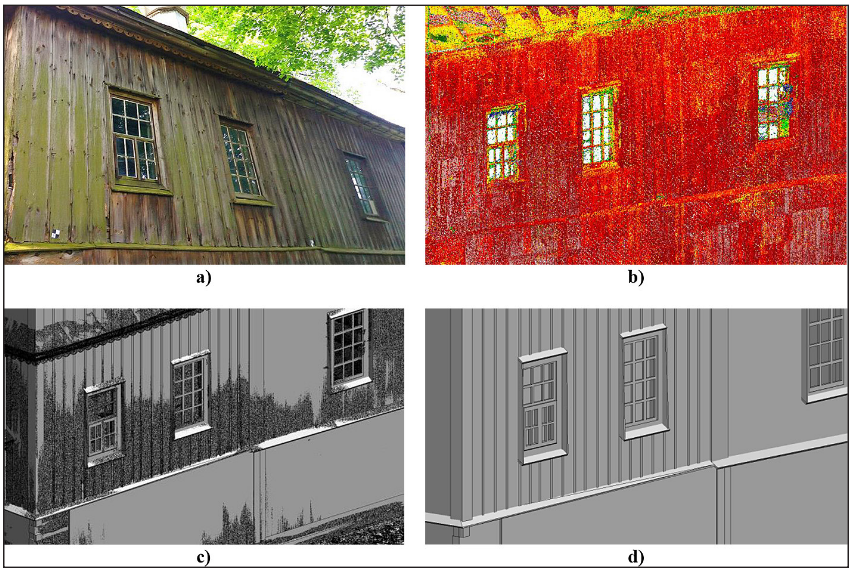


Figure 7. Model based on the TLS point cloud, LOD for walls and windows: (a) detail, (b) TLS point cloud, (c) model during generation, (d) 3D model

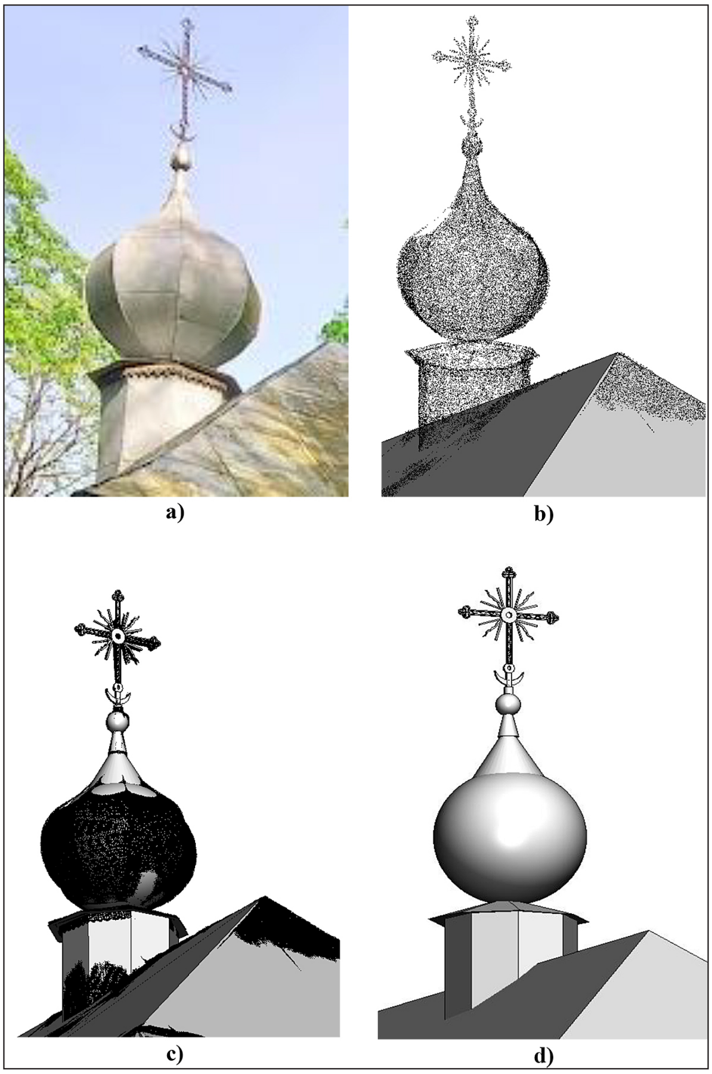


Figure 8. Model based on the TLS point cloud, LOD for the roof and dome: (a) detail, (b) TLS point cloud, c) model during generation, (d) 3D model

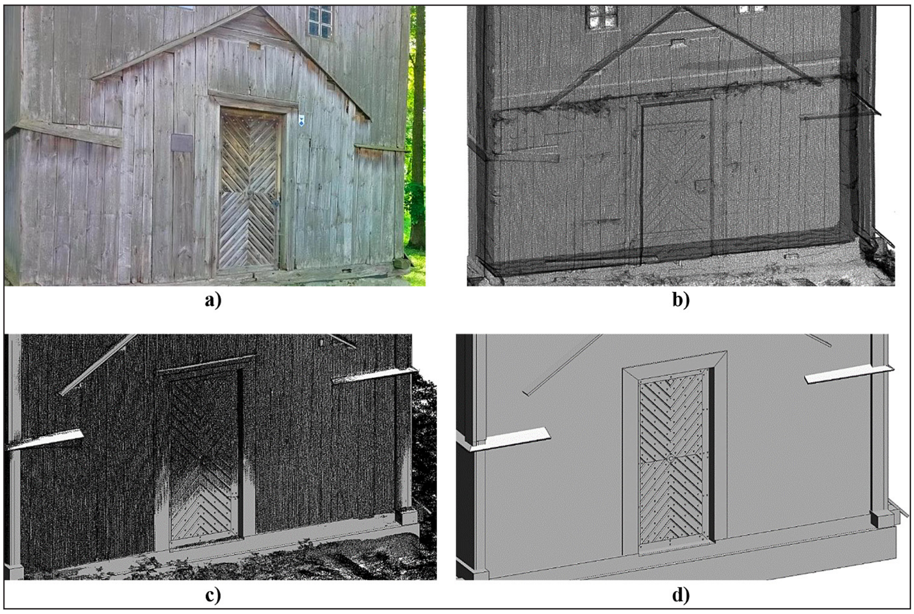


Figure 9. Model based on the TLS point cloud, LOD for walls and door: (a) detail, (b) TLS point cloud, (c) model during generation, (d) 3D model

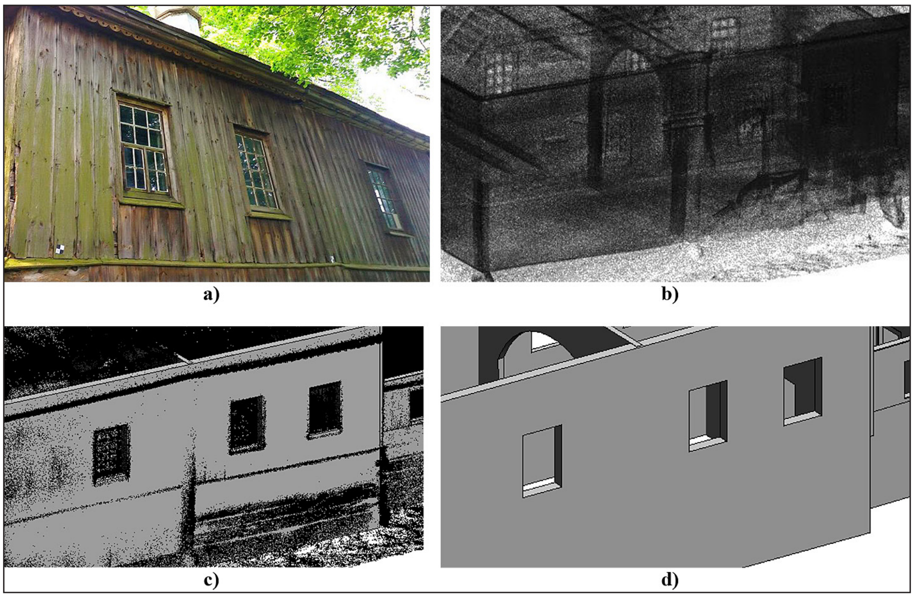


Figure 10. Model based on the MLS point cloud, LOD for walls and windows: (a) detail, (b) MLS point cloud, (c) model during generation, (d) 3D model

RESULTS AND DISCUSSION

The 3D modelling process yielded a detailed and complete model of the object, which can be used to visualise its exterior and precisely represent the interior. The data from terrestrial laser scanning were used to build a precise 3D model (Fig. 13) with complete information on the object's structure (Fig. 14). Thanks to high resolution and scanning data accuracy, even the minutest architectural details could be represented, such as elevation texture, roof details, or ornaments. For most details, LOD4 models were built (Fig. 7, 8, 9). The models contain the exterior geometry and details of the interior, including rooms, internal walls, bearing structures, and secondary items. Models at LOD4 fully represent the actual object.

The 3D model from the MLS data reached LOD3 (Fig. 15, 16) in locations where the point cloud was sufficiently complete, and it was possible to identify individual details and structural elements. The high level of precision of MLS data

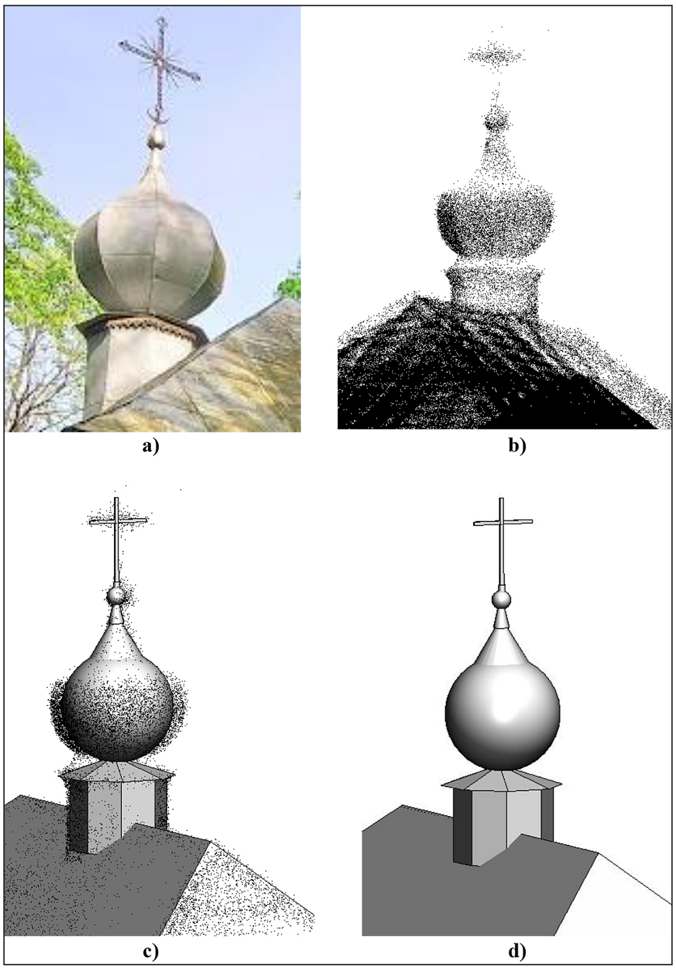


Figure 11. Model based on the MLS point cloud, LOD for the roof and dome: (a) detail, (b) MLS point cloud, (c) model during generation, (d) 3D model

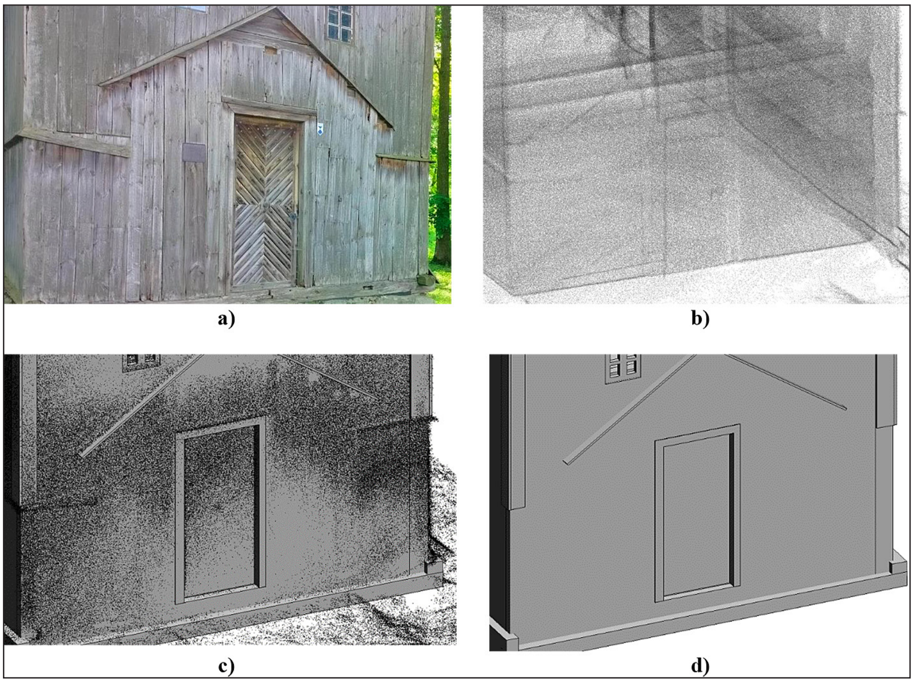


Figure 12. Model based on the MLS point cloud, LOD for walls and door: (a) detail, (b) MLS point cloud, (c) model during generation, (d) 3D model

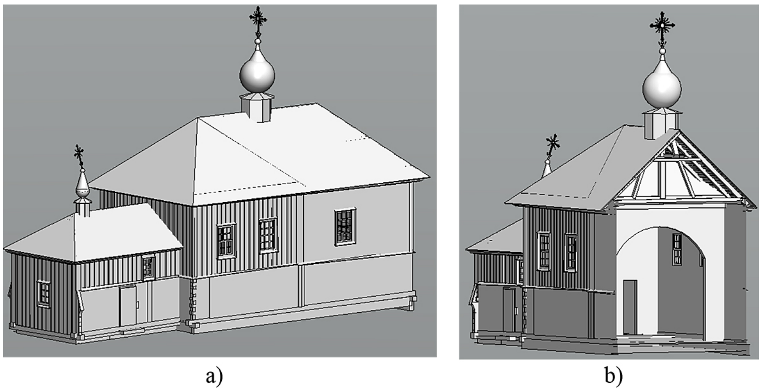


Figure 13. Three-dimensional model for the TLS point cloud: (a) complete object, (b) section view: interior and structure

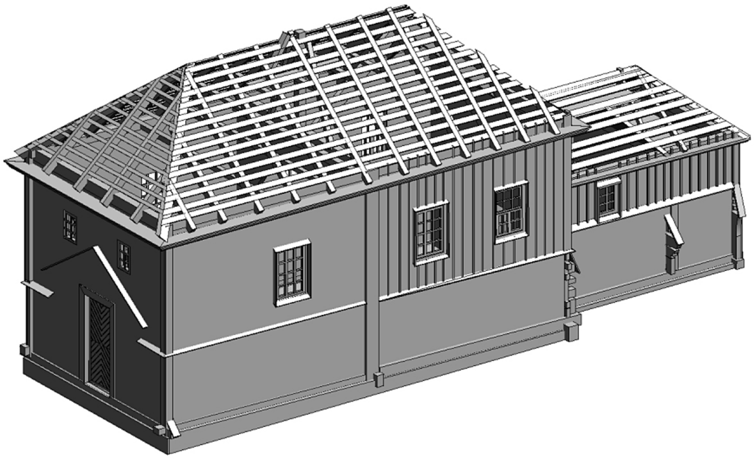


Figure 14. Object structural model from TLS data

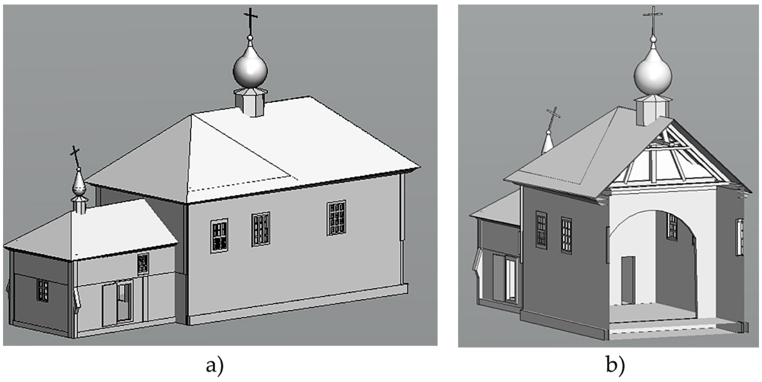


Figure 15. Three-dimensional model for the MLS point cloud: (a) complete object, (b) section view: interior and structure

facilitated the reproduction of such exterior details as elevations, roofs, and other important architectural details. Parts of the object that were inaccessible, not visible, or where the point cloud was incomplete and not sufficiently detailed were modelled following LOD2 specifications. Such models contain simplified geometric forms for a general representation of the building without detailed information about structural or ornamental components.

Levels of detail of 3D models help adjust the scope and accuracy of building representation depending on the project and resources available. For example, a model with a high level of detail contains precisely represented architectural details,

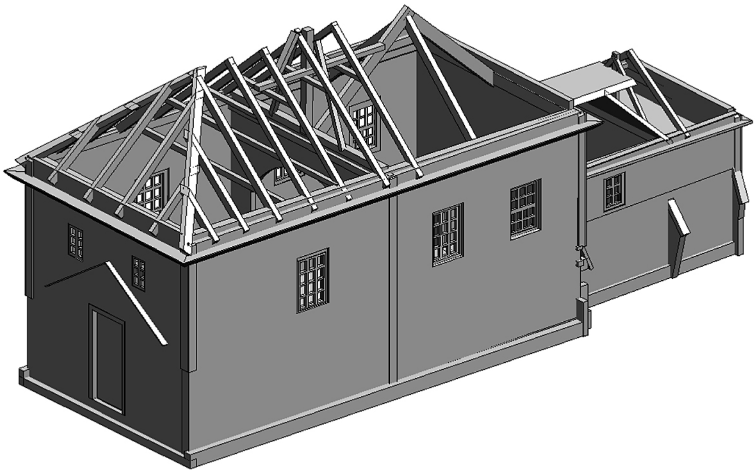


Figure 16. Object structural model from TLS data

such as ornaments, material textures, and exact dimensions, which is critical for preservation endeavours. Lower levels of detail are suitable for rapid visualisations, where the general outline is needed without minor details. This way, the model is more cost-effective and easier to process [8].

Both the TLS (LOD4) and MLS (LOD3) models can be useful in different applications, such as urban planning, heritage conservation, redevelopment, or crisis management simulations. Laser scanning provides high-precision and accurate building representation so that the model can be integrated into other data sources, such as plats or architectural documentation. LOD refer to the geometric and semantic precision of 3D building models, which affects the quality of spatial analyses. Differences between LODs, especially regarding the geometric reference (such as roof height or building outline position), may significantly affect the analytical results of shading, building volume, or building area calculations. Different data acquisition techniques affect model generation on various levels [5].

Modelling at LOD4 using TLS input is particularly relevant to projects where complete knowledge about the object's structure is needed and for heritage objects where preservation of the minutest details is critical for renovation and conservation efforts. Mobile laser scanning turned out to be a very effective tool thanks to its speed, cost-effectiveness, and ability to scan complete objects. Its contribution was particularly valuable in the case of components that were hard to reach, such as the roof truss system, or the dome, which were scanned incomplete due to limited visibility and complexity of the details (Fig. 16). Thanks to its precision, TLS can be used to build detailed architectural models that can be adapted to various LODs depending on the specific application. Still, higher LOD requires integrating TLS into other technologies, such as UAV scanning, for more complete building data [36]. Despite the limitations caused by the inaccessibility of some parts of the building, MLS provided complete spatial data for effective modelling of a significant portion of the building. The technology offers a significant advantage in surveying and design work by providing accurate and detailed data at minimal financial and time costs. Although the MLS cloud had more noise and measurement errors than the TLS cloud and offered a much lower resolution, it still remains a comprehensive and reliable source of data for 3D model building. The main reasons why MLS is growing increasingly popular are mobility and rapid data collection in dynamic conditions, especially in hard-to-reach places. Although less precise than TLS, MLS can reduce data collection time, which cuts operating costs, especially in the case of large projects where time is of the essence [26]. Then again, even though TLS is more expensive and time-consuming, it offers a much greater precision and level of detail, which is critical for projects focused on accuracy, such as heritage surveys [16, 26].

CONCLUSIONS

The results demonstrate that standardisation in 3D building modelling based on various laser scanning technologies is central for the effective development of models adapted to project and

LOD requirements. TLS is best suited for projects requiring a high degree of detail (LOD4) due to its precision and ability to represent intricate architectural details, such as ornaments or roof truss systems. It is particularly important for documenting and restoring heritage objects, where complete representation of the structure and details is the underpinning of conservation efforts. MLS offers rapid and budget surveying capabilities, which makes it the optimal tool for projects on a tight schedule and budget that can settle for LOD3 or lower. Mobile laser scanning can quickly collect data from large areas, including places that are difficult to reach, so it is perfect for dynamic on-site conditions. Practical applications of MLS include rapid building surveying, which can be complemented by details from TLS, yielding comprehensive 3D models.

TLS requires several hours of fieldwork using stationary laser scanning equipment. The resulting point cloud is typically large and dense, requiring specialized software for processing tasks such as optimization, filtration, and unification to retain the desired information while removing extraneous data. Although time-consuming, this process ensures exceptional accuracy, making TLS indispensable for projects requiring high-fidelity models, such as heritage conservation or diagnostic assessments. Mobile laser scanning (MLS), by contrast, offers rapid and cost-effective data acquisition, making it an optimal tool for projects with tighter budgets or schedules that require LOD3 or lower. MLS can quickly collect data from large areas, including hard-to-reach locations, due to its mobility and real-time data acquisition capabilities. However, MLS point clouds often contain more noise and require additional cleaning and filtration compared to TLS data.

Standardisation of 3D modelling based on LOD and integration of TLS and MLS data facilitates better use of the potential offered by both technologies. The data they contribute can be used to generate high-precision models for conservation and heritage visualisation purposes, such as in virtual museums. Such models facilitate better building management and allow the general public to 'visit' digital representations of cultural heritage sites. Moreover, advances in laser scanning technologies and their integration into other tools, such as UAVs, further improve the potential to collect data from places that are difficult to reach. When combined with artificial intelligence algorithms that streamline point cloud post-processing, the modelling process can benefit from more automation, shorter processing times, and more precision. Implementation of such standardised processes allows engineers to complete heritage protection, documentation, and presentation projects more effectively and build 3D models adapted to diverse applications, from conservation to urban planning.

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