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ANALYSIS OF EFFECTIVENESS OF USING 3D SCANNERS IN PREPARATION OF ARCHITECTURAL AND CONSTRUCTION DOCUMENTATION: CASE STUDY OF HISTORIC BUILDING

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Abstract

The article discusses the application of advanced technologies, such as 3D laser scanning, photogrammetry and 3D printing, in the documentation and preservation of historic façades and interiors. These methods are compared with traditional techniques, including manual measurements and casting, highlighting their clear advantages in terms of precision and time efficiency. Digital technologies enable the creation of highly accurate 3D models without interfering with the structure of the objects, thereby minimizing the risk of damage. These models can be used not only for documentation purposes but also for producing replicas of architectural details, which is crucial for cultural heritage preservation. The article also includes an analysis of time efficiency and measurement accuracy, demonstrating that 3D scanning significantly accelerates the inventory process (with a time savings of 70-80%) and provides greater measurement precision compared to traditional methods. These technologies are particularly valuable for heritage sites, where maintaining the integrity of the object and accurately reproducing intricate details are paramount.

Keywords: *3D Laser Scanning; Photogrammetry; 3D Printing; Digitization of Historic Structures; Preservation of Cultural Heritage; Efficiency Analysis*

Introduction

Laser scanning techniques have emerged as a cutting-edge tool widely utilized in the inventorying of heritage objects. This technology enables the rapid and precise collection of geometric data for objects with highly complex forms, preserving both the shape and texture of intricate details. This capability is particularly critical for heritage objects, which demand accurate representation, capturing even the slightest deviations in structural elements and the finest architectural details [1-3]. Traditional measurement methods, such as manual surveying, can be time-consuming and less accurate, whereas laser scanning facilitates data acquisition in significantly less time while ensuring superior accuracy [4].

Scanning is a sophisticated technological process that involves the optical capture of geometric data from physical objects using various types of light waves [5]. This method facilitates the preparation of Building Information Modeling (BIM) or Industry Foundation

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Classes (IFC) documentation [6] and the development of numerical models for structural analysis, based on an accurate representation of the existing state. It enables the acquisition of precise spatial data, allowing for the faithful reproduction of an object's shape, dimensions and details in digital form. During this process, the collected data is stored as a point cloud, which contains coordinates defining the relative position of individual points on the object's surface. Each point in the cloud has clearly defined XYZ coordinates. The point cloud thus serves as the foundation for further work, including the creation of digital 3D models.

After generating a point cloud, it undergoes further processing. The first step is cleaning, which involves removing artifacts—undesirable data that can arise from interference, measurement errors or external factors such as light reflections from smooth surfaces or mirrors. The purpose of cleaning is to eliminate points that could compromise the accurate representation of the object. Once cleaned, the point cloud is converted into a triangular mesh, enabling the creation of a three-dimensional representation of the object's geometry. This mesh model serves as a digital representation of the object, which can be further utilized in engineering, design and technical analyses (Fig. 1).

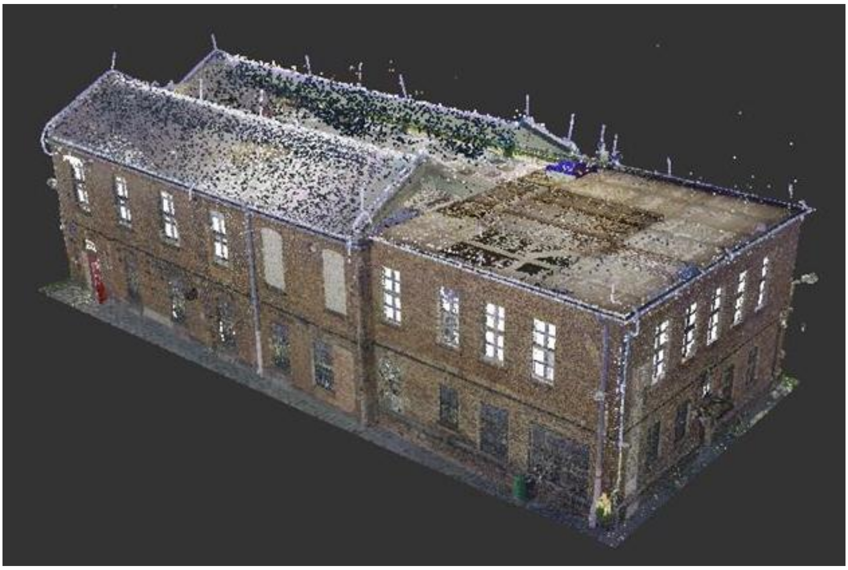

Fig. 1. The point cloud

Scanning techniques are classified into active and passive types, depending on the device used [7]. Active scanners, such as laser scanners (Fig. 2) and structured light scanners, project light onto the object, which is then reflected and captured by the device's sensors. Passive methods, by contrast, rely on ambient lighting and texture features to capture data.

Laser scanners utilize a laser beam, known for its high precision, making them particularly effective for scanning small to medium-sized objects. In contrast, structured light scanners emit light patterns onto the object's surface using an LED projector. The deformations in these patterns determine the object's 3D shape. This technology not only captures geometry but also records the texture and color of objects, which is crucial for scanning artworks, sculptures and other items where visual details are significant. However, structured light scanning has its limitations.

One of the primary challenges is achieving image stability, as the LED projector's light can be sensitive to environmental factors such as ambient lighting, viewing angles and object surface properties. To ensure stable imaging and accurate data capture, precise device handling is essential. Mechanical stabilizers, such as tripods or turntables, are commonly used to maintain controlled scanner movement and image stability. Additionally, fixed reference markers or fiducial markers are often employed to improve scanning accuracy. These markers help with the precise localization of the scanner and the synchronization of data, minimizing errors and enhancing the overall precision of the scanning process.

Fig. 2. 3D scanner Leica RTC360

Passive scanners operate by capturing reflected natural light or infrared radiation without the need to emit their own light. These devices are most commonly used for scanning large-scale objects, such as entire buildings or outdoor environments. The scanning duration depends on the required accuracy level and the size of the scanned object. To achieve high precision in passive scanning, it is often necessary to use reference points or markers, which facilitate correct device positioning and help eliminate spatial reproduction errors.

All 3D scanning technologies enable the acquisition of continuous object imagery, meaning the scanner captures data across the entire surface of the object in a single scan cycle. This approach is more efficient and accurate than traditional measurement methods, which require multiple measurements at different points.

Through 3D imaging techniques, the point cloud serves not only as a visualization tool but also as a fundamental element in the reconstruction of object geometry [8]. This reconstruction is particularly critical in reverse engineering, where the digital model of an object forms the basis for subsequent engineering and design processes. In this context, the point cloud can be used to recreate the original geometry of an object when its documentation has been lost or destroyed. This capability is essential for the renovation or reconstruction of buildings, bridges, machinery or other complex structures.

Point clouds play a pivotal role in the creation of advanced CAD (Computer-Aided Design) models, which form the foundation for subsequent design activities. These models enable engineers, architects and designers to accurately replicate existing objects while also facilitating modifications, optimizations or structural improvements. CAD models are integral to performing stress analyses, allowing the evaluation of how a structure will respond to various loads based on its geometric data. The detailed information provided by point clouds supports the development of more complex analyses, such as computational simulations that predict an object's behavior under different conditions. Additionally, by integrating point cloud data with manufacturing processes, more precise production workflows can be implemented. This includes 3D printing, which allows for the creation of accurate prototypes and replacement parts. 3D scanning has revolutionized the documentation, reconstruction and preservation of objects, proving essential across various fields. In architecture, 3D scanning facilitates the accurate representation of both interior and exterior building components, which is invaluable for renovation, restoration and the design of new structures. This technology simplifies the creation of precise construction plans and detailed technical drawings, serving as a foundation for future modifications and upgrades.

In heritage conservation, 3D scanning has become an indispensable tool for documenting historical structures, enabling the creation of digital archives that can be used for protection and reconstruction if needed [9, 10]. The technology preserves architectural details that might otherwise be lost over time and supports meticulous conservation planning, minimizing the risk of damaging original elements. By capturing intricate features with high precision, 3D scanning helps safeguard cultural heritage for future generations.

In the field of engineering, 3D scanning enables the precise reproduction of not only architectural structures but also machine components, industrial equipment and installations. This capability facilitates technical analyses such as wear assessment, tolerance checks and process optimization. Furthermore, 3D scanning technology is widely used in the creation of virtual environments in industries like video game development, architectural visualizations and animated films. Digital reproduction of objects allows for the realistic creation of interactive environments, where users can navigate and engage with 3D models. Beyond documentation and reconstruction, 3D scanning has become an invaluable tool in planning maintenance actions and analyzing the technical condition of objects. With accurate measurements and 3D models, engineers and assessors can conduct detailed technical audits, identify potential hazards and monitor changes over time. This ability allows for faster detection of issues and the implementation of appropriate corrective actions.

Additionally, 3D scanning aids in creating models for facility management purposes, enabling more efficient management of building maintenance and infrastructure. This technology facilitates systematic inspections, forecasts maintenance needs and supports decision-making based on precise digital data. As a result, 3D scanning significantly improves the efficiency of management and maintenance processes, ensuring better-informed, timely actions to preserve and optimize the functionality of structures and equipment.

Historic Buildings

Historic buildings serve as valuable witnesses to past eras, representing not only places of significant historical importance but also carriers of rich cultural and artistic heritage. Each of these structures embodies unique values that have shaped the urban landscape and reflect the social, technological and aesthetic development of their time. These monuments stand out from contemporary constructions, particularly due to their distinctive styles, which are often the result of various artistic movements of the period in which they were built. In addition to stylistic diversity, these buildings are characterized by exceptional craftsmanship and the use of natural materials, such as wood, stone and brick, which were manually processed and tailored to the specific needs of each project. These traditional construction techniques and material choices contribute to the uniqueness and longevity of these structures, whose design and intricate details continue to inspire admiration.

Every element of a historic building, from intricately carved facades to stained glass windows with vibrant, artistic compositions and hand-crafted woodwork details, exemplifies the highest level of craftsmanship. In the age of mass production, such craftsmanship has become increasingly rare and difficult to find. These remarkable details not only serve aesthetic functions but also form an integral part of the building's history, reflecting its purpose, symbolism and role within the community. In contrast to modern buildings, often designed with a focus on functionality, energy efficiency or minimalism, historic structures are filled with artistic and symbolic ideas that transcend mere practical requirements. Monuments often reflect the ideals of their time and their design and construction aimed not only to express technological progress but also the aesthetic, political or religious ambitions of the societies that built them. As a result, historic buildings hold value not just as functional structures but also as carriers of cultural narratives, passing on to future generations what was most important to those who built them.

A building needs to satisfy a series of strictly defined criteria to be considered a monument, allowing for an assessment of its value in historical, scientific, artistic and social contexts [11]. A key factor in this process is historical value, which is linked to the role the building held in the history of a given region or nation. The building may be associated with significant historical events, such as wars, revolutions or political transformations, which have influenced the shaping of society and its structures. Additionally, scientific value is also crucial—the building may serve as a valuable source of information about construction technology, materials or usage methods of a specific period. Artistic value takes into account the aesthetic aspects of the structure, such as its unique style, architectural details, decorations and the quality of materials used, which are particularly representative of the artistic movements and philosophical ideas of the time.

Another fundamental criterion for assessing a monument is the authenticity of the building, which refers to the preservation of its original form, as well as the original materials and techniques used in its construction. Authenticity ensures that the building not only retains its appearance but also remains true to its original function and history. Valuable monuments are those that have not been significantly altered or modernized in ways that obscure their original character. Preserving original construction techniques, particularly in the context of unique methods and materials, is crucial, as such buildings can provide valuable insights into the development of construction and engineering practices in the past. In some cases, for a building to be considered a monument, it is recommended to preserve as many original elements as possible, such as windows, doors, sculptures or decorative details, which fully reflect the specifics of the given era.

The age of a building is another important factor in the process of designating a structure as a monument, although it is not the only determining factor. Many countries set a minimum age of at least 50 years, below which a building does not yet meet the criteria to be considered a monument. However, this age is not a rigid boundary and depends on the cultural context, region and the specifics of the building in question. There are cases where younger buildings, particularly those with exceptional artistic or historical value, can be recognized as monuments, while older ones that have been altered or damaged due to later interventions may not meet the requirements for protection.

An important aspect that can influence the decision to recognize a building as a monument is its cultural context. The building must have significant importance in the history and identity of the region, being linked to important events that occurred within or around it. This could be a building where key political, social or cultural events took place and its history is closely tied to the local or national memory [12]. Additionally, the building may represent an excellent example of the architectural style of its time, serving as a symbol of the period in which it was built. In such a case, the structure becomes not only a witness to history but also a representative of the artistic and aesthetic values presents in the society that created it.

The maintenance of monuments presents a complex challenge, demanding a careful balance between preserving their authenticity and updating them to meet modern functional and technological standards. Contemporary renovations must consider many factors, such as maintaining the historical integrity of the building, its functionality and ensuring appropriate conditions for use in today's world. The conservation and renovation of monuments become particularly difficult as they often require the use of modern technologies, which must be implemented in such a way that they do not compromise the original materials and structure of the building while also ensuring comfort and safety. It is essential that any intervention in a heritage building be well thought out and minimal so as not to disrupt its historical character.

Another important aspect that must be considered during renovation work is legal regulation [13-15]. Many countries have introduced laws protecting cultural heritage, which impose restrictions on the scope and methods of conservation activities. These regulations ensure proper protection of monuments from irreversible damage while also requiring that all renovation efforts comply with legal and administrative requirements. The need to adhere to appropriate norms and standards makes the renovation process more complex and costly, but it is a crucial element in safeguarding cultural heritage against destruction. In many cases, monuments are also protected at the international level, which further emphasizes the importance of proper legal provisions.

As a result, historic buildings are no longer merely static monuments of the past; they become living witnesses of history, which, through appropriate preservation and conservation, can continue to be used and appreciated by future generations [16]. They are also an important source of inspiration for contemporary architects and designers who draw ideas from them related to aesthetics, construction techniques and spatial concepts. The value of monuments goes beyond their role as museum objects – they are an integral part of the identity of local communities and an inspiration for creators seeking to combine modernity with respect for the past. Therefore, historic buildings remain not only monuments of bygone eras but also serve a cultural and educational function, influencing contemporary society and its approach to history, architecture and heritage protection.

The analysis of the effectiveness of using 3D scanners in the preparation of architectural and construction documentation in this paper was carried out using the example of the building at 41 Piotrkowska Street in Lodz (Fig. 3).

Fig. 3. The tenement at 41 Piotrkowska Street in Lodz

The building at 41 Piotrkowska Street in Lodz is a unique testament to the architectural transformations that took place in the 19th and 20th centuries. Its history dates back to the 1840s, when it was initially built as a wooden house by Andrzej Matz. This structure was typical for the early stage of Lodz's urbanization. At the time, like other buildings from this period, it was a simple, functional structure with minimal architectural complexity. However, the changes that occurred in the second half of the century perfectly illustrate the urban and social transformations of this rapidly developing city.

In the latter half of the 19th century, Wilhelm Matz decided to replace the wooden building with a masonry, single-story house, marking a shift towards a more durable and modern construction. This change was a response to the growing spatial needs and the push to modernize the city's architecture, as Lodz was undergoing intense industrial and urban growth. In the 1870s, in response to the increasing demand for housing, the building was transformed into a two-story tenement, reflecting the growing importance of the location and the need to adapt buildings as the city's population and development increased. This period also saw the emergence of multi-story tenements, which became characteristic of Lodz's urban layout.

Another significant change occurred in 1903, when the new owner, Robert Weyrauch, carried out a further renovation, adding a third floor and a rear wing, which transformed the building's character and gave it a modern, multi-story form. This adjustment responded to the growing housing demands and the development of the textile industry, which not only required more workers but also needed additional living spaces for the increasing number of city dwellers. These changes, both in terms of function and architectural form, highlight the evolution of Lodz's architecture, transitioning from simple wooden houses to more complex, multi-story masonry tenements, which had become the standard in the city's architecture by the end of the 19th and early 20th centuries.

The transformations of the building at Piotrkowska 41 illustrate how the city's rapid growth influenced the shaping of residential and urban spaces. The increase in population and the expansion of the textile industry required adaptations to the existing buildings. Tenements became a symbol of Lodz's development as one of Poland's major industrial centers while also standing as witnesses to the social and architectural changes that shaped the city's face in the 19th and 20th centuries.

Sculptural Details

Laser scanning technology, including LiDAR, photogrammetry, handheld laser scanners and 3D printing, significantly enhances the process of generating 3D models of historic façades adorned with intricate sculptural details [17]. These methods are primarily valued for their high level of non-invasiveness, which is crucial when working with heritage structures where preserving the integrity of the object is of utmost importance. Compared to traditional techniques, such as hand-casting plaster molds, digital technologies offer significant reductions in both time and cost. While traditional methods involve physical contact with the surface and carry the risk of damage, laser scanning and photogrammetry eliminate the need to physically touch the original, offering precision at the micron level, which is nearly impossible to achieve manually.

The models generated through scanning can serve not only for documentation but also for producing casts. The use of SLA (Stereolithography) 3D printers enables the creation of highly detailed forms that can then be used to make replicas in plaster or resin, a process that is less time-consuming and more repeatable than manual modeling. This method also allows for the digital archiving of architectural details, which is essential for the protection of cultural heritage. If the original decorations are damaged, the digital models can be used as a basis for accurately recreating details, something traditional plaster casts may not always guarantee due to form degradation over time. Thus, this technology becomes not only a tool for creating replicas but also a safeguard of cultural heritage.

Analysis of Efficiency

The efficiency analysis was carried out using the inventory of the tenement house located at 41 Piotrkowska Street in Lodz (Fig. 3). The inventory process included the creation of a floor.

Time Efficiency

The inventory process included the creation of floor plans, cross-sections through all staircases and elevation drawings (including the front façades with intricate stucco details). The first aspect analyzed was the time efficiency of traditional architectural and construction inventory methods versus 3D scanning technology using laser scanners. Traditional documentation, which involves manual measurements with a tape measure and rangefinder, is time-consuming, especially in historic buildings with complex geometry and hard-to-reach elements. Measuring a façade requires repeated movement around the building, the use of scaffolding or lifts and photographic documentation. For a medium-sized building, this process typically takes between two and five working days for a two-person team.

For interiors, such as apartments, service spaces or common areas (corridors, staircases), the traditional inventory method involves individual measurements of each room, walls, door and window openings, installations and other permanent features. This process is particularly time-consuming in buildings with complex layouts, where measurements must be carefully adapted to irregular room shapes or unique architectural details. Traditional inventory for a 50 m² apartment usually takes between four and six hours, with larger and more complex spaces, such as service units or apartments with unconventional layouts, possibly requiring up to two full working days. Additionally, traditional methods require manually transferring the measurements to design software, introducing the risk of errors and further extending the project timeline.

3D scanning technology addresses these issues by significantly reducing the time required for data collection and increasing precision. In the study, two Leica scanner models—RTC360 and BLK360 G2—were used to comprehensively document the historic building. The RTC360 scanner was used for the exterior façades, requiring only 15 measurement stations and allowing for full façade documentation in just two hours. For interiors, which had many rooms and intricate architectural details, the BLK360 G2 scanner was used, requiring a total of 677 measurement stations. Of these, 35 stations were added to fill in missing data due to limited access to certain rooms or areas. Thanks to 3D scanning technology, the entire interior was recorded in just four working days. The data processing, which included point cloud refinement, artifact removal and filling missing fragments, took an additional day, while the creation of the full technical documentation took five working days. This resulted in a total of ten working days for completing the building's full 2D documentation. In comparison, a full traditional inventory would take at least thirty working days, excluding any corrections due to measurement errors.

3D laser scanners, through point cloud registration, enable quick and precise capturing of both large surfaces and details. Building façades, regardless of their complexity, can be documented in just 5-10 minutes per measurement station, which practically allows the entire façade to be recorded in a few hours. For interiors, data registration for a typical 50 m² apartment takes no more than an hour, while larger service units can be scanned within a few hours, without the need to move furniture or make additional preparations. Moreover, 3D scanning eliminates the time-consuming process of manually transferring data – point clouds can be automatically integrated with BIM and CAD systems, enabling immediate use of data in the design process.

The use of 3D scanning technology brings clear benefits not only in terms of time savings but also in improving the precision of the documentation. In historic buildings, where detailed reproduction of structural elements and architectural details is crucial, laser scanners allow for capturing elements that are often overlooked or insufficiently accurate in traditional measurements. The analysis clearly indicates that 3D scanning is particularly effective in cases of objects with complex spatial layouts, requiring comprehensive documentation with high precision.

Measurement Accuracy

Drugim The second aspect analyzed was the measurement accuracy. To assess this, different ceilings and walls in the aforementioned tenement building (Fig. 3) were compared. The point cloud data collected with the scanners (Figs. 4 and 5) was compared with manual measurements obtained from architectural inventories conducted in 2019.

It is important to note that accurately measuring the ceiling using traditional methods is quite complex. Simplifications are typically made, which do not account for the thickness of plaster layers or finishing coatings. In architectural inventory, actual dimensions of elements should be considered, rather than applying a generalized estimate of ceiling thickness across all sections.

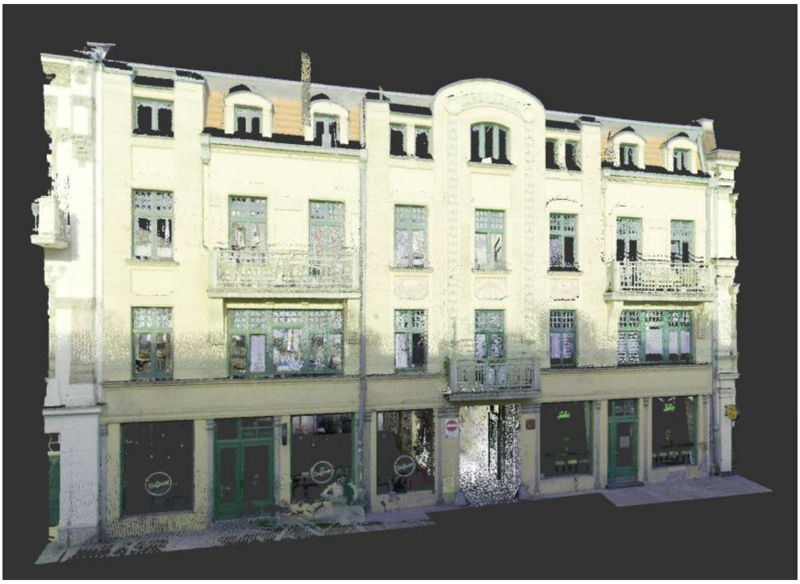

Fig. 4. The point cloud of the front elevation of the tenement house at 41 Piotrkowska Street in Lodz

Fig. 5. The point cloud of the interior elevation of the tenement house at 41 Piotrkowska Street in Lodz

Due to the size of the building, the 3D scanning was carried out in multiple stages. Each stage involved scanning one floor. The last scan for a lower floor was done on the landing between that floor and the next. Then, the scan for the next floor began from the same measurement position (without moving the scanner). This process allowed for the precise connection of scans from each floor during data processing, using the same position, which served as both the starting point for the scan of the upper floor and the ending point for the scan of the lower floor.

Standard deviation and mean value are the primary tools used in statistics to evaluate measurement accuracy. The mean value indicates the average of a sample, while the standard deviation shows how much the data points deviate from the average. Together, these two measures provide a comprehensive picture of the data – both its central tendency and the degree of dispersion.

In the context of ceiling thickness measurements, the standard deviation of the differences obtained using traditional methods and 3D scanning was 5.17cm, with an average difference of 13.28cm (Table 1). Such a significant difference, averaging 13cm, has a substantial impact on the strength parameters of the analyzed elements. For example, a ceiling with a thickness of 45cm demonstrates significantly higher load-bearing capacity compared to a ceiling with a thickness of 30cm, which directly influences the structure's ability to withstand dead and live loads.

Table 1. Measurement results of ceiling thicknesses

No.	Ceiling thickness – manual measurement [cm]	Ceiling thickness – laser measurement [cm]
1	45	30.5
2	46	48
3	40	29.5
4	50	34.5
5	45	30
6	45	34.5
7	45	28
8	50	36
9	45	22.5
10	45	27
11	45	25
12	45	26.5
13	40	29.5
14	30	18
15	39	32
16	38	23.5
17	30	24
18	45	34

A high standard deviation value indicates a significant spread in the obtained results, which clearly proves that traditional methods do not provide sufficient measurement precision. The lack of accuracy leads to the use of averaged ceiling thickness values during the inventory process. Such assumptions may result in incorrect assessments of load-bearing capacity and structural strength in the future, which, in turn, poses a potential risk of failure, especially considering that ceilings in historic buildings are often around 100 years old.

During the measurement of the thickness of internal walls, the standard deviation of the differences between the traditional method and 3D scanning was 2.88cm, while the average value of these differences reached 2.40cm (Table 2).

The results obtained using the laser scanner are significantly more accurate, which is especially important in the case of tenement houses, where measurement discrepancies can reach several centimeters. Precise measurements with a laser scanner allow for estimating the material of the wall without making any boreholes. Based on the thickness and geometric features, combined with knowledge of construction techniques, it is possible to determine the wall's composition while maintaining the integrity of the historic structure.

Table 2. Measurement results of internal walls

No.	Internal wall thickness – manual measurement [cm]	Internal wall thickness – laser measurement [cm]
1	34	39.5
2	14	9
3	10	7.5
4	48	47.5
5	34	33
6	8	7
7	12	13
8	34	40.5
9	45	52
10	18	18
11	53	49.5
12	37	40.5
13	66	69.5
14	30	30
15	34	34
16	12	9.5
17	32	33.5
18	32	34
19	48	49
20	12	11.5

In buildings of this type, often featuring high rooms that can reach up to 4 meters, even small deviations in the thickness of partition walls can lead to significant differences in their weight. This, in turn, affects the loads that must be considered in structural analyses. It is important to emphasize that tenement houses, being older buildings, are more susceptible to degradation, which increases the risk of structural failures. Therefore, accurately determining the weight of partition walls becomes crucial for assessing their impact on the safety of the entire structure.

Conclusion

The article analyzes modern technologies used in the inventorying and conservation of historical monuments, with a particular focus on 3D laser scanning, photogrammetry, handheld laser scanners and 3D printing. The use of these technologies significantly enhances the process of creating 3D models of historic facades, enabling precise reproduction of stucco details while minimizing the risk of damage to original objects. Compared to traditional methods, such as manually creating plaster casts, digital technologies allow for significant savings in time and costs while maintaining high measurement accuracy.

The temporal efficiency of 3D scanning was examined, highlighting its advantage in the inventorying process, enabling the rapid and accurate reproduction of details on historic facades, both external and internal. Thanks to integration with BIM and CAD systems, data obtained through scanning can be immediately used in the design process, eliminating the risk of manual errors. These technologies also allow for the creation of digital archives of details, which can be used in the future to reconstruct damaged elements.

The accuracy analysis of the measurements showed that 3D scanning provides smaller deviations in the measurements of wall and ceiling thickness, which is crucial in assessing the stability of historical buildings. The findings from the analysis indicate clear benefits from using modern digitization methods in conservation work. These technologies not only streamline inventorying processes but also improve the quality of cultural heritage protection, serving as an indispensable tool in heritage management.

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