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TOOLS FOR THE KNOWLEDGE OF THE BUILT HERITAGE

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DIGITALIZATION OF EXISTING BUILDINGS TO SUPPORT RENOVATION PROCESSES: A COMPARISON OF PROCEDURES

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Abstract

The low energy efficiency in our built environment underscores the urgent need to renovate existing buildings and implement cost-effective interventions. Increasing end-user awareness and providing a clear framework for efficient workflows for professionals to widely adopt renovation best practices is critical. Digital technologies are crucial in this context, as they streamline the renovation process by reducing time, costs, and errors and improving interoperability. A major application of these technologies in the Architecture, Engineering, and Construction (AEC) sector involves organising data into digital models that can manage various process stages, from planning to monitoring. The initial data collection on existing buildings is essential, yet current methods are often expensive and time-consuming. Although research has explored the trade-off between accuracy and feasibility in data acquisition and processing, a balanced approach that considers the affordability of survey methods and the effectiveness of the resulting data for further modelling has yet to be finalised. This study compared three data acquisition and processing strategies based on their limitations, potential, and requirements for BIM-based digital modelling. Despite some limitations in detailed roof and façades geometrical modelling, all methods were suitable for energy performance simulations. Results provide insights into optimising digital acquisition methods for large-scale renovations.

Keywords

Existing building, Retrofitting, Data acquisition, Data processing, 3D modelling.

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1. INTRODUCTION

Despite global efforts to address climate change, the building sector remains one of the most impactful in terms of emissions and consumption. It is widely recognized that the renovation of existing buildings, often poorly performing, is one of the possible actions to achieve pursued targets [1]. The adoption of digital tools and procedures in the Architecture, Engineering and Construction (AEC) sector not only offers potentially significant advantages but is also progressively becoming imperative [1–5]. In this context, Building Information Modelling (BIM) plays a pivotal role, thanks to the benefits it potentially offers to various stakeholders in the AEC industry [3–6].

While the time is ripe for its adoption at the professional level in designing new buildings, its use in renovation projects is still constrained by several limitations

[3, 6–14]. One of the key reasons for the gap between BIM applied to new and existing assets is the difference in the management of data and information used as input to create virtual models. In the former case, established standards are clearly defined for each project phase, both by formal regulations and community common practice. At the same time, it is more difficult to adopt these standards for representing existing assets [6, 10]. Indeed, available data does not always meet modelling requirements (e.g., density, metric reliability, geometric accuracy, visual fidelity [18]) that depend on models' goals, i.e., documentation and reconstruction, simulation, design, and the monitoring of various interventions (e.g., energy efficiency, structural integrity, valorisation).

Given the wide range of potential input data and the need to avoid information redundancy, it is essential to clearly define the model's purpose from the outset [6, 11, 12]. For the construction of a three-dimensional model, geometrical information is always necessary but required features and accuracy change consistently with modelling goals. So far, the level of development, detail, and accuracy have been the object of interest of many studies and regulations. Semantic and volumetric reconstruction is necessary to carry out performance evaluations [12], while a more detailed representation of complex geometries can be necessary for philological documentation [6, 7, 15], executive design of interventions [1, 10, 16, 17] or for running Life Cycle Assessments [11].

Many researchers have explored innovative technologies and methodologies for acquiring three-dimensional point clouds finalised to build virtual models [7–9, 14–17, 19–23]. These include range-based, i.e., terrestrial or mobile laser scanners [6–9, 14, 15, 19, 22] and image-based systems, i.e., terrestrial and aerial photogrammetry [9, 14–16, 20–23]. At the current state, terrestrial laser scanners are recognized for their accuracy [7, 8, 14, 16], despite their high cost and procedural constraints have spurred interest in mobile lasers [19, 22] and photogrammetric solutions, which offer dynamic and fast data acquisition, but with some trade-offs in precision [12, 20, 21, 23].

Two key insights from the above-mentioned studies are worth focusing on: the potential for integrating different acquisition systems to overcome specific constraints without compromising the usefulness of data for defined purposes [9, 15, 18, 23] and the necessity of having a systematic methodology aimed at balancing accuracy with feasibility under real-world conditions [18]. However, cited studies mostly focus on one of these aspects at a time, typically acquisition [7–9, 14, 16–23] or modelling issues [3–6, 10–13, 24], then taking both into account can bring a valuable contribution to achieving convergence.

This study contributes to examining these issues by comparing the results obtained from an experimental survey campaign and assessing their relevance for the construction of a BIM-based model. This work examines such models with a view to simulating current and predicted energy performance and design interventions. Tests included the investigation of a case study (acquisition and processing of geometric data) following three different strategies and the construction of an as-is model in a BIM environment. The tested strategies were therefore evaluated according to the appropriateness of the results for developing an effective model and their cost-effectiveness and timeliness. The illustrated experimental activities have been conducted within the European project ARV, aimed at defining and validating strategies based on digital procedures to support renovation processes.

The paper is organised as follows. In Section 2, tested strategies for the digitalization of existing buildings and the case study are described. Section 3 illustrates, compares and assesses the results of the strategies applied to the case study. Finally, Section 4 brings together conclusive considerations on tested strategies and outlines future research developments.

2. PHASES, MATERIALS AND METHODS

Three different strategies (S1-S3) were tested on a representative case study to compare their feasibility and the suitability of their results for the investigation of current energy performance. The common trait of the three strategies lies in the potential benefits they offer to the users, as their implementation is expected to be more cost and time-efficient than traditional methods.

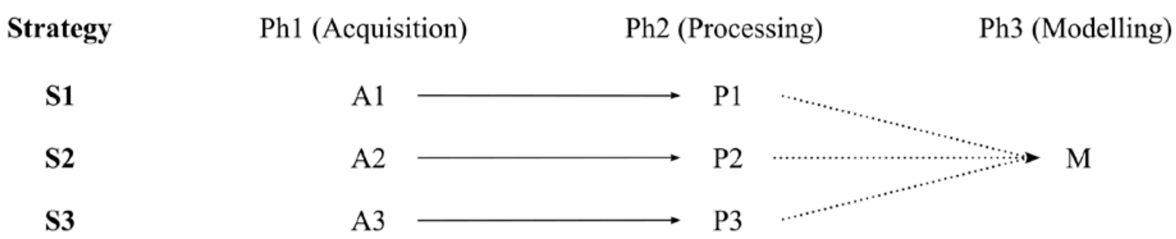

Fig. 1. *A scheme showing the relations among tested Strategies (S1, S2, S3) for Acquisition (A), Processing (P) and Modelling (M). Source: © 2023, the research group.*

This study is subdivided into three main phases, as depicted in Figure 1, where the first two phases belong to and characterise the application of each strategy (Section 2.2), namely:

- a first phase (Acquisition, Ph1), where the data necessary to reconstruct the building geometry are acquired through scans and pictures;
- a second phase (Processing, Ph2), where acquired raw data are processed, separately or combined, to obtain three-dimensional point clouds of the external surfaces of the building. After defining the necessary requirements linked to the model goals, the suitability of acquired and processed data is then assessed;
- in the third phase (Modelling, Ph3), the data collected in the previous two phases that complied with the defined requirements are finally assembled into a BIM environment (Section 2.3). In this phase, several tests are carried out to verify the suitability of the exported three-dimensional model for running energy simulation.

2.1. THE ARV CASE STUDY

A residential building was chosen as a case study to perform its digitalization in a BIM environment. The case study is one of the six demonstration cases developed in the ARV H2020 European project, which aims to create climate-positive circular communities and increase the building renovation rate in Europe. The Italian demonstration project consists of the renovation of a private residential building located in Trento, in northeastern Italy (Fig. 2). It is a T-shaped three-story building occupying an area of 254 m², surrounded by a courtyard. It houses nine independent units and their unheated ancillary spaces (cellars and attics). The elevation of the north wing of the building starts from the ground floor, while the other part includes a lower basement and is staggered in height by half a floor. The outer walls have plaster finishes, while the northern wall presents some stones slightly protruding from the flat surface. Balconies protrude from the south and the west façades, while the north and east façades feature single and double-hung windows of various sizes. The structure is made of concrete and stone, and there is no insulation between the interior and the

Fig. 2. *An aerial view of the case study (left) and a view of the northeast side (right).*

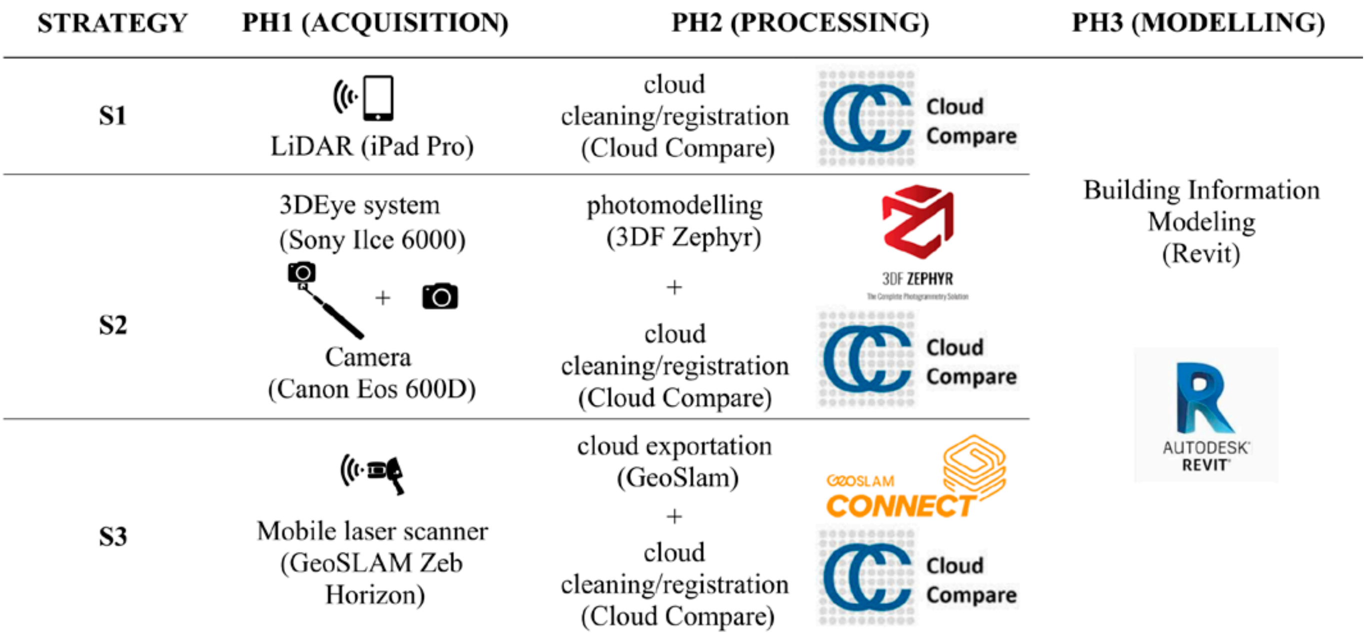

Fig. 3. *The scheme shows adopted tools tested for each strategy (S1, S2, S3). Source: © 2023, the research group.*

unheated rooms or between the interior and exterior of the building. The heating and cooling systems are independent for each apartment, and the windows were recently replaced in two of the nine units.

The retrofit solution involves the use of a prefabricated wood-based modular system, designed as a retrofit kit to enhance the energy efficiency, indoor comfort, and architectural aesthetics of the existing building and applied on the east and north façades for demonstration purposes [24, 25]. The manufacture and installation of the prefabricated panels require very accurate geometrical reconstruction of the building's shape to ensure proper fit [16, 17, 24]. A functionally equivalent ETICS system is applied on the other walls.

2.2. STRATEGIES APPLIED TO THE CASE STUDY

In the following paragraphs, the methods adopted for the first two phases (Acquisition and Processing) of each strategy are described, and an overview of tools (Fig. 3), costs and time is provided. Building characteristics such as size, shape, and context were considered when planning the acquisition activities. To obtain reference points valid for all the strategies necessary for processing and comparing other acquired data, 100-point coordinates on the existing building surfaces were preliminary recorded through a total station (Topcon GPT 1001). In addition, the contractor provided a dense cloud obtained from the combination of a TLS cloud and a cloud from photo-modelling through an unmanned aerial vehicle photo. At the end of the processing phase (second phase), for each strategy, different outputs have been imported into Cloud Compare free software using the coordinates of the topographic points as references.

2.2.1. POINT CLOUD FROM LOW-COST LIDAR SCANS (S1)

The first tested strategy consists of acquiring building external surfaces with LiDAR (Light Detection and Ranging) scanning technology. This one has been recently developed [14, 19] also into everyday devices [23], making it accessible in terms of costs and ease of use.

The LiDAR technology of an iPad Pro was used to acquire scans through a free application, Scaniverse, that allows objects of different sizes to be scanned. The maximum distance for scanning is 5 m for large objects (building portions) and 2 to 5 m for small objects (e.g., windows, details, etc.). The costs associated with instruments only included the purchase of the iPad. Since the building is taller than 5 m, a lifting platform was necessary to reach the second and third floors from an adequate distance. Including tests, 30 scans were acquired for each level, and each scan represents a portion of the

Fig. 4. *The acquisition phase with iPad Pro from the lifting platform (left). An overview of acquired scans (right). Source: © 2023, the research group.*

existing building, overlapping with those of surrounding portions (Fig. 4).

Single scans, exported from the app in .las format, were imported into Cloud Compare, and 9 of them were selected. They were aligned to the topographic points with a semi-automatic procedure that implies the recognition of at least 3 reference points. Aligned clouds were cleaned through segmentation and noise reduction and then joined into a single cloud. Cloud alignment and cleaning are semi-automatic procedures. The processing time depends on the number of scans and, therefore, on the building size. There were no costs related to the use of software in the acquisition and processing phase since tests are carried out with free apps and software (Scaniverse, Cloud Compare).

2.2.2. POINT CLOUD FROM PHOTOGRAMMETRY (S2)

The second strategy involves the acquisition of pictures of the building and their use for three-dimensional photo-modelling. The ease of purchasing acquisition tools (cameras) makes this solution appealing for widespread diffusion. Two sets of tools were used for the acquisition of photos:

- 3DEye system, composed of a 9 m telescopic pole, a mirrorless camera (Sony Ilce 6000), a gimbal device to control camera orientation and stabilisation, and a tablet to control framing and shooting from the ground level. This system allows the acquisition of photos of the external walls of the entire building from a distance of about 2 m and different orientations;
- Reflex camera (Canon Eos 600D), used from the ground level and a lifting platform, which allowed acquiring photos of entire facades from different perspectives.

The costs related to instruments involved the purchase of 2 cameras and the auxiliary devices to use the telescopic system (telescopic stick, gimbal, and tablet). Through the 3DEye system, a set of 960 detailed photos was acquired from the ground level (Fig. 5), and a set of 142 context photos was acquired through the reflex camera from the ground level and the lifting platform.

The 3DF Zephyr software by 3DFlow was used to generate a point cloud through a photogrammetric process. All the context photos and 802 from the detailed ones have been selected, considering that overlapping between photos is necessary for the software to correctly reconstruct the position of the cameras. After importing them into the software workspace, 50 reference points, coinciding with topographic points, were identified on each photo to generate the scattered cloud. Then, the 50-point coordinates from the topographic survey were inserted to correct camera positions and generate the dense cloud. Processing time depends on the number of photos and the building size since individuating reference points is a manual procedure. Processing costs involved the purchase of the software licence.

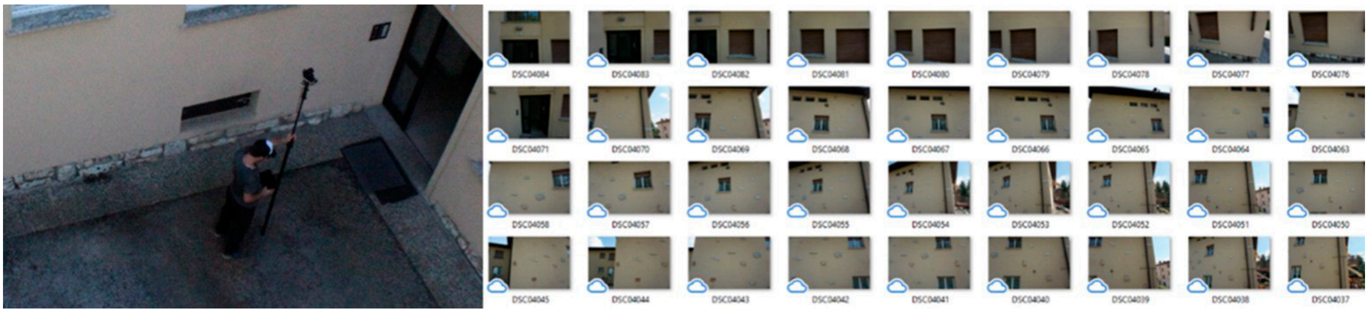

Fig. 5. *The acquisition phase with the 3DEye system (left). An overview of acquired photos (right). Source: © 2023, the research group.*

2.2.3. POINT CLOUD FROM SLAM (S3)

The third strategy consists of adopting the SLAM (Simultaneous Localization And Mapping) scanning technology to record building geometric features. This technology permits obtaining point clouds comparable to TLS ones for density and accuracy without the constraint of a static, slow acquisition [14, 19]. Theoretically, these devices can acquire points up to 100 m distant, but the loss of precision increases with distance and the cost of these tools is still relatively high.

A portable dynamic and georeferenced device by GeoSLAM, Zeb Horizon (provided by Semprebonlux s.r.l.), was used for the acquisition of a single scan from the ground level and the lifting platform (Fig. 6), but since the building height is about 12 m, it could have been scanned entirely without using the platform.

Once acquired, the scan was exported from GeoSLAM software in .las format and imported into Cloud Compare free software as a point cloud. Then, it was aligned with topographic points and cleaned. Processing costs include purchasing a licence of compatible software to export the acquired cloud.

2.3. POINT CLOUDS REQUIREMENTS FOR ENERGY AND GEOMETRICAL MODELLING

After transferring raw data into a digital environment as point clouds, the third phase (Modelling, Ph3) started. Firstly, it was assessed that collected data matched specific requirements consistently with the model goals. In particular, their functionality for the following goals was tested:

(a) transfer to an energy analysis software (e.g., Design Builder) for as-is and post-intervention simulations;
(b) design of the renovation intervention through prefabricated panels.

Geometrical and informative modelling carried out in Revit followed some well-established steps outlined by several works [4, 8–10]:

i) insertion and localization of topographic and point cloud in Revit;
ii) creation of the levels using the cloud as a reference;
iii) insertion of perimeter walls using the cloud as a reference;

Fig. 6. *The acquisition phase of the north façade with GeoSLAM Zeb Horizon from the ground floor photos. Source: © 2023, the research group.*

iv) insertion of the roof by tracing the cloud;
v) insertion of openings and balconies on the façades using the cloud a as reference;
vi) creation of internal subdivision, slabs and walls separating units;
vii) insertion of room entities that define the volume and use of the different spaces;
viii) insertion of information on installations for each unit, i.e., heating or cooling plants;
ix) insertion of information on stratigraphy for each type of object inserted into the Revit model (e.g., walls, floors, windows, roofs), i.e., layers thickness and related materials thermal properties (density, thermal conductivity, emissivity);
x) building localization and orientation.

Steps i) to v) are needed for both goals (a) and (b), but different levels of detail and accuracy are required for the two purposes. In fact, too many details in the geometric reconstruction typically led to errors in the transmission of surfaces and volumes from the BIM software to the energy analysis software (a) [4, 15]. In this case, an orthogonal grid can be traced from the cloud and used to obtain a simplified volumetric model, making the millimetre accuracy of the cloud scarcely meaningful. Conversely, in order to be useful for the design of the intervention through prefabricated elements (b), the model must have reliable geometry of the external surfaces, including out-of-plumb, bulging, and non-perfectly orthogonal angles. In this case, the positioning of openings, balconies, pipes, and other elements protruding from the façade must have a maximum error of a few millimetres (1σ 4mm-7mm), as explained in [16, 17]. Therefore, external surfaces and openings should be modelled using the cloud as a reference only if it satisfies strict correspondence with the existing building. In this study, the obtained clouds are evaluated, considering the levels of geometric accuracy consistently with both (a) and (b) goals.

Finally, all the steps, including the insertion of non-geometrical information (vi-x) deduced from a technical report, are necessary for the building energy modelling and simulation (a).

3. RESULTS

In this Section, the results obtained through each of the three strategies are illustrated in terms of:

- resulting cloud features, i.e., number of points, medium density, minimum and maximum distance from the topographic survey and the reference cloud, measured through the Cloud-to-cloud function of Cloud Compare (as summarised in Tab. 1);
- cost-effectiveness, using quantitative indicators such as costs of the instruments and software, processing time and ease, and suitability of outputs for modelling with both (a) and (b) purposes (as summarised in Tab. 2).

Strategy	Raw data	Dimension	Medium density	Min. distance	Max. distance	Standard deviation 1σ
	-	[points]	[points/m]	[mm]	[mm]	[mm]
S1, LiDAR cloud (iPad Pro)	30 scans	5.707.700	20.465	d = 3,0	D = 27,4	90
S2, photogrammetry cloud (3DEye system + reflex)	944 photos	1.835.233	15.216	d = 5,8	D = 98,3	65
S3, SLAM cloud (GeoSLAM Zeb Horizon)	1 scan	45.492.604	270.147	d = 2,1	D = 30,0	50

Tab. 1. *Comparison of clouds obtained through the tested strategies.*

Strategy	Cost*	Acquisition time	Processing time	Modelling suitability	
	[€]	[hours]	[hours]	(a)	(b)
S1, LiDAR cloud (iPad Pro)	1.000/ 1.500	1 (ground level) 2,5 (lifting platform)	0,25/cloud (alignment)	Yes (no roof)	No (yes ground attach)
S2, photogrammetry cloud (3DEye system + reflex)	4.000 + softwar e	1 (ground level) 2 (lifting platform)	more than 16 (ref. points individuation)	Yes (no roof)	No
S3, SLAM cloud (GeoSLAM Zeb Horizon)	15.000/ 60.000	0,5 (ground level + lifting platform)	0,25/cloud (alignment)	Yes (no roof)	Yes (no roof)

* Reported costs are relative at the time of writing. The values are indicative and are given to compare tested strategies.

Tab. 2. *Comparison of costs, acquisition and processing time and modelling suitability related to the tested strategies.*

3.1. POINT CLOUD FROM LIDAR SCANS (S1)

In Figure 7a, the main results obtained through S1 are reported in terms of cloud visualisation. As can be seen, the acquisition obtained with the LiDAR incorporated in iPad Pro allowed the generation of a sufficiently homogeneous cloud (Fig. 7b) that fits well into the topographic survey boundaries. Some portions are less accurate, namely, those scanned from farther than 5 m, those strongly exposed to bright light or backlighting during the acquisition procedure, and large homogeneous areas, such as plaster-finished surfaces. The comparison with the TLS cloud (Fig. 7c) shows that lying planes are not always unique and perfectly straight, mainly due to a lack of reference points.

This strategy proved to be successful in the acquisition from the ground level and narrow spaces, thanks to the ease of handling the device. Scanning distance from the object, lack of reference points on the surfaces, and lighting conditions influenced the density and accuracy of the clouds. Reflecting objects, such as metal and glass, were not appropriately acquired. Instead, proper three-dimensional reconstruction is guaranteed for surfaces rich in detail or three-dimensional references, as seen for the grounding or in the presence of objects protruding from flat surfaces, such as stones on the north façade.

Scanning the upper levels from the lifting platform did not lead to high-quality results due to difficulties in manoeuvring and, therefore, control scans and overlapping. However, acquisition times were relatively fast (less than 1 hour to scan the first floor and about 2.5 hours for upper levels) compared to a traditional static survey (TLS or topographic survey). It took about 30 minutes per scan, resulting in about 4.5 hours to obtain the final single-point cloud.

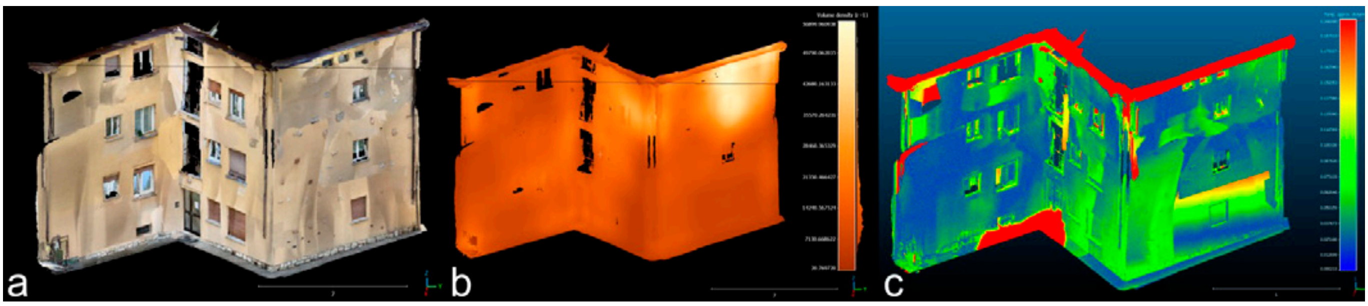

Fig. 7. *(a) The point cloud of the northeast façades obtained through iPad Pro scans; (b) the cloud density distribution; (c) the cloud compared with TLS cloud, with the closest points highlighted in blue. Source: © 2023, the research group.*

3.2. POINT CLOUD FROM PHOTOGRAMMETRY (S2)

In Figure 7a, the main results obtained through S2 are reported in terms of cloud visualisation. The generated dense cloud fits into the topographic survey boundaries; however, it is sparse, and its density is not homogeneously distributed (Fig. 8b). The minimum and maximum distances from topographic reference points have a remarkable gap because the cloud is very sparse in some points and therefore difficult to compare with the topographic cloud.

Some areas are more scattered and correspond to those strongly exposed to bright light and backlighting during the acquisition procedure and to those for which positions were not correctly reconstructed for lack of reference points (Fig. 8a). In general, many pictures acquired from different perspectives provided a correct three-dimensional reconstruction of the object. By combining both sets of photos – context and detail – the density and accuracy of the clouds were optimised. The comparison with the TLS cloud showed that the planes reconstructed through photogrammetry are almost straight (Fig. 8c).

The influence of lighting conditions, reflecting objects, and reference points on density and accuracy are also valid for this strategy. Indirectly, the distance from the object also influenced the resulting clouds since as the distance increases, the resolution of photos and cloud density decreases. However, even if the obtained cloud is relatively sparse, photogrammetry allows for obtaining a cloud with straight planes for façades. Therefore, this technique is reliable for reconstructing the building's geometric features.

In addition, the acquisition of photos through a telescopic system has fewer physical constraints than traditional or mobile scans. Therefore, it is possible to acquire data on slightly taller objects (9-15 m). Acquisition times were relatively fast compared to a traditional static survey (TLS or topographic survey). Including 3DEye telescopic stick handling around the entire building for each floor, the acquisition of both sets took about 1 hour for the ground level and about 2 hours for the upper levels. Processing times required more than one day because it included many tests, and since cloud density and accuracy depend on the number of photos used for the photogrammetric reconstruction, but processing time increases with the number of photos.

3.3. POINT CLOUD FROM SLAM (S3)

In Figure 9a, the main results obtained through S3 are reported in terms of cloud visualisation. The acquisition through a SLAM device allowed obtaining a cloud that fits well into the topographic survey boundaries and ho-

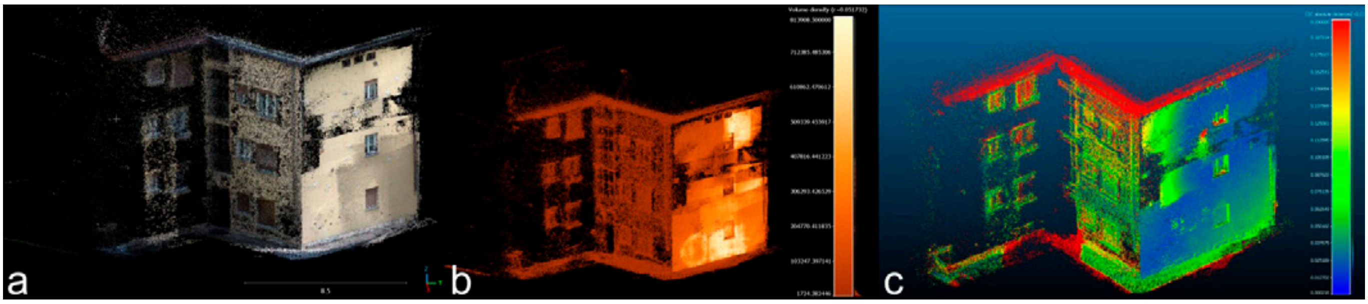

Fig. 8. *(a) The point cloud of the northeast façades obtained through photogrammetric reconstruction; (b) the cloud density distribution; (c) the cloud generated with photogrammetry compared with TLS cloud, with the closest points highlighted in blue. Source: © 2023, the research group.*

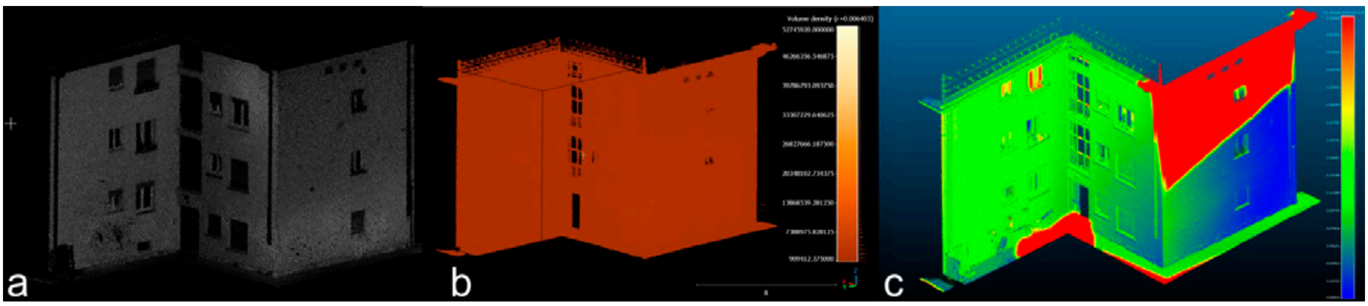

Fig. 9. *(a) The point cloud of the northeast façades obtained through SLAM scanning; (b) the cloud density distribution; (c) the cloud acquired with GeoSLAM Zeb Horizon compared with TLS cloud, with the closest points highlighted in blue, the farthest in red. Source: © 2023, the research group.*

mogeneously dense (Fig. 9b). As shown in Figure 9c, the comparison with the TLS cloud shows that the reliability decreases with increasing scanning distance since more distant points (red points in the image) have not been reached with the lifting platform but have been scanned from the ground.

This third strategy performed well in the acquisition from the ground level and narrow spaces, thanks to the device's ease of handling. It took about half an hour, including manoeuvring the lifting platform. Unlike the first two strategies, which revealed weakness in acquiring surfaces with few reference points, SLAM technology proved suitable for acquiring large and homogeneous surfaces. Processing was fast since it is mostly semi-automatic, and a single scan had to be aligned to the topographic points. In addition, the quality and reliability of the clouds depended on distance but not outdoor conditions. This means that the quality and reliability of clouds obtained are ensured even in uncontrollable conditions, such as natural lighting and intrinsic features of the building. Despite the costs of implementing this strategy, it allows for the acquisition and processing of data on small and medium buildings in a very short time.

3.4. ASSESSMENT OF REQUIREMENTS FOR DIGITAL MODELLING

The last consideration regarding the obtained results deals with the suitability of obtained point clouds for modelling goals. According to the comparison with the topographic survey and TLS point cloud, the accuracy of data acquired through the three strategies was acceptable to build a three-dimensional reconstruction of the external shape of the case study, as defined in point (a) of

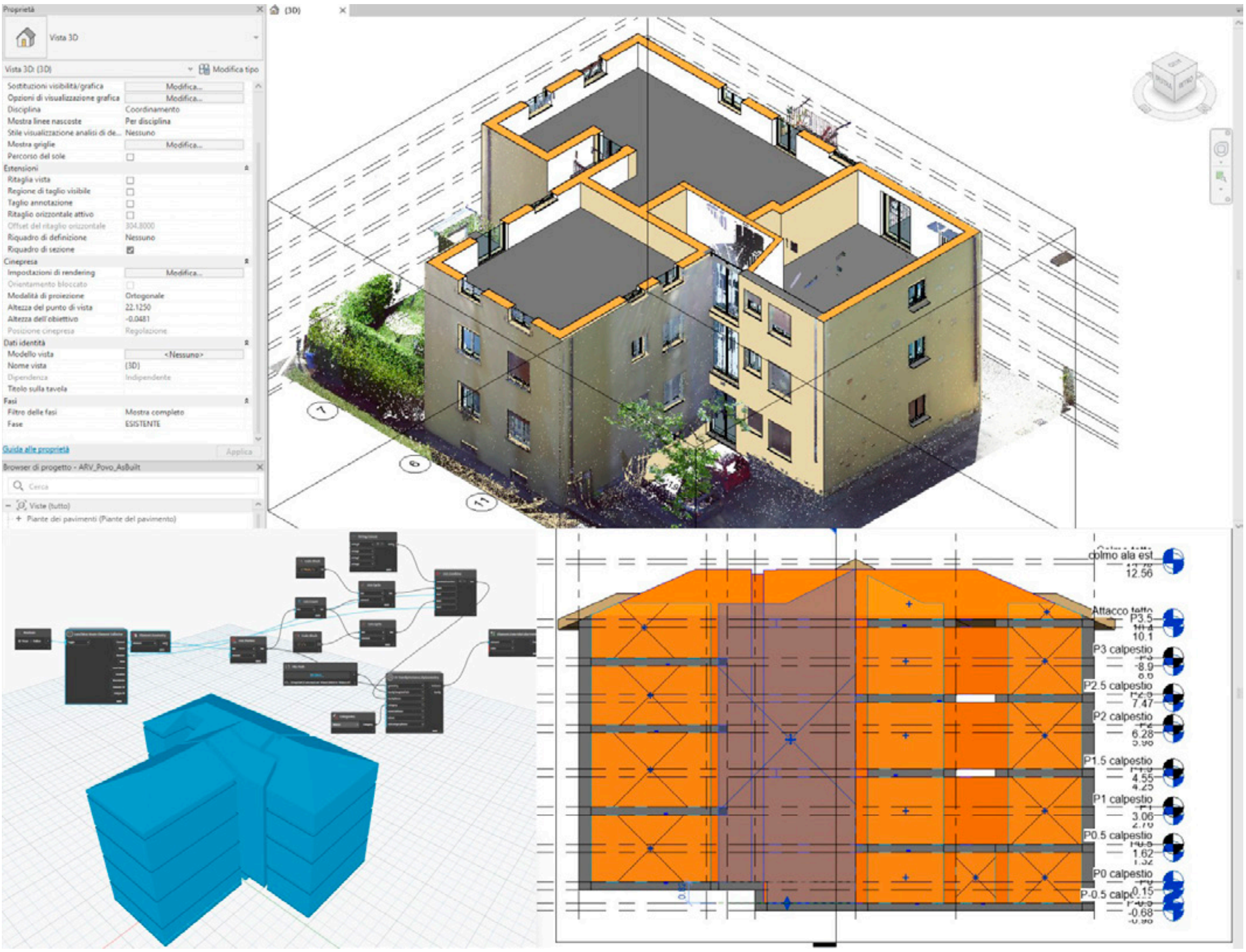

Fig. 10. *The point cloud of the case study overlapped with the 3D model in the BIM environment. 3D and 2D visualisation of rooms allow for verifying proper separation between spaces before import in energy analysis software. Source: © 2023, the research group.*

paragraph 2.3. In particular, steps ii) and iii) are used to position openings and other objects lying on the façades (step v).

The BIM model was exported in .hbjson and .idf formats via the Pollination plug-in, allowing it to manage surfaces and volumes directly from Revit. At first, it was not possible to derive a model on which to carry out the analysis due to irregular geometries, non-orthogonal angles and excessively fragmented spaces. To solve this problem and avoid errors in the recognition of closed regions and to allow the correct computation of volumes (Fig. 10), near-orthogonal corners and non-perfectly-straight walls have been rectified, and indoor layouts have been simplified, assuming habitation units as homogeneous thermal zones. Another issue dealt with the rooms, which cannot be managed from the plug-in interface and need to be placed correctly in the Revit model, on the right level, and with proper height settings. A 3D visualisation of rooms (Fig. 10) allowed a quick check of their correct position. After several exportation tests from Pollination and subsequent adjustments, the three-dimensional geometry appeared readable in the energy analysis software (Design Builder).

All the resulting clouds allowed the reconstruction of an as-is volumetric model for running energy simulations, even if none of the obtained clouds could have been used to properly model the roof geometry (step iv).

None of the obtained point clouds could have been used for a detailed design project with prefabricated panels, as defined in point (b), since, as can be seen in the last row of Table 1, their accuracy does not meet the required criteria for off-site construction, 1σ between 4 and 7 mm, according to [16, 17].

4. DISCUSSION

This study aimed to compare different acquisition and processing strategies based on key parameters such as cost, time, and accuracy while assessing their suitability for the construction of a digital informative model. This experiment explored the potential of these strategies for digitising the built environment for different purposes. The methodological approach allowed for a balanced evaluation, considering both the accuracy of the results for rapid retrofit interventions and the practical feasibility in terms of ease, time, and cost.

Using a low-cost LiDAR-equipped device (iPad Pro) to scan the building, the first strategy proved sensitive to factors like distance from the object and lighting conditions, resulting in irregular and inconsistent surface densities. However, the device's affordability, ease of use, ability to avoid occlusions, and speed of acquisition and processing are notable strengths.

The second strategy, which generated a point cloud using photogrammetry (3DEye system and a reflex camera), shared similar strengths and weaknesses but was hindered by a slower processing workflow and lower quality in the resulting clouds.

The third strategy, employing GeoSLAM scans, revealed similar limitations and advantages compared to the first approach. While GeoSLAM produced better results under real-world conditions, its higher cost remains a drawback.

Photographic sets and SLAM scans are less constrained by distance than common LiDAR devices, making them more suitable for surveying entire buildings. However, the density and accuracy of LiDAR-generated clouds are similar to those produced by SLAM technology. As a result, while it may not be feasible to scan an entire medium-sized building using a low-cost LiDAR device, it remains a viable option for smaller, accessible sections such as ground-level areas. From the experimental findings, it is clear that while the first two strategies are easy to apply, they are insufficient for the complete 3D modelling of medium or large buildings. Integration of different techniques can yield better results, though the quality and reliability of the data may still be affected by uncontrollable factors like lighting and the specific features of the building. The advantages and limits revealed by each strategy are summarised in Table 3.

Integrating the resulting clouds into a BIM-based model was tested, and their suitability for two modelling purposes was evaluated. Combining energy evaluation tools within the BIM workflow requires simplified geometry models to overcome interoperability challenges between systems, and the accuracy obtained by clouds can be sufficient for a volumetric model aimed at running pre- and post-intervention energy simulations. In

Strategy	Limits	Advantages
S1, LiDAR (iPad Pro) scans cloud	Distance from the object Homogeneous surfaces Light conditions	Easy to handle Avoid occlusions Fast acquisition and processing Low-cost
S2, Photogrammetry cloud (3DEye sys. + reflex camera)	Distance from the object Homogeneous surfaces Light conditions Slow processing	Easy to handle - avoid occlusions Fast acquisition Low-cost
S3, SLAM cloud (GeoSLAM Zeb Horizon)	Distance from the object High costs	Easy to handle Avoid occlusions Fast acquisition and processing

Tab. 3. *Limits and advantages of tested strategies for acquisition and processing.*

contrast, the geometric uncertainties encountered do not make resulting clouds suitable for the three-dimensional reconstructions aimed at the detailed positioning of prefabricated components, such as modular systems for retrofitting.

Through this experimental process, the study identified potential solutions to fill the gap between accuracy needs and actual feasibility. However, some questions still need to be addressed, such as the integration of different levels of detail within the same BIM model for various purposes, the implementation of models for comparing retrofitting solutions, simulating pre- and post-intervention energy performance, designing high-precision interventions, and the validation of these models' reliability.

5. CONCLUSIONS

This study contributes to the growing body of research exploring methodologies for the digitization of existing buildings, offering a comparative analysis of three strategies – LiDAR (iPad Pro), photogrammetry (3DEye system + camera) and SLAM (GeoSLAM) – oriented towards 3D modelling for the energy renovation of buildings. Each method was evaluated based on its feasibility, cost-effectiveness, and suitability for 3D modelling aimed at energy performance simulations and design of retrofitting intervention.

LiDAR (iPad Pro) offered fast acquisition and processing, especially for ground-level data. However, its accuracy decreased at longer distances, under poor lighting conditions, and when scanning larger or homogeneous surfaces. Photogrammetry provided reliable geometric data for straight surfaces but required more time and manual intervention for aligning reference points. Its results were influenced by lighting conditions and distance, leading to sparse clouds in some areas. SLAM emerged as the fastest and most efficient method for capturing large surfaces and navigating tight spaces, with results that were less affected by lighting. However, accuracy decreased with distance.

Despite these differences, all three methods generated point clouds suitable for developing geometrical models for energy performance simulations. However, none were accurate enough for detailed design tasks such as prefabricated panel construction, mainly due to inaccuracies in the façade details.

The experimentation findings emphasise the trade-offs between speed, cost and accuracy of each method, highlighting the importance of setting specific requirements upstream of a project. The results suggest a careful selection of data acquisition and processing methods tailored to modelling goals, particularly when high-precision data is required. Hybrid approaches integrating multiple technologies may best balance cost and precision.

Future improvements should aim to refine tested methods, enhancing the combination of efficiency and accuracy, potentially through integrated approaches. Furthermore, research must be carried out to implement and validate modelling strategies according to different purposes.

Authors contribution

Conceptualization, E.B. and G.M.; data curation, E.B. and G.A.M.; writing – original draft preparation, E.B.; writing – review & editing, G.M.; visualization, E.B.; supervision, R.A., M.D., G.A.M.; funding acquisition, R.A.

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