Advanced Deviation Analysis Visualization for BIM in Heritage Environment

Ygor Fasanella, Paolo Borin, and Rachele Bernardello

Abstract This paper presents a methodology leveraging modern technologies such as BIM, laser scanning, and virtual reality to address challenges in maintaining historical buildings. The focus is on a scan-vs-BIM deviation analysis workflow, enabling the identification of modelling inaccuracies and structural issues by comparing HBIM models with point cloud surveys. The proposed approach facilitates decision-making processes by providing an accessible and detailed visualization of results. The methodology begins with a structured BIM model and a corresponding point cloud. Using Autodesk Revit and a tailored Dynamo script, distances between building elements and their surveyed points are calculated and organized for compatibility with various platforms. The results are then transformed into interactive 3D visualizations using Python, where points are spatially and color-coded based on deviation values. The workflow integrates immersive technologies, such as virtual reality, to explore the results interactively and at real scale, enhancing insights beyond traditional 2D graphs and screen-based methods. This immersive visualization highlights critical details and supports improved decision-making in structural analysis and conservation efforts. The paper also discusses the potential for augmented reality to further enhance these visualizations, offering direct comparisons between BIM models, point clouds, and the physical building. With a BIM-based and open-source approach, the methodology ensures broad accessibility and reusability, making it a robust tool for deviation analysis and visualization in heritage conservation projects.

Keywords XR · Spatial visualization · BIM · 3D modelling · Digital survey

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1 Introduction

Existing buildings, particularly historical ones, suffer from multiple structural and functional changes over time that significantly alter their original shape. The maintenance of the existing heritage is one of the most important yet difficult practices to implement. Leveraging modern technologies such as BIM (Building Information Modelling), laser scanning and virtual reality [1], this paper proposes a method to facilitate the decision-making process for interventions on these buildings. Specifically, the visualization of results from a scan-vs-BIM deviation analysis applied to heritage structures is discussed. Scan-to-BIM and scan-vs-BIM practices for automatic construction progress monitoring and quality control between as-designed BIM model and as-built building are studied a lot nowadays.

The aim of this study is to develop a workflow for managing deviation analysis between a BIM model and a point cloud survey of existing buildings, with particular attention to democratize the visualization of the results from this analysis to facilitate decision-making processes. The proposed methodology allows for a detailed examination of the accuracy of an HBIM model compared to reality, identifying both modelling errors in digital model and structural issues in the real environment (Fig. 1). Starting with an already structured BIM model and its relative point cloud, the first part of the process consists in automatically calculating the distance between the geometry of a category of building element and its corresponding points in the digital survey. Results are structured in a specific and pre-defined way that can be followed in any digital environment, making this method generalizable to any situation. A script already developed in [2] is used as starting point to optimize, in terms of both generalization and efficiency, the calculation of the deviation values. This script is strongly adapted to get as output the results structured to be used to create the visualizations in the second part of the process. In the literature, once the results from the deviance analysis are collected, standard analysis will be performed producing mainly static values, as already proposed, and 2D graphs. Here, instead, thanks to the proposed structure, data are processed to produce a 3D interactive visualization where each point is located and coloured by its coordinates and distance value. In the last step, to further improve the visualization of these data, immersive technologies, such as 3D virtual reality headsets, are proposed to interactively explore the analysis in a real-scale virtual environment. The process enables detailed analysis and highlights aspects that may not be noticeable with traditional screen interactions.

2 State of the Art

The proposed research focuses on two main topics: scan-vs-BIM, concerning the analysis of deviations between the model and the point cloud, and the use of advanced visualization techniques, including within virtual reality environments, in the field

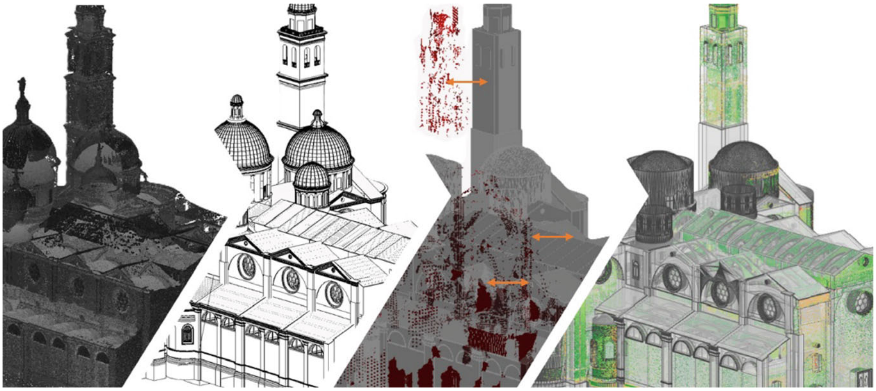

Fig. 1 Steps of the process (Modeling: P. Borin and R. Bernardello, Analysis and Editing: Y. Fasanella)

of historical building conservation. Particular attention is given to the representation of data to support the decision-making process for the preservation of built heritage.

2.1 Scan-Vs-BIM

Scan-vs-BIM is a well-known practice in the analysis of discrepancies between a digital model and the reality captured by three-dimensional surveys, such as point clouds obtained through laser scanning or photogrammetry [2]. This methodology spread due to the increasing accessibility of advanced surveying technologies and modelling tools, enabling comparisons between geometric models and the actual state of structures, assuming that point clouds have the spatial accuracy and continuity to be considered representative of reality [3]. However, this practice is not yet fully established and lacks a standardized, widely recognized methodology for large-scale application, particularly in the context of historical buildings (HBIM) [4].

Most of the current literature focuses on scan-to-BIM practices [5], aimed at the automatic semantic enrichment of point clouds [6, 7] and the automated digital reconstruction of BIM models [8]. In contrast, research on scan-vs-BIM primarily addresses construction progress monitoring for new buildings [9, 10] or the inspection of prefabricated or mechanical elements [11, 12], rather than analysing existing structures, particularly historical ones.

Despite these differing objectives, valuable insights into methodologies applicable to historical contexts can still be derived [13]. In this regard, deviation analysis is the most widely used technique for comparing BIM models with survey data. For instance, [11] describes a method where a synthetic point cloud is generated from the BIM model and compared with the actual survey points. The most common approach, however, involves identifying and measuring spatial distances between the surfaces of model objects and the points in the survey cloud, calculating deviation values [14]. These results can be mapped to provide detailed visual representations and are often used to detect modelling errors, geometric changes related to structural degradation, or deviations caused by subsequent interventions on the original structure. A VPL approach to perform the deviation analysis, create visualizations based on results and propose a standardization for level of reliability is used in [15].

Another critical aspect of the scan-vs-BIM approach is the standardization of output data to ensure not only compatibility with various software and visualization tools but also the replicability and scalability of the methods used. Recent studies have emphasized the automation of these analyses, highlighting the importance of improving process efficiency as well as the accuracy and organization of the results [16].

2.2 Data Visualization

Another key aspect at the centre of this research is how the data resulting from the analyses is processed and visually represented, with the goal of enhancing its comprehensibility and improving the decision-making process based on it. Data representation plays a crucial role, especially in the context of the built environment, where the complexity of information requires tools that are both intuitive and technically accurate.

In the current state of the literature, various methods have been proposed to represent the results of deviation analyses, particularly in the context of historical buildings. Tabular visualizations and standard two-dimensional graphs remain by far the most common, offering static representations that are often limited in their ability to convey spatial information. Less frequent is the use of point clouds coloured according to specific criteria [17]. While such representations provide an initial level of visual intuition, the criteria employed are often basic and not tailored to the specific context in which they are applied.

In some cases, two-dimensional images are used, combining the overlay of coloured point clouds with sections or elevations of the analysed element. However, these methods remain static and, despite their value, fail to offer a fully immersive or interactive experience. Three-dimensional approaches are rarer and often lack significant chromatic components or effective integration between the point cloud and the analysed model [18].

Finally, the use of innovative methodologies that integrate fully structured three-dimensional data representations with a high degree of interactivity and accessibility is still almost absent in the literature. Such tools could represent a significant advancement, providing more intuitive and powerful decision-support systems, particularly for professionals working on historical buildings with complex structural and conservation challenges.

2.3 Virtual Reality

The use of virtual reality (VR) is emerging in the digitalization of the construction sector. For example, in the early stages of building design, VR proves to be a valuable resource by providing an environment that closely resembles reality, enabling more informed decision-making in advance and improving communication between designers and clients [19]. In this context, virtual reality also emerges as a powerful tool for the study, conservation, and restoration of historical buildings. Its ability to create immersive experiences allows complex data to be visualized in a three-dimensional, real-scale environment, offering professionals a deeper understanding of the state of conservation and structural issues [1]. When combined with the capabilities and resources provided by technologies like BIM, virtual reality is used to simulate restoration interventions, plan maintenance strategies, and represent information derived from technical analyses [20]. These mixed virtual environments, where digital data and information are integrated with point clouds representing reality, enable users to explore buildings in new ways. By facilitating interaction between the digital model, 3D surveys, and the physical environment, VR supports decision-making through an integrated and intuitive perspective [21]. Virtual Reality thus holds the potential to democratize access to technical information, facilitating communication between experts and non-technical stakeholders through accessible and interactive visual representations [22].

3 Methodology

The methodology adopted begins with deviation analysis between the objects in the model and the corresponding points in the point cloud. The output of this initial phase is a structured dataset, which is subsequently processed to produce advanced visualizations in Virtual Reality's environments, enabling detailed inspection of both the model and the real building. The explained methodology is supported by a particularly representative case study of a sixteenth-century historical church.

3.1 Level of Accuracy (LoA)

The objective of this research is to propose a method for verifying the geometric accuracy of a BIM model in relation to the point cloud of the real building it represents, specifically within the context of historical buildings. This aims to assist professionals in addressing questions such as: are there geometrical issues in the BIM model, or is the real element genuinely deformed?

In this regard, it is important to reference the concept of Level of Accuracy (LoA), as described by the United States Institute of Building Documentation (USIBD) in

[23]. This document considers both the accuracy of the point cloud relative to reality (determined by the precision of the instruments used during the survey) and the level of accuracy of the BIM model relative to the point cloud itself (Fig. 2). The former is not addressed in this study, as it is assumed that digital survey procedures, supported by auxiliary topographic surveys, achieve an accuracy in the order of magnitude higher than the accuracy between the model and the survey.

Another aspect highlighted in the guide is the importance of the analysed element relative to the purpose of the deviation analysis. The document concludes by proposing reference ranges to verify the model's accuracy, following the logic that higher levels indicate greater precision. As shown in Table 1, the USIBD document suggests predefined ranges while allowing users to define custom ranges based on their specific needs. In the context of historical buildings studied in this research, for instance, a user defined level of accuracy (UDLOA) for heritage structures could be defined within the range of 15–30 mm.

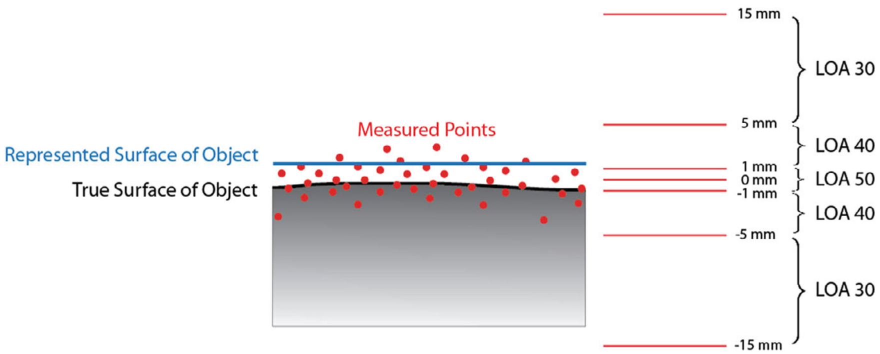

Fig. 2 Accuracy of measured points vs represented surface vs real surface (USIBD Document C120 TM [Guide]—Version 3.0—2019 Copyright ©2019 by the U.S. Institute of Building Documentation)

Table 1 Level of Accuracy ranges (USIBD Document C120 TM [Guide]—Version 3.0—2019 Copyright ©2019 by the U.S. Institute of Building Documentation)

Level	Upper range	Lower range
UDLOA	User defined	User defined
LOA10	15 cm	5 cm
LOA20	5 cm	15 mm
LOA30	15 mm	5 mm
LOA40	5 mm	1 mm
LOA50	1 mm	0

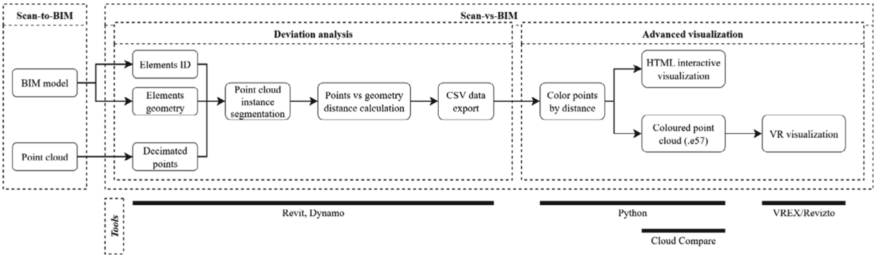

Fig. 3 Workflow of the methodology (Editing: Y. Fasanella)

3.2 Workflow

As mentioned in the previous paragraphs, this research builds upon the subsequent phases of the scan-to-BIM process. Therefore, the workflow described in this chapter and presented in Fig. 3 assumes the prior availability of a point cloud of the building and its corresponding BIM model to perform the deviation analysis and produce the visualizations that will later be presented.

3.3 Deviation Analysis

The first phase of the process involves performing the deviation analysis. To carry out these operations, a proprietary environment was chosen, utilizing Autodesk Revit 2024 modelling software, which also offers a Visual Programming environment through the Dynamo plugin (version 2.18). Using Dynamo, a script (Fig. 4) was developed to import the geometries of the elements from the model and the points from the point cloud, classify the points based on the closest element they reference, calculate their distance from the nearest surface, and export the data in CSV format, organized according to a predefined structure.

Importing elements and points. The first part of the script manages the two main inputs in parallel: the elements to be analysed and the point cloud file.

Through the use of some filters and initial parameters, it is possible to define which elements to analyse by specifying their category and/or entering the unique ID of each. Once the elements are selected, their solid geometry is extracted using

Fig. 4 Dynamo script (Editing: Y. Fasanella)

the *Element.GeometryFast* node, developed within the *Synthesize* package, and the ID of each element is retrieved using the default *Element.ID* node. Both geometries and IDs are organized into lists, ensuring that the unique correspondence between the parts is maintained throughout the entire process.

Simultaneously, all files associated with the point cloud linked to the model are selected. After verifying which ones are correctly active, the relevant instances are loaded into Dynamo for further processing.

Points segmentation. The second phase involves the import of the point cloud points and their subdivision according to the element they refer to.

Using the *GetPoints* method, the points from the point cloud are imported. These are not imported in full but are decimated to ensure a more efficient computational process. This method allows the user to set both the number of points to extract and the maximum distance between them. Additionally, the final and crucial parameter required by the method is the volume within which the selection will occur. This is where the first connection between the points and the elements is made. For each iteration, a bounding box is created around the considered element, and the point selection is performed only on those points within this bounding box (Fig. 5a).

The resulting list of points requires further filtering because it not only represents the selected element but also contains points from surrounding elements. To address this, the geometries of the surrounding elements are also extracted, and points that are closer to these surrounding geometries than to the geometry of the element under

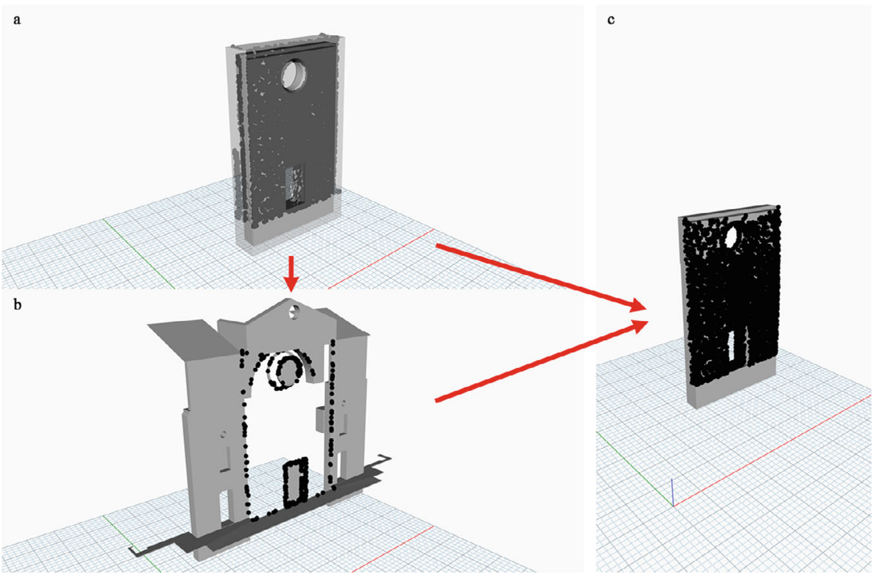

Fig. 5 Point could segmentation: **a** selected element's geometry with bounding box and included points; **b** nearby elements' geometry with the points related to them; **c** element geometry with its final related points (Editing: Y. Fasanella)

consideration are removed (Fig. 5b). This results in the final list of points that are correctly associated with the analysed element (Fig. 5c).

Distance calculation. In the third phase, the calculation of the distance of each individual point from the geometry is performed. Points are initially classified as either external or internal to the element, as the modelled object may overlap with some points. Subsequently, using the Dynamo predefined ***Geometry.DistanceTo*** node, the Euclidean distance of each point is calculated relative to the nearest point on the closest surface of the input geometry (i.e., the geometry of the element under analysis).

Export data. The last step of the process involves structuring the data for proper export and populating specific properties directly on the analysed model elements.

For each element, the following parameters are populated with appropriately calculated values:

- PCA_E_GLB_MXD: the value of the distance of the farthest point from the element's geometry;
- PCA_E_GLB_AVD: the average distance of the points from the geometry;
- PCA_E_GLB_PTS: the total number of points considered for the analysis of the element;
- PCA_E_GLB_PT^mq: points density, calculated as the ratio of the number of points to the surface area (points per square meter);
- PCA_E_GLB_mq^PT: the average area of influence for each point, calculated as the ratio of the surface area to the number of points (square meters per point).

Finally, a CSV file is exported for each analysed element (Fig. 6). In the file, each row corresponds to a single point, while the columns are structured as follows:

- ID: a unique identifier for the element analysed;
- X: the X coordinate of the point in the model's reference system;
- Y: the Y coordinate of the point in the model's reference system;
- Z: the Z coordinate of the point in the model's reference system;

```
ID,X,Y,Z,Distance
542088,19.855204478596,8.95169226777213,14.2781145357957,0.0720043940075001
542088,19.8598250505976,8 .80724971755102,14.2801145357957,0.0766249660091241
542088,19.8580862058767,8.89515293944326,14.0881145357957,0.074886121288209
542088,19.8505005429096,8.82085315668886,13.7671145357957,0.0673004583211601
542088,19.8583371228236,8.86003973621875,13.8311145357957,0.0751370382351269
542088,19.8478589679933,9.16660165210419,13.7931145357957,0.0646588834047961
542088,19.8595426657957,8.9543718445708,14.2511145357957,0.0763425812072498
542088,19.8530996100909,9.19842201775898,14.7921142357957,0.0698995255024002
542088,19.8634175715791,8.79471601127564,16.4161142357957,0.0802174869906409
542088,19.8537860205592,9.23388367086017,16.8131142357957,0.0643183117471686
542088,19.8591559387391,8.90088492614971,14.8941142357957,0.0759558541506777
```

Fig. 6 CSV data structure (Editing: Y. Fasanella)

- Distance: the Euclidean distance of the point from the nearest surface of the element.

The final outputs of this phase consist of as many CSV files as there are analysed elements. This process is crucial as it ensures that data is saved at each iteration, thereby preventing the total loss of information in case issues arise during the procedure.

3.4 Advanced Visualization

The straightforward and structured organization of the data up to this point ensures the replicability of the method in subsequent steps, even in non-proprietary environments outside of Revit, regardless of the procedure used to perform the deviation analysis.

Colour scale. An important aspect considered in this research for producing an advanced visualization is the use of colour scales suitable for the type of data being represented, considering the wide audience such visualizations can reach. Therefore, the choice of colours is crucial to ensure the immediacy in understanding the meaning of the data.

First, it is essential to identify the type of data to be visualized in order to select the most appropriate colour scale. For the analysis of deviations, the data are of a sequential type, as they refer to a distance value that increases continuously starting from zero. However, in this specific case, the meaning attributed to the data is related to comparison with a threshold value (i.e., a maximum acceptable distance), highlighting how close they are to this limit or whether they exceed it, making them unacceptable. In this context, the data acquire a divergent meaning, despite their inherently sequential nature. For this reason, a divergent colour scale has been chosen, allowing the reader to immediately understand which points are within an acceptable distance, which are approaching the limit, and which exceed it. The adopted colour scale, one of the most commonly used, ranges from green to red.

An additional aspect considered, albeit marginally, in the choice of colours concerns the possible visual difficulties of users. Although the green–red scale is not completely suitable for people with colour blindness, the selected shades partially mitigate this issue. The use of a tool like *ColorBrewer* [24] was essential for this purpose. In Table 2, the RGB values of reference used in the chosen colour scale are shown. These RGB values are normalized in the range [0, 1] to match the normalized values of the point distances.

Web interactive image. The first type of advanced visualization consists of three interactive graphs. The user can rotate, zoom, and select elements to better view

Table 2 RGB values used for the colour-scale (Editing: Y. Fasanella)

Normalized value	0	1/3	2/3	1
RGB	(26, 150, 65)	(166, 217, 106)	(253, 174, 97)	(215, 25, 28)

their characteristics and associated data. Using a Python script developed with the *Pandas*, *NumPy*, and *Plotly* libraries, it was possible to integrate HTML to create an interactive image. In Fig. 7, on the left, the full set of points representing the entire building is shown in blue (decimated to 5% to avoid overloading the image), while the analysed element is highlighted in red. The central figure illustrates all non-decimated points, color-coded according to the colour scale chosen. Finally, the right-hand section includes a box plot that graphically represents the distribution of the points, while also highlighting the mean and median values.

Virtual Reality visualization. In this phase, a Python script was created to generate a new CSV file in which all the output files from the previous phase are combined, and three new columns are added that map the RGB values for each point based on its distance (Fig. 8). The colour mapping is performed for each individual element by normalizing its distance between the values of 0 and 1 and then calculating the corresponding RGB value. In this case, since all the points are to be visualized simultaneously in the same environment, the possibility to specify a maximum accepted distance value was also added, so that all values above this threshold do not influence the normalization and are always coloured red. This facilitates the identification of the most problematic elements.

The single CSV file, containing data for all elements, is imported into the CloudCompare software and used to generate an actual point cloud in.e57 format, utilizing the RGB column values to colour the points. To keep the process replicable and open-source, the BIM model is exported from Revit in IFC format.

At this point, it is possible to import the point cloud file and the IFC file of the BIM model into virtual reality software that supports these functionalities, such as VREX or Revizto (Fig. 9). Using a virtual reality headset (Meta Quest 2 here), it is then possible to enter a digital environment where various features are available for first-person interaction with the model and querying the information.

Among the various software available on the market, VREX and Revizto were chosen due to their accessibility, either free of charge or through a simple registration, and the functionalities they offer in the context of this research. In addition to

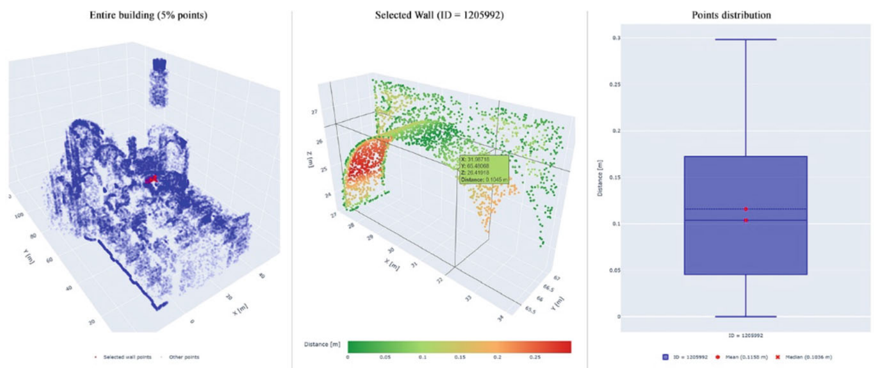

Fig. 7 Web interactive visualization (Editing: Y. Fasanella)

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ID,X,Y,Z,Distance,R,G,B
542744,31.4766215674241,7.42756246500152,36.5232062357957,0.05436048239[illegible]188,102,186,87
542744,31.7769950245117,7.44320811223213,35.6392062357957,0.070006129624832,124,197,94
542744,31.0763269100102,7.38223932250353,35.1462062357957,0.0090373398962198,39,156,69
542744,31.8561592115921,7.37661958856704,34.9692062357957,0.0034176059597368,31,152,66
542744,31.3634453778366,7.38762313463089,35.2242062357957,0.0144211520235817,46,160,71
542744,30.9111097726357,7.43924193224875,35.6172062357957,0.0660399496414428,118,194,92
542744,31.1713941952955,7.4335833705372,35.9652062357957,0.0603813879298958,111,190,90
542744,30.9474843699197,7.43036000270475,36.4892062357957,0.0571580200974484,106,188,88
542744,31.4213087606373,7.44434023020935,35.4082062357957,0.0711382476020477,126,198,94
542744,31.6755824917489,7.38310405081666,34.9282062357957,0.0099020682093558,40,157,69
542744,31.6027147856811,7.44136464995894,36.8212062357957,0.0681626673516362,121,196,93
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Fig. 8 Updated CSV file with RGB columns (Editing: Y. Fasanella)

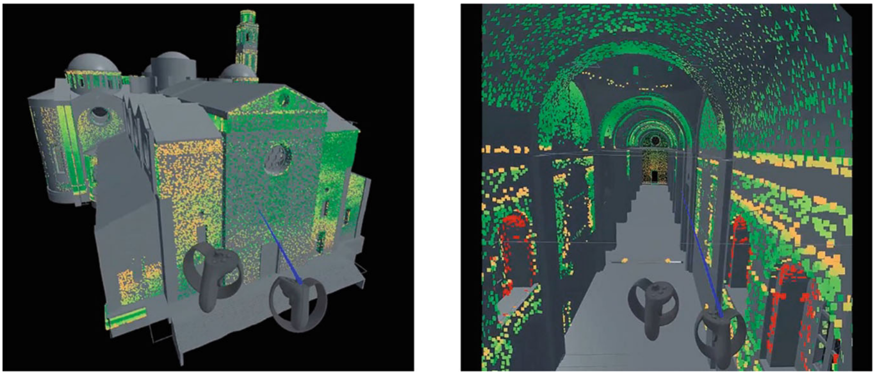

Fig. 9 Example of Revizto virtual reality environment. On the left a view from outside of the building and on the right an internal view of it (Editing: Y. Fasanella)

supporting the import of IFC and e57 files, these tools provide the ability to visualize information and properties of the model elements—a fundamental feature for a detailed inspection of the analysis.

4 Results and Discussion

The proposed workflow has produced significant results in assessing geometric discrepancies between BIM models and point clouds of historical buildings. The adoption of a custom script in the Dynamo environment allowed for effective segmentation of the points and precise calculation of spatial deviations. The potential of this method lies in the fact that the import of elements is independent of the architectural category they belong to, but is solely related to the geometry with which they are created. However, limitations are also observed in this regard, as Dynamo may encounter errors when handling overly complex geometries. The data resulting from the script, structured in CSV format, represents a solid foundation for the subsequent phase of advanced visualization. The integration of immersive virtual environments, through the use of VR headsets, significantly improved spatial understanding of the deviations, allowing for interactive exploration of discrepancies at real scale. However, the functionalities offered in these environments vary significantly depending on the software used. Some tools stand out for their variety of advanced features but are limited in performance, while others offer greater efficiency but lack interactive tools (Fig. 10).

An innovative aspect of the workflow is the establishment of a direct link between the model elements and the analysed points using unique IDs, potentially also IFCGUID in the case of a complete IFC implementation. This approach enables tracking specific deviations for each element, improving both the reliability and interpretability of the data. This feature is particularly useful for ensuring detailed and replicable analysis in various application contexts. Despite this, some limitations arise. Specifically, point cloud formats represent a significant technical barrier, as they often do not support storing points organized according to specific rules, such as segmentation based on element IDs. Overall, the results highlight the potential of the proposed method in integrating VR technologies to improve decision-making,

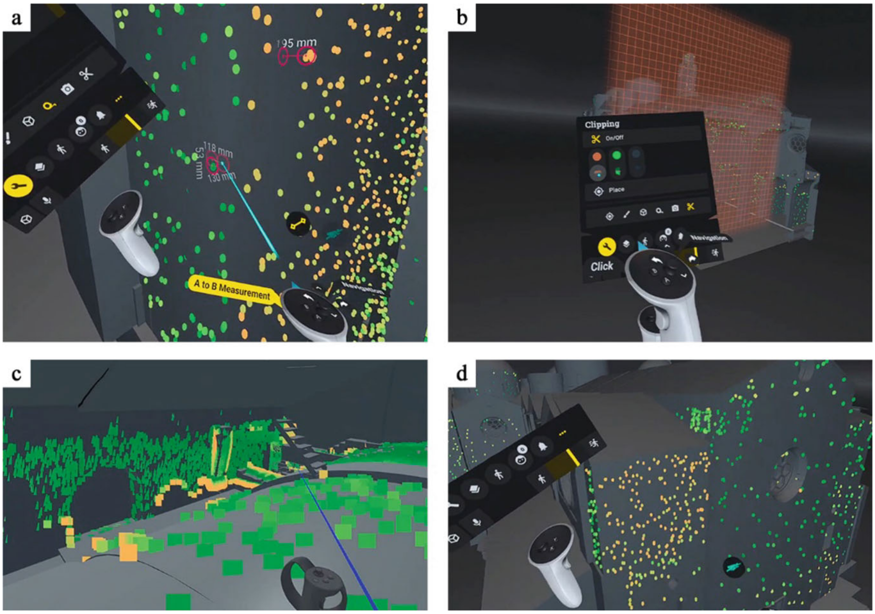

Fig. 10 Pros and cons of VR software: **a** VREX tools to measure distance between points and surfaces; **b** VREX clipping planes to crop model; **c** Revizto high points density but not properly square visualization; **d** VREX properly circle visualization of points but low density (Editing: Y. Fasanella)

making the analysis more accessible to a wide range of stakeholders. The replicability and open-source nature of the method strengthen its relevance for future developments and applications in cultural heritage.

5 Conclusions and Future Developments

The proposed research has demonstrated effectiveness in analysing discrepancies between BIM models and point clouds, highlighting the potential of VR technologies to improve understanding and management of information in the context of historical heritage. To overcome some of the limitations identified, it may be interesting to integrate certain phases of the process into a Common Data Environment (CDE), promoting centralized and collaborative data management, as suggested, in a broader view, by the BIM method. Furthermore, improving virtual reality software is crucial to providing a smoother and more comprehensive experience, with advanced tools for the simultaneous visualization of geometries and spatial data. A potential future development is the expansion towards mixed reality (MR) applications, allowing the coloured point cloud to be overlaid directly on the physical environment. This integration could facilitate in-situ comparison between deviance analysis and the real building, further enhancing the effectiveness of restoration and maintenance interventions. Finally, adopting standardized formats for point clouds, capable of supporting rule-based segmentation, represents a priority to increase the efficiency and scalability of results.

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