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Turning a Point Cloud into a Building Information Model (BIM)

Defining and Validating the Accuracy Requirements for Existing Buildings

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Abstract: Digitization of existing buildings is one of the main future goals, leading to efficient planning, renovation and maintenance. Among the existing buildings, a significant share is protected as a cultural heritage and their management is supervised because interventions on the protected sites are limited. Building information modeling (BIM) provides the opportunity to integrate accurate as-built information into the digital environment where it can easily be accessed and used. A digital representation of building creation usually starts with the acquisition of spatial data (point cloud), which is then used to create a semantically enriched model with certain geometric accuracy (BIM). In order for the model to serve its purpose, it is important to define how accurate the model should be. Since there are currently insufficient definitions of geometric requirements for specific BIM use cases, the research hypothesis was that the quality of BIM greatly depends on the modeler. The identified issue was approached with a study case. Using the point cloud of the existing building, the BIM was made and validated based on pre-defined accuracy requirements. Different accuracy validation methods were used in the process. Based on the results of the study case, conclusions and recommendations for efficient BIM creation were prepared.

Keywords: *Digitalization of Existing Buildings—Point Cloud—Building Information Model (BIM)—Geometric Accuracy*

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Introduction

The digitalization of existing buildings, including those protected as cultural heritage, is one of the main future goals to streamline the planning and funding of buildings’ revitalization as well as to convert them into healthy and resilient living and working environments. Furthermore, one of the usual renovation goals is to make them more energy efficient (Andriasyan et al., 2020). Considering all the building phases, the management-and-operation phase represents 60% of all the costs (Alavi and Forcada, 2019). In order to make this phase more efficient, we need accurate as-built information (Esfahani et al., 2021), which could be a part of the Building information modeling (BIM) communication process. A digital representation of the building’s creation usually starts with capturing the spatial data (point cloud), which is then used to prepare a semantically enriched model with a specific geometrical accuracy (BIM). Most of the existing buildings do not have a BIM (Hossain and Yeoh, 2018) and creating one can be a complex, multiple-step process. Different tools and standards concerning different aspects of the BIM for existing buildings are available; however, determining the requirements for turning point clouds into models of different accuracies remains undefined.

In order to determine the methodology for the definition and validation of the geometric accuracy, it is important to understand the complete process of implementing the BIM for existing buildings, as each of the steps in the process affects the end result. Based on existing literature (Biagini et al., 2020, Computer Integrated Construction Research Program, 2019; Ortega and Mort, 2017; Scherer and Katranuschkov, 2018) the schema containing the five main steps, being planning, reality capture, data processing, modeling and inclusion of the model into the common data environment, was outlined.

In the planning phase, the potential use of the BIM, as well as the requirements enabling it, need to be determined. Reality capture consists of an appropriate surveying method and the gathering of additional information related to the building, ensuring the requirements from the first phase are met. Laser scanning and photogrammetry are two techniques currently being used to capture point clouds (Werbrouck et al., 2020). Since point clouds are unstructured and the point cloud’s processing also requires large computing power, they are usually preprocessed and manipulated (cropped, aligned, scaled, triangulated into meshes, turned into planes etc.) That leads to a modeling phase, where some of the unnecessary geometrical details are lost. Depending on the purpose of the project, different levels of accuracy need to be maintained for different building elements. The modeling phase of the project can require lots of effort and knowledge. To ensure efficient use of BIM, the information included in the model need to be accurate. While the semantic and geometrical accuracy are important, the geometrical accuracy was the focus of our study.

Since there are currently insufficient definitions of geometric requirements for specific BIM use cases, the research hypothesis was that the quality of BIM greatly depends on the modeler. The identified issue was approached with a study case. First, the point cloud of an existing building was prepared to serve as basis for the BIM model. To validate the model, accuracy requirements were defined and different validation methodologies were tested. Based on the results of the study case, conclusions and recommendations for BIM model creation were prepared.

Study case

In our study, the point cloud of an existing building located in Germany, was used. The building “Halle 6” was built 50 years ago and was used as an industrial plant. It is a part of a larger complex of buildings. The point cloud of the building was prepared by terrestrial laser scanner. To ensure the quality of the point cloud, reference and control points were determined, measured by the terrestrial geodetic method with a relative accuracy of 3 mm, which is used in the process of registration of 3D LIDAR images.

Fig. 1. A part of the façade of "Halle 6" that was the focus of our study (© Authors).

One of the building facades, represented in Figure 1, was chosen as the focus of the research. The BIM model of the facade was to be used for planning of the renovation, which would include changing of windows and doors. By that, the building would become more energy efficient.

Modeling

BIM model of the facade was made in Revit. The model was made based on the point cloud, meaning the coordinate reference system of the model and the point cloud was the same and there are no errors from geo-referencing. The model was done manually, tracing the point cloud. First, the model was assembled out of basic elements from the Revit library, then some of the elements were replaced by uniquely modeled entities to match the existing structures as closely as possible. Since the façade consisted of some of the repeating elements (shelves, columns), those were manually modeled with greater detail, using family templates in Revit. One of the challenges was determining the correct size of the windows and doors, as their edges were covered with different layers of plaster.

Defining the accuracy requirements

To validate the model, the accuracy requirements were determined for the elements of the chosen facade. The USIBD Level of Accuracy (LOA) specification guide (2019) was used as the basis. The guideline defines five LOAs with specific tolerance ranges (LOA50: 0 mm to 1 mm, LOA40: 1 mm to 5 mm, LOA30: 5 mm to 15 mm, LOA20: 15 mm to 5 cm and LOA10: 5 cm to 15 cm) and suggests different LOAs for specific building elements with different Uniformat levels (e.g., shell, exterior vertical enclosures, exterior walls). It also distinguishes between the relative and absolute accuracy – the first one representing the accuracy of true element dimension and the second, the accuracy of the location of the object in a coordinate system (Kavanagh, 2017).

In the validation phase, large deviations of the model, such as missing elements, as well as the relative accuracy of the openings would be analyzed. In the renovation, the windows would be replaced with new ones. BIM would be used to plan the construction and create the bill of materials.

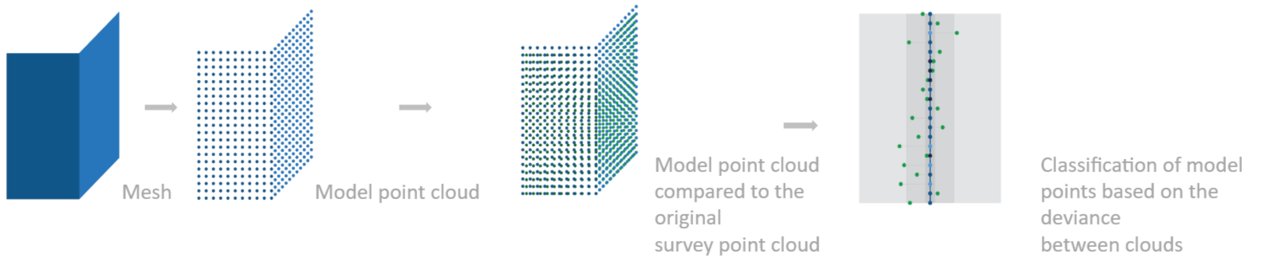

Fig. 2. Accuracy validation based on cloud to cloud comparison (© Authors).

For the new windows to fit the existing openings, it was important that the modeled elements were modeled with correct sizes. According to the USIBD specification guide, the windows should be modeled with the acceptable deviation of 1 to 3 cm (relative accuracy).

Defining the validation methodology

The accuracy of the BIM model was validated through a comparison of two data sets (the model and the point cloud). The point cloud was considered to represent the ground-truth dimensions. Although the measuring instrument can have an important impact on the end result, the intrinsic error of the point cloud was not taken into account in the represented study case, since it was prepared with the high accuracy laser scanner.

The first accuracy-evaluation method, represented in Figure 2, relies on the analysis of absolute accuracy (true location of a point in a coordinate system). The methodology described by Bonduel et al. (2017) was used in order to detect the non-modeled elements, large deviations and modeling errors (easily recognized deviations, e.g., elements placed at wrong locations) as well as the classification of the points into the USIBD LOA range categories. The point cloud, made out of the visible surfaces from the Revit model, was compared to the original (source) point cloud in an open-source software tool called Cloud Compare. Points with large deviations and parts of the cloud with occluded zones were excluded from the deviation analysis. The results were represented in the form of a color map on the model point cloud. The points were then classified into USIBD LOA ranges and the percentage of points falling into a certain LOA category was determined. The deviation analysis was also made with another software tool, working as a Revit plugin. The second tool was used in order to compare the results and the process needed to obtain them.

Trying to validate the relative accuracy of the windows, the results of cloud to cloud comparison were found hard to interpret. For that reason, other methodologies to determine the relative accuracy of windows were tested.

Firstly, the Random sampling consensus algorithm (RANSAC) was used to automatically determine the planes fitting the point cloud window and measure the dimensions of the edges, created by plane intersections. The method was previously used by Tan Y. et al. (2020) for the purpose of geometric quality inspection of prefabricated housing units. In the study, the laser scanner was carefully positioned to ensure required accuracy and spatial resolution of the point cloud. Since the density of a point cloud of our facade was uneven and there were parts with missing points, there were many issues with plane recognition and the method was found to be inappropriate.

Secondly, the dimensions of windows from the point cloud were determined by the selection of points, representing element edges and calculating the distances between them. The point selection was done using section views of the windows and selecting points, representing windows edges, multiple times. Since the edge of the element in the point cloud is represented by multiple points, the exact point representing the edge was impossible to determine, leading to the results of multiple selections varying up to 10 mm. Since the required geometry accuracy was 3c m that was a sufficient accuracy for our use case. For the final dimension of each window, represented in point cloud, we took the mean value of five measurements. After determining the dimension of the element from the point cloud, a list of those same dimensions was made in Revit and the dimensions were compared to each other. The differences in dimensions of the model and the point cloud were compared with the pre-defined accuracy requirements, which determined whether or not the elements were modeled accurately enough. The method is represented in Figure 3.

Results

Cloud to cloud comparison results were represented with a color map and numerical indication of points, classified into the LOA categories. The results are represented in Figure 4. Color map was done using Cloud Compare and Undet, a tool, working as a Revit plugin, which enabled fast and easy validation of the accuracy in the modeling phase. Using both tools, the results were the same. The results of the analysis show, that most of the points, representing the wall, fit the requirement (LOA30). Larger deviations are visible in places of missing window shelves and in some other parts of the wall. While the model of the existing wall is represented with a completely flat BIM element, that is not the case in real world.

The same method was used to determine the accuracy of the windows and the results are showcased in Figure 5. In our study case, the windows on the facade were supposed to be of the same sizes. To determine their accuracy, the surfaces, surrounding three windows, were analyzed. If the location of the window was a bit off, while the dimension was right, the accuracy results would be worse. The exact location of the windows in our case was not important and the method was found to be inappropriate to determine the accuracy of true element dimension.

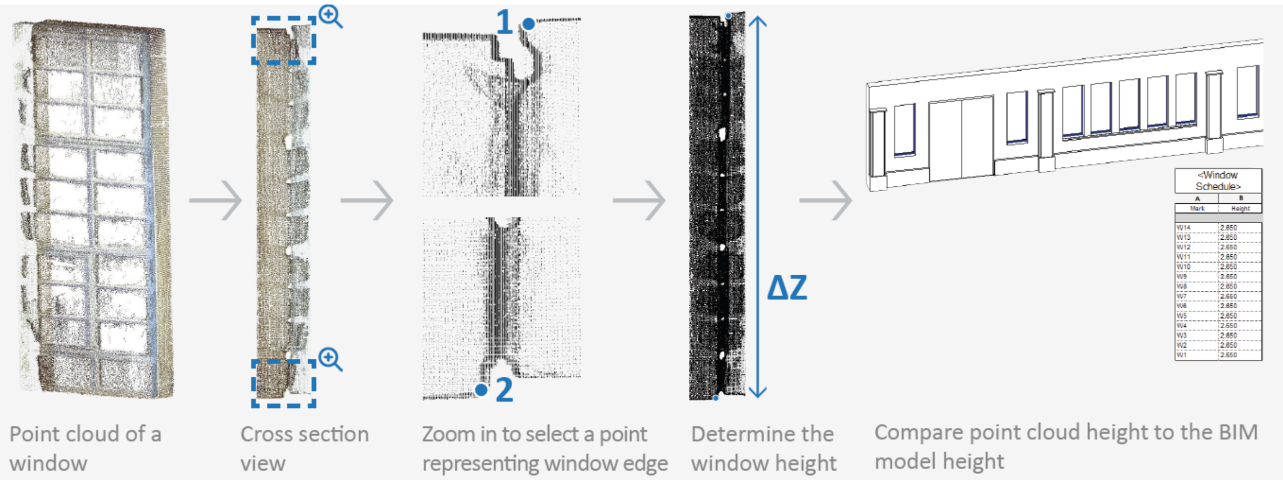

Fig. 3. The process of determining the accuracy of window sizes of the BIM model using the point cloud as ground-truth dimensions reference (© Authors).

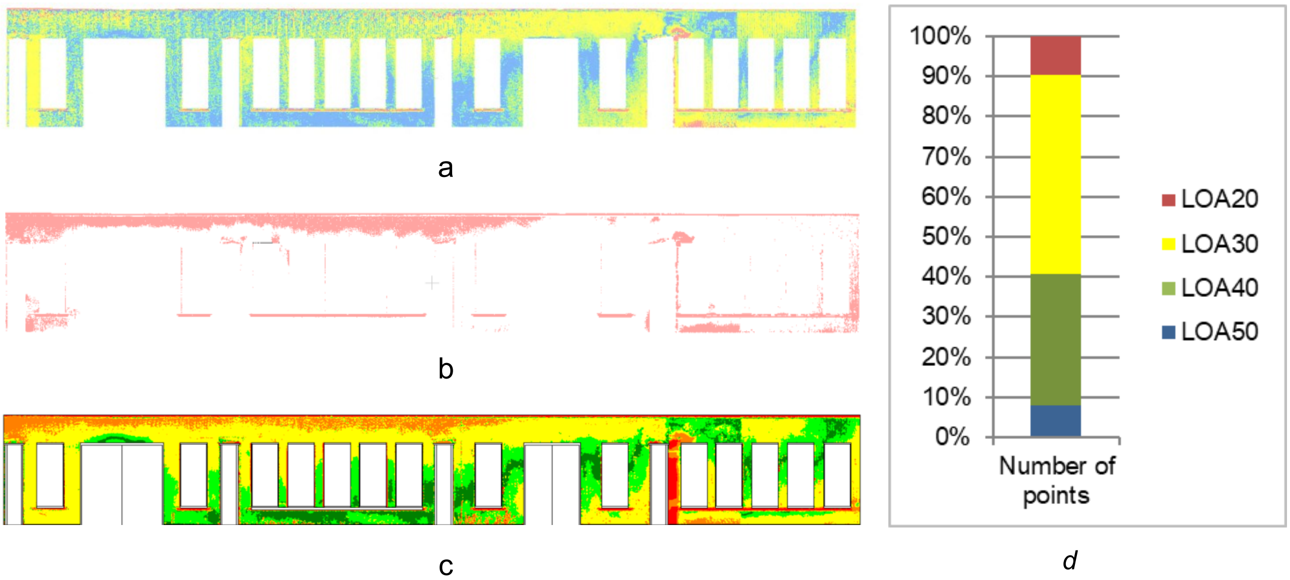

Fig. 4. Results of cloud to cloud analysis of the facade, represented with color maps and numerical indication. a) Color map of the wall with points, classified into different LOA categories (Cloud Compare analysis, b) Color map of the wall with points, showing large deviations – LOA20 (Cloud Compare analysis), c) Color map of the wall with points, classified into different LOA categories (Undet analysis), d) Numerical indication of points, representing the facade (Cloud Compare analysis (© Authors).

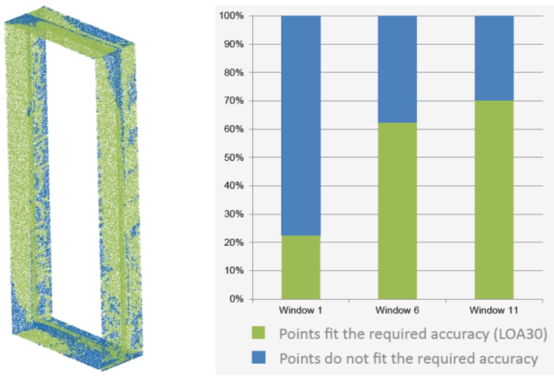

Fig. 5. Results of cloud to cloud analysis of windows of same sizes, represented with a color map of one of the windows and the numerical indication of the three windows (© Authors).

To validate the relative accuracy of windows, point selection method was used. Even though the windows sizes should all be the same, point cloud measurements were not. The results are represented in Table 1. The difference between measurements was 27 mm in case of window width and 10 mm in case of window height. One of the reasons were the occlusions in the point cloud in case of some of the windows, where choosing the point, representing the edge of the window, was hard to determine. An example of the occlusion is represented in Figure 6. Another reason were different layers of plaster covering the edges of windows, preventing to gain the exact measurement of the window from the point cloud alone.

Measurements from the point cloud were compared to the measurements of elements from BIM, which were automatically extracted from Revit. Besides the model, created by our research team, two other BIM models, created by other teams for the purpose of evaluating renovation options, were used in this phase.

Table 1. Measurements of the windows from the point cloud

Window dimensions from the point cloud		
Window No.	**Width (Point cloud dimension)**	**Height (Point cloud dimension)**
W1	1045	2637
W2	1053	2635
W3	1047	2636
W4	1050	2640
W5	1039	2640
W6	1064	2640
W7	1059	2642
W8	1064	2641
W9	1060	2643
W10	1066	2641
W11	1064	2642
W12	1066	2638
W13	1063	2644
W14	1064	2645

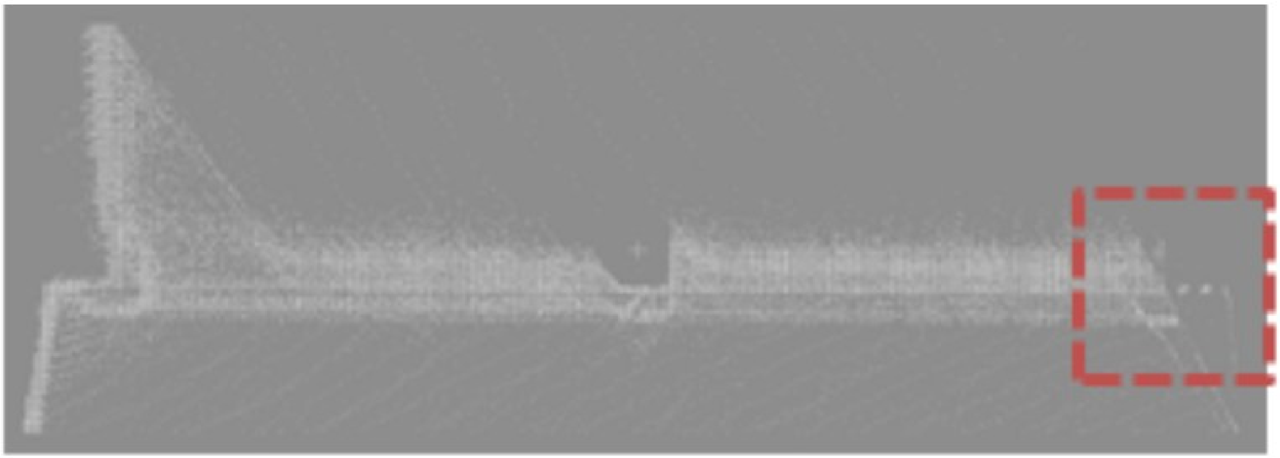

Fig. 6. The floorplan section view of one of the windows – the occluded zones represent an issue when determining the correct window size (© Authors).

The case study facade has 14 windows of same size. In three models, those 14 windows were represented with same BIM element, used 14 times. For each of those three models, the width and height of the windows was determined by the modeler. The dimensions of modeled windows from different models vary and are represented in Table 2. In width, the difference between models is 10,5 cm and in height 3 cm. In modeling phase, the determination of window dimension depended on the modeler knowledge and precision. In our case, only one part of the point cloud was used to model all of the windows. The dimensions were determined based on elevation and section views. The dimensions of other windows in the point cloud were not checked during the modeling phase.

Table 2. Measurements of windows of three different BIM models

Window dimensions in three different models		
	Width (BIM)	**Height (BIM)**
1_Our model		
All 14 windows	1000	2650
2_model by Metrika360		
All 14 windows	1080	2650
3_model by Bereich6		
All 14 windows	975	2620

Comparing the point cloud measurements to the ones from BIM, there are different deviation values for different windows, as the point cloud measurements of windows, that were supposed to be of the same sizes, were different. The results, represented in Figure 7, still show that in model one, BIM windows are too narrow and too high. In model two, windows are too wide and too high. And in model three, BIM windows are too narrow and too short. Based on previously defined requirements, only the height of the windows from model three fits the required accuracy.

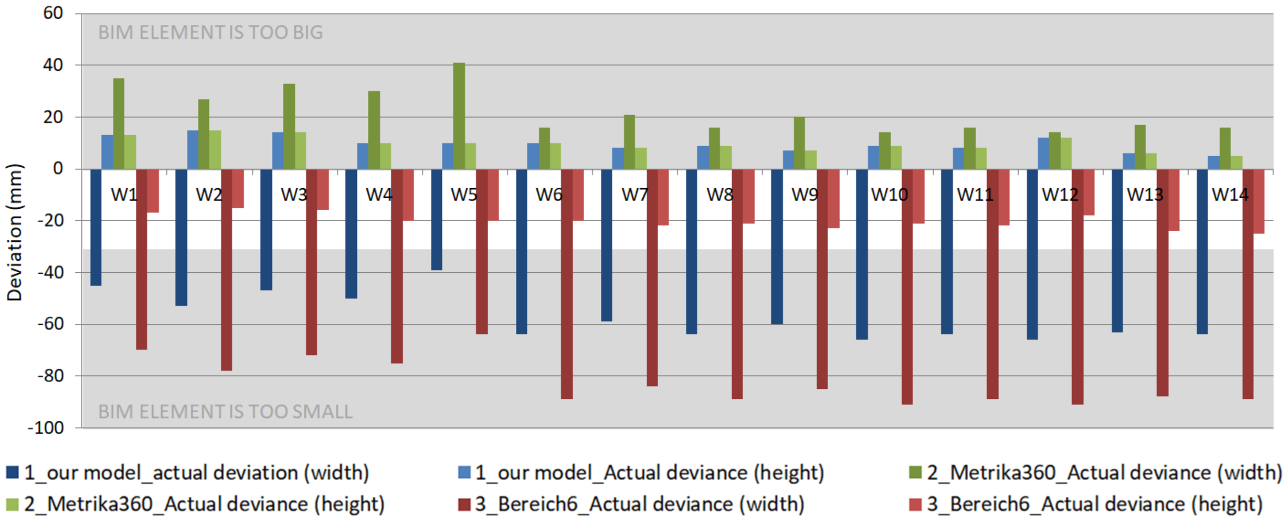

Fig. 7. Results of point selection analysis – window dimensions of three different models were compared to the point cloud window dimensions (© Authors).

Conclusions and recommendations

The results showed that the quality of the model depends on the knowledge and precision of the modeler and also the quality of the survey method (occluded zones in the point cloud represent an issue). While validating the accuracy of the entire building can be a time consuming process, it is important to determine which elements of the building and which of their properties are important for the specific case. Close attention should be given to those elements in the survey, modeling and validation phase.

To improve the quality of the model, important elements and accuracy requirements should be defined in the planning phase, using expert knowledge. The elements should be carefully documented at the existing site, using the right survey techniques (e.g. laser scanning in combination with photographs, measuring tape measures, material samples or old building documents). Laser scanning should be done in a way, to avoid occlusions in parts of the building with important elements. When needed, on-site tape measurements might provide the solution to determining the correct size of some of the partially visible building elements (e.g plaster, covering window edges, can be partially removed to measure the exact window size). In modeling phase, elements should be modeled, using different views and zooming in to the important parts of those elements. In case of repeating elements, it is advised to make a model based on multiple parts of the point cloud, representing the element. Parts with least amount of occlusions should be chosen and mean dimension values of multiple point cloud elements taken for the dimension of BIM element. In validation phase, it is important to first check if all of the important elements are modeled and then check if they are modeled right. The absolute or relative geometric accuracy should be validated, using the right validation method. Validation should be done in a way to provide quick and easy to interpret results. While BIM plugins provide quick results, they might sometimes be hard to interpret. When needed, other methods, should be used. In our study case, the point selection method was done manually and was a time-consuming process. In the future, automation of the process should be considered.

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Conflict of Interests Disclosure

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