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The Impact of Point Cloud Simplification on the Accuracy of the Viewshed

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Contemporary visibility analyses, particularly relevant in environmental and landscape studies, require the processing of very large datasets derived from point clouds. While such data provide high accuracy, they also involve substantial computational demands and long processing times, which limit their practical applicability. This article presents a detailed analysis of the impact of point cloud simplification on the accuracy of viewshed. The viewshed diagrams were generated using the ray tracing method, and the analysis included an evaluation of discrepancies between results obtained from simplified datasets and reference outcomes based on the complete, unprocessed dataset. In addition, the computation time required to generate viewshed under different levels of simplification was investigated. The findings made it possible to identify the maximum acceptable levels of simplification as well as the potential computational gains in terms of the number of processed points. The results demonstrate that properly selected simplification levels can significantly enhance the efficiency of ray tracing-based visibility analyses while preserving their practical reliability.

Keywords: visibility analysis, viewshed, point cloud, geometric accuracy, 3D data processing, spatial analysis.

1. Introduction

In contemporary expert assessments, two factors are of primary importance: the precision of analyses and the time required for their execution. Engineers face the challenge of achieving the highest possible accuracy of results within the shortest feasible time. This problem concerns various fields of analysis, including visibility assessment [1]. Determining visibility requires a range of analyses, such as three-dimensional (3D) models, photographic documentation, or visibility diagrams [2]. Visibility analysis based on a viewshed diagram, constructed from a terrain model generated using point clouds [3], demands substantial computational resources [4] in order to fully exploit the accuracy provided by the point cloud. Unfortunately, the volume of data is so large that the analysis time becomes very long and, in some cases, impossible to achieve within reasonable limits [5]. Time is therefore a critical factor, as the generation of a single viewshed has an exponential effect on the production of a visibility map, which may consist of hundreds or even thousands of diagrams. Studies on the visual protection surface (VPS) method have shown that the resolution of 3D models and the density of viewpoint sampling significantly influence the accuracy of viewshed analysis results, while computational costs increase exponentially with increasing data detail [6]. This highlights the need for a systematic evaluation of the impact of point cloud simplification on the reliability of viewshed analyses.

To accelerate the generation of viewshed maps, various point cloud simplification methods are applied [7]. Several approaches to point cloud simplification can be distinguished. One group includes methods based on hierarchical clustering, while others simplify data through the sampling of characteristic points (feature-based sampling) [8, 9]. These methods rely on advanced, often proprietary, computational models.

There are also random approaches [10], which are relatively simple and widely used in various applications. Their drawback, however, is the lack of determinism – the results may vary with each execution of the algorithm.

It is worth noting that many of the above methods are not widely available: point cloud processing software often does not implement them, or the generated results are not reproducible.

The most commonly used approaches, implemented for instance in AutoCAD and CloudCompare, are based on reducing the density of the point cloud according to a specified minimum distance δ between points [11]. Formally, this process can be expressed as selecting a subset $P' \subseteq P$ from the original point set $P = \{p_1, p_2, ..., p_n\}$ such that:

$$\min_{q \in P'} \|p_i - q\| \geq \delta.$$

More advanced approaches rely on local curvature analysis. Other methods employ information entropy.

In this article, the method of reducing point density according to a specified minimum distance between points was employed as the primary technique for simplifying the input data. Nevertheless, excessive simplification can introduce distortions and, consequently, lead to incorrect analytical results, which is unacceptable. For this reason, the simplification process was subjected to a detailed two-stage examination.

The first parameter of primary importance was accuracy. Since the accuracy of results decreases as the data are simplified, the study investigated the minimum level of accuracy that does not cause significant distortions. The second critical aspect considered was computation time. Here, the analysis focused on the time required to generate viewshed diagrams at different simplification levels, with the aim of identifying the shortest processing time corresponding to the minimum acceptable accuracy of the viewsheds.

2. Materials and methods

2.1. Point cloud

For the analysis, publicly available LiDAR data from geoportal.gov.pl were used (Fig. 1), derived from the national airborne laser scanning resource [12, 13]. The dataset corresponds to a digital elevation model (DEM) covering the area marked M-34-64-D-d-4-1-2-1 in Kraków, with an average density of 12 points/m^2. The area was scanned in 2023. Point elevations range from $h_{\min} = 161.69$ m to $h_{\max} = 334.12$ m above sea level, resulting in a total elevation difference of $\Delta h = 172.43$ m. Recorded slope values vary from 0° up to an extreme maximum of 88°. The selected area is characterized by diverse landforms, including a prominent hill, flat surfaces, urban structures, and forested terrain, as well as faults indicated by very steep slopes. This heterogeneity allows for the evaluation of simplification-induced errors across different types of topographic conditions.

a) b)

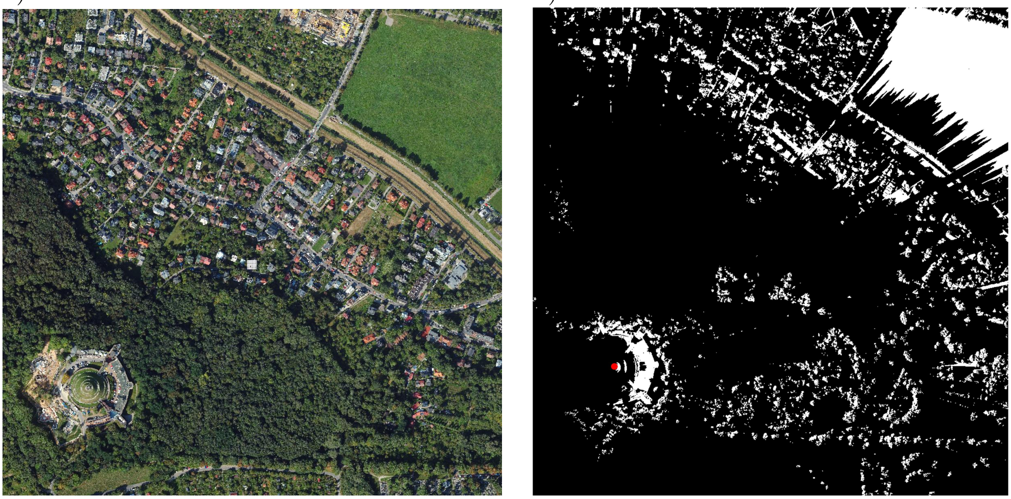

Fig. 1. Comparison of the point cloud (a) and the resulting viewshed (b). The observation point is marked with a red dot.

The point cloud was acquired using airborne LiDAR, where x, y coordinates were determined from GPS positioning and the z coordinate was calculated from the return time of a laser pulse emitted vertically toward the ground [14–16]. Each point is represented by spatial coordinates (x, y, z) and additional attributes such as RGB color values or point classification [17]. The dataset used in this study was provided in LAZ format [18], which allows efficient compression of large point clouds while preserving their accuracy.

2.2. Viewshed vs. visibility analysis

The term viewshed, introduced several decades ago by Tandy [19] and later developed by Benedikt [20], can be defined as a graphical representation of visible and non-visible areas from a specific observation point with coordinates (x, y, z) [1] (Fig. 1b). Such a diagram allows for the straightforward identification of areas obscured by terrain or other structures and those visible from the observer's position. In computational applications, viewshed analysis is typically performed using line-of-sight calculations based on digital terrain models or 3D spatial representations. Viewshed diagrams are highly versatile; for instance, they are widely used in spatial planning to evaluate whether new constructions interfere with the surrounding environment or landscape. They are also applied in tourism development, where viewsheds help identify optimal viewpoints along planned trails, thereby enhancing their attractiveness to visitors.

In contrast, visibility analysis (also referred to as visibility mapping) is a broader concept. A visibility map [2] can be understood as a composite structure consisting of multiple viewsheds generated from different observation points. The distribution and density of observation points strongly influence the resulting visibility map, affecting both its spatial resolution and analytical reliability. This integrated visualization enables the identification of panoramic routes and the assessment of cumulative visibility across an area. As a result, visibility analysis provides a more comprehensive perspective, supporting urban design, landscape management, and the development of recreational infrastructure.

2.3. Generating viewsheds based on point clouds

In order to generate a viewshed [1], different types of elevation data representations can be used. One approach involves creating a surface from the point cloud, for example in the form of a regular grid or a triangulated irregular network (TIN) [4] (Fig. 2). The TIN surface, based on the Delaunay triangulation algorithm, provides high precision and is frequently employed in visibility studies. Alternatively, many popular GIS tools, such as QGIS, allow viewsheds to be generated directly from digital elevation models (DEMs) or digital terrain

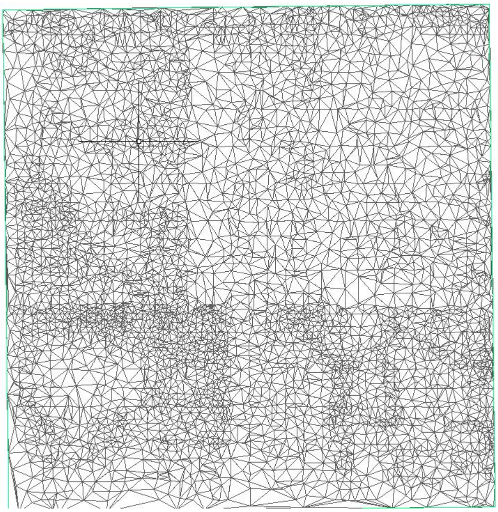

Fig. 2. Tin surface for the area analysed in the study.

models (DTMs/DSMs) in raster form – but viewshed charts are not as highly accurate as those based on point clouds.

Regardless of the chosen method, the process involves placing an observation point at a given location and analyzing terrain obstruction along the line of sight. The result is a graphical representation of visible and non-visible areas, typically encoded in binary form (e.g., visible areas shown in white and non-visible areas in black).

2.4. Computing machine parameters

The calculations were executed on a high-performance workstation featuring an Intel(R) Core(TM) i9-14900K processor (3.20 GHz), 64 GB RAM, and a 64-bit operating system on x64 architecture.

2.5. Point cloud simplification method

The method applied for point cloud simplification was increasing the minimum distance between points. This approach is implemented in software such as AutoCAD Civil 3D or CloudCompare. It is based on an iterative traversal of the points and checking the distance between a given point and the others. Although the intermediate results may vary depending on the order of point evaluation, the final outcome is always the same, since the initial and final points are fixed [21]. The organization of the point cloud does not change, as points are only removed rather than restructured. However, the surface generated from the simplified point cloud in the form of a TIN differs from the original, since it is constructed without the deleted points. As a result, the generated surface produces different outcomes in the viewshed diagram.

Formally, let the original point cloud be defined as:

$$P = \{p_1, p_2, ..., p_n\}, \qquad p_i \in \mathbb{R}^3.$$

The goal of simplification is to select a subset $P' \subseteq P$ such that the minimum Euclidean distance between any two points in P' is not smaller than a predefined threshold δ:

$$P' = \{p_i \in P : \min_{q \in P',\, q \neq p_i} \|p_i - q\| \geq \delta\}.$$

Here, δ is the simplification threshold that determines the minimum allowed spacing between points.

For point clouds with densities of 4 to 20 points per square meter, the average spacing between points is typically on the order of several tens of centimeters. This spacing depends on the scanning geometry during data acquisition and it is not constant. Within a single square meter, distances between neighboring points can range from as little as 1 cm to as much as 70 cm [22]. The spacing is further influenced by the specific LiDAR sensor model employed. For the dataset used in this study, analysis showed that the minimum spacing between points was 4 cm, corresponding to an average density of 12 points per square meter.

During the simplification process, points closer to each other than a specified threshold δ were removed. Seven thresholds were defined:

$$\delta \in \{10\,\text{cm},\ 20\,\text{cm},\ 30\,\text{cm},\ 50\,\text{cm},\ 80\,\text{cm},\ 100\,\text{cm},\ 200\,\text{cm}\}.$$

For each of the simplified point clouds, a viewshed diagram was generated and compared against the reference diagram derived from the full, non-simplified dataset. The differences between them were analyzed. In addition, the computation times were recorded, including both the simplification stage and the viewshed diagram generation stage.

Increasing the minimum distance between points plays a central role in the simplification of point clouds. The specified distance thresholds allow control over the degree of simplification and its adaptation to the needs of the analysis. Higher thresholds result in sparser point clouds, which reduce detail but at the same time accelerate the generation of viewshed diagrams. Comparing viewshed diagrams obtained from different levels of simplification enables an evaluation of the effect of simplification on the accuracy of visibility analysis. Furthermore, incorporating the time required for point cloud simplification makes it possible to optimize the overall workflow of viewshed diagram generation with respect to both computational efficiency and analytical accuracy.

To evaluate the accuracy of the viewshed diagrams, three indicators were applied. The first one is the error rate, which measures the difference between the simplified and the reference (non-simplified) diagram. It is calculated by comparing individual pixels of both diagrams and expressed as the percentage of differing pixels relative to the total number of pixels in the image.

The second indicator concerns the magnitude of a single error. It quantifies the size of the area affected by an error, forming a contiguous patch. The larger the value of a single error, the greater its significance for the overall result, as it indicates a stronger influence on the analysis.

The third indicator is an author-based visual–analytical assessment focusing on the visual interpretability of differences between the simplified and reference diagrams. The analysis was conducted by the authors and evaluated whether simplification-induced changes affected key visibility patterns, the spatial continuity of visible areas, and the presence or absence of critical occlusions relevant to viewshed interpretation. This analysis examined the extent to which these differences affect the correctness and interpretation of the results. In particular, it assessed whether changes introduced by simplification could distort or influence the understanding of spatial relationships visible in the reference diagram.

Together, these three indicators provide a more comprehensive evaluation of the quality of the simplified diagrams. The percentage error offers an objective measure of the differences, while the qualitative analysis addresses their potential impact on result interpretation.

3. Results

To evaluate the impact of point cloud simplification on visibility analysis, seven thresholds of minimum point spacing were tested: 10 cm, 20 cm, 30 cm, 50 cm, 80 cm, 100 cm, and 200 cm. The corresponding figures illustrate how the viewshed diagram changes depending on the adopted minimum distance between points. For each threshold, three key elements are presented:

– viewshed diagram: illustrates the simplified diagram at a given minimum point spacing,
– differences relative to the non-simplified diagram: highlights discrepancies between the simplified and the original, full-resolution diagram,
– significant differences marked in red: indicates differences with a substantial impact on the quality and accuracy of the diagram. These are highlighted in red for clarity.

Figure 3 shows the relationship between the error of viewshed diagrams and the adopted minimum distance between points. As the simplification threshold increases, the error systematically grows – from values close to zero for the full

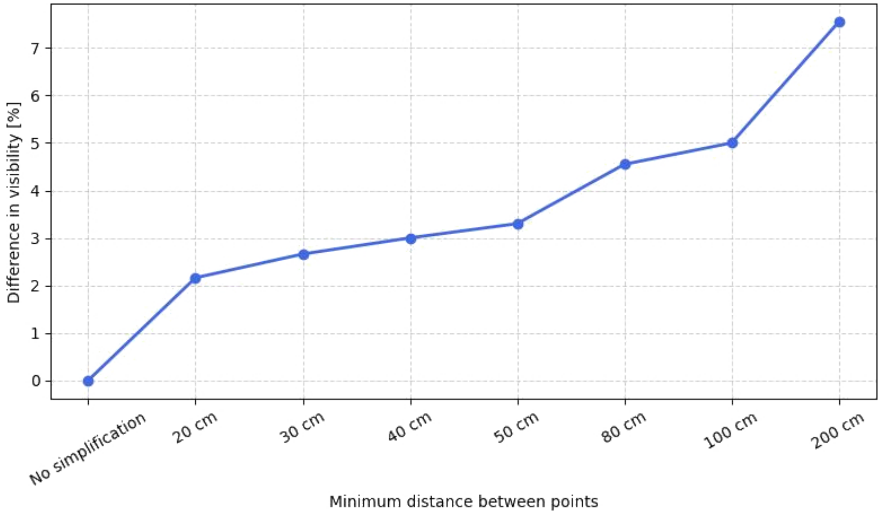

FIG. 3. Relationship between the percentage error in viewshed diagrams and the minimum distance threshold applied during point cloud simplification.

dataset up to more than 7.55 % for the 200 cm threshold. This demonstrates that excessive simplification leads to noticeable distortions in visibility analysis.

Figure 4 illustrates the number of points remaining in the cloud after applying different simplification thresholds. A sharp decrease can be observed – from nearly 80 million points without simplification to fewer than 1 million points at the 200 cm threshold. These results clearly confirm that the method effectively reduces the complexity of the point cloud.

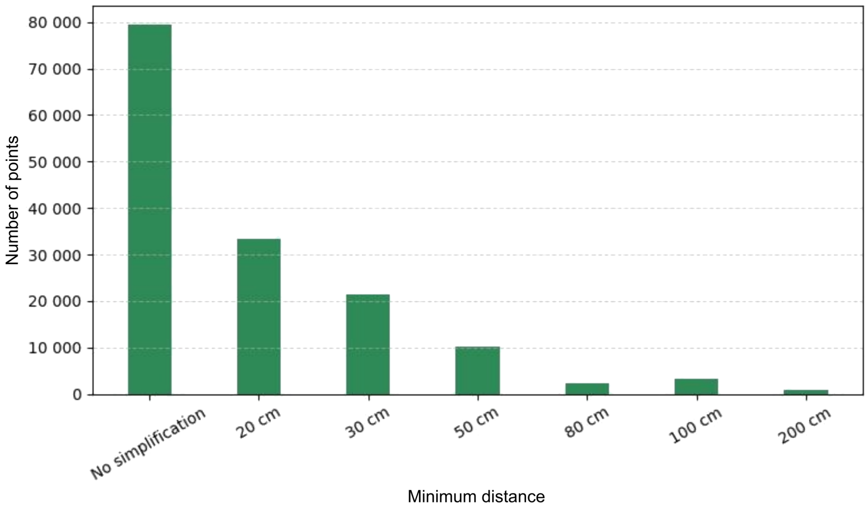

FIG. 4. Number of points in the point cloud as a function of the minimum distance between points.

Figure 5 presents the computation time required to generate viewshed diagrams depending on the degree of simplification. The results indicate that simplification significantly shortens computation time – from approximately 10 000 seconds for the full cloud to below 1000 seconds for the highest threshold. This means that reducing the number of points substantially improves computational efficiency, though at the cost of accuracy.

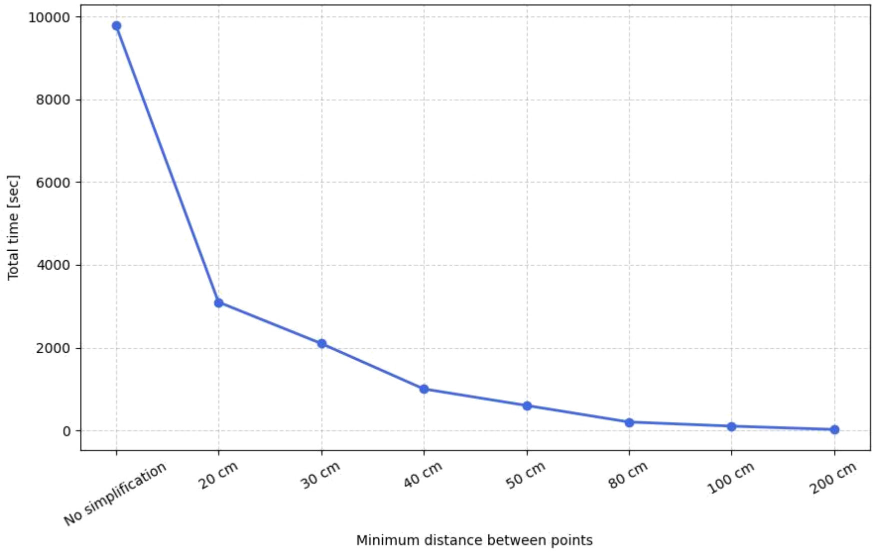

Fig. 5. Computation time required to generate a viewshed diagram as a function of the minimum distance between points in the point cloud, excluding the time needed for simplification and surface generation.

A summary of the numerical values is provided in Table 1, which lists the times of individual stages of viewshed diagram generation, the number of points

Table 1. Results of point cloud simplification for different minimum distances.

Minimum distance [cm]	Simplification time [s]	Surface generation time [s]	Number of points	Simplification [%]
No simplification	0	71	79 477 954	100.00
20	41	42	33 435 357	42.07
30	43	21	21 370 480	26.89
40	50	15	15 000 000	18.90
50	58	10	10 236 052	12.88
80	48	4	2 398 782	3.02
100	45	4	3 327 330	4.19
200	18	0	854 506	1.08

for different minimum distance thresholds, and their percentages relative to the original point cloud.

Table 2 presents a comparison of visibility differences resulting from the level of point cloud simplification. It can be observed that the greater the degree of simplification, the more significant the differences in the results become. This leads to a reduction in the consistency of the visibility map compared to the reference map, which was generated from the full, non-simplified point cloud.

TABLE 2. Difference in visibility results as a function of the minimum distance threshold.

Minimum distance between points [cm]	Difference in visibility [%]
No simplification	0.00
20	2.16
30	2.66
40	3.00
50	3.30
80	4.55
100	5.00
200	7.55

Reducing the minimum distance between points to 20 cm (Fig. 6) had only a minor effect on the accuracy of the viewshed diagram. The analysis showed that most areas remained unchanged, with the only noticeable differences occurring in regions of local forest density. This affected visibility only in a small portion of the area and had no significant impact on the overall quality of the diagram.

a) b) c)

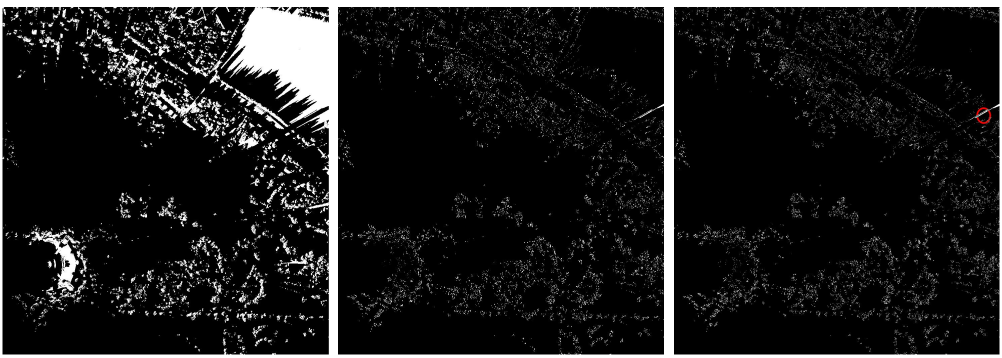

FIG. 6. Comparison of visibility analysis results for the 20 cm simplification threshold: a) viewshed diagram generated with a 20 cm minimum point spacing, b) differences compared to the reference (non-simplified) diagram shown as absolute visibility changes, c) significant differences highlighted in red.

A more detailed error analysis revealed that the difference amounted to only 2.16 % (Table 2) compared to the diagram generated from the full point cloud. Such a small discrepancy can be considered acceptable in the context of maintaining result precision.

In the following section, the analysis is based on absolute differences in visibility and is discussed using three complementary images. The first image presents the viewshed result generated with a given simplification threshold, the second shows absolute differences with respect to the reference (non-simplified) model, and the third provides the differences highlighted in red. These red markings are manual annotations made by the authors based on visual inspection and serve illustrative purposes. Their aim is to help the reader identify the most visually apparent discrepancies between the images. The markings do not result from automatic detection, and no magnitude threshold was applied.

The most substantial benefit of applying the 20 cm simplification threshold was the considerable improvement in computational efficiency. The computation time was reduced to 3042 seconds (Fig. 5), representing a significant acceleration compared to processing the full point cloud. This reduction enables faster generation of viewshed diagrams, which is particularly important in practical applications where data processing time is a critical factor.

Reducing the minimum distance between points to 30 cm (Fig. 7) resulted in a greater number of differences compared to the original chart. These differences were more noticeable; however, their impact on the overall quality and interpretation of the data remained minimal. Nevertheless, from the standpoint of accuracy and reliability of the data, it is recommended to carry out a detailed verification of these differences to ensure that they do not negatively affect the key conclusions drawn from the charts.

a) b) c)

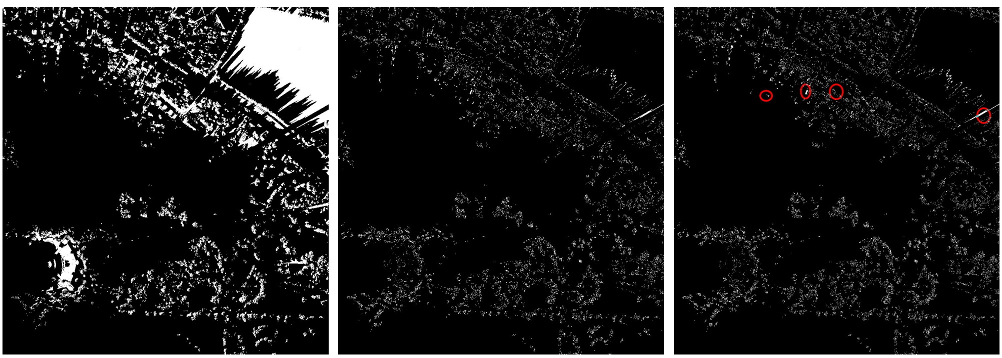

Fig. 7. Comparison of visibility analysis results for the 30 cm simplification threshold: a) viewshed diagram generated with a 30 cm minimum point spacing, b) differences compared to the reference (non-simplified) diagram shown as absolute visibility changes, c) significant differences highlighted in red.

An error of 2.66 % (Table 2) in relation to the original chart is higher than the previous 2.16 %, but it still falls within acceptable limits. This level of error is particularly permissible in the case of generating more extensive charts, where data processing speed may take precedence over absolute precision.

Reducing the distance between points to 30 cm also has a significant impact on computational performance. In practice, this means that the time required to generate the chart is just under 840 seconds (14 minutes) (Fig. 5), which is considerably shorter compared to the original 9660 seconds (161 minutes) (Fig. 5). As a result, despite the slightly higher error, this method can be effectively applied in scenarios where processing time is a key factor and minor deviations from ideal accuracy are acceptable.

In the case of a minimum distance of 40 cm (Fig. 8), the results begin to deviate dangerously from the original. In practice, this means that the accuracy of the generated data deteriorates significantly, resulting in an error exceeding 3 % (Table 2). Such a deviation may lead to incorrect conclusions and decisions based on these data.

a) b) c)

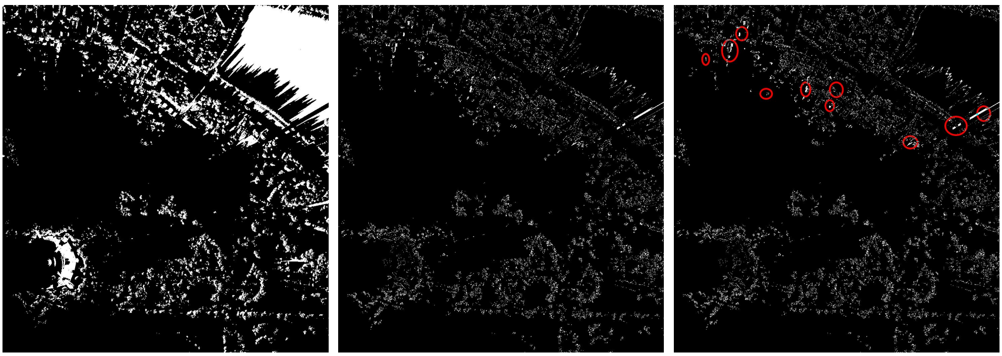

Fig. 8. Comparison of visibility analysis results for the 40 cm simplification threshold: a) viewshed diagram generated with a 40 cm minimum point spacing, b) differences compared to the reference (non-simplified) diagram shown as absolute visibility changes, c) significant differences highlighted in red.

Although the difference between 2.66 % and 3.0 % is small, exceeding the 3 % threshold causes noticeable changes in the nature of errors larger clusters of differences begin to appear (Figs. 7 and 8), leading to increased ambiguity in the interpretation of results. Based on this, it can be estimated that the acceptable error threshold is approximately 3 %, because above this value we observe a significant deterioration in the quality of the analysis.

Therefore, it is recommended that charts created using this distance be treated only as auxiliary charts supporting the main analysis, but not as the primary result. Auxiliary charts may be useful for quickly estimating trends or general tendencies, but due to the higher level of error, they should not be used for making critical decisions. In cases where precision is crucial, methods with smaller point spacing should be relied upon, as they ensure greater accuracy.

Reducing the minimum distance between points to 50 cm (Fig. 9) caused a significant decrease in the number of points, reducing them to only 12 % of the initial amount. Such a loss of data has serious consequences for the quality of the chart. On the viewshed chart, an increasing number of differences appeared in comparison to the original chart, which resulted in an error of 3.3 % (Table 2).

a) b) c)

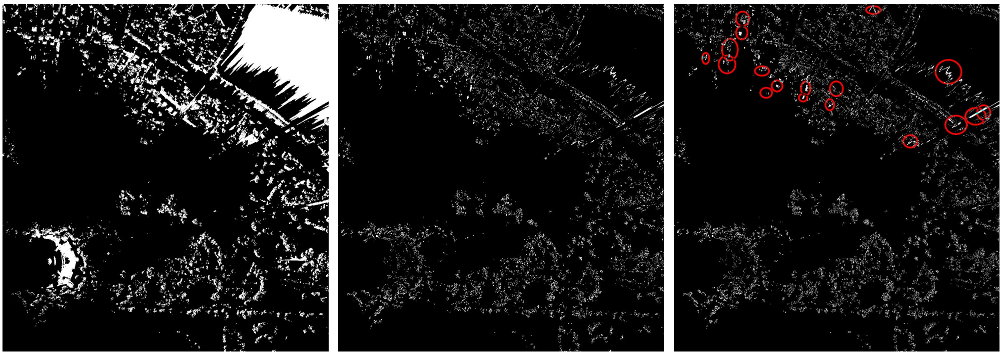

Fig. 9. Comparison of visibility analysis results for the 50 cm simplification threshold: a) viewshed diagram generated with a 50 cm minimum point spacing, b) differences compared to the reference (non-simplified) diagram shown as absolute visibility changes, c) significant differences highlighted in red.

An error level of 3.3 % indicates considerable deviations from the actual state of the analysis. Such a large discrepancy may distort the results and lead to incorrect conclusions; therefore, the chart obtained with this level of point reduction should be treated only as a supporting tool. It cannot be used as an accurate representation of the actual state of the analysis due to the substantial loss of information and potential interpretative errors.

Using a chart based on such a significantly reduced number of points may only be justified in situations where quick orientation in the data is required or where other methods are not feasible. However, for precise and reliable analyses, it is necessary to retain a larger number of points to ensure an accurate representation of the actual state of the analyzed objects or phenomena.

Reducing the minimum distance between points to 80 cm (Fig. 10) drastically shortens the time required to generate the viewshed chart. Compared to the full dataset, this time becomes almost negligible, which can be a major advantage in situations requiring rapid data processing. However, this substantial gain in performance comes with serious compromises in accuracy.

a) b) c)

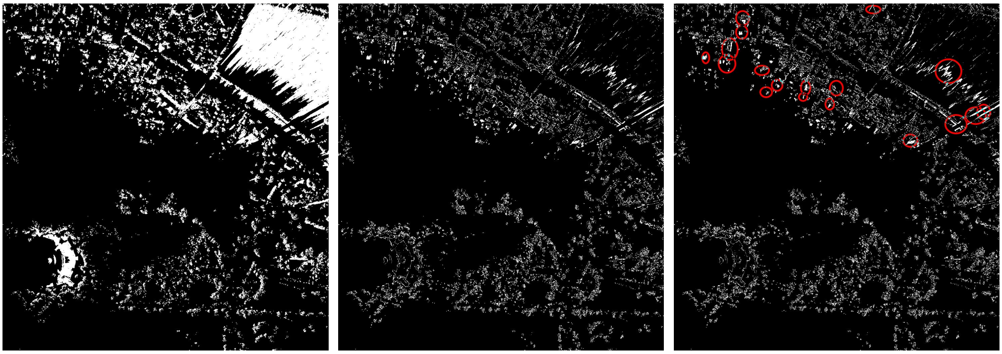

Fig. 10. Comparison of visibility analysis results for the 80 cm simplification threshold: a) viewshed diagram generated with a 80 cm minimum point spacing, b) differences compared to the reference (non-simplified) diagram shown as absolute visibility changes, c) significant differences highlighted in red.

An error exceeding 4.55 % (Table 2) means that the simplified chart diverges significantly from the chart based on the full dataset. In practice, this indicates that the differences between the simplified chart and the original are numerous and may lead to incorrect conclusions. Such a level of inaccuracy can introduce substantial distortions in data interpretation, which in turn may affect decisions made based on these charts.

Therefore, viewshed charts generated with a minimum point spacing of 80 cm should be regarded as quick, preliminary analytical tools. They can be useful for gaining a rapid overview of the data and guiding subsequent steps of analysis by highlighting areas that require closer examination. However, for precise and reliable analyses, it is necessary to create more detailed charts with smaller minimum point spacing to ensure full consistency with the original and to avoid significant errors.

Reducing the minimum distance between points to 100 cm (Fig. 11) significantly shortened the time required to generate the viewshed chart, reducing it to just 65 seconds (Fig. 5). Although this result is highly advantageous in terms of performance, it comes with serious compromises in data accuracy.

An error level of 5 % (Table 2) indicates a substantial deviation from the chart based on the full dataset. The numerous differences between the simplified chart and the original may lead to incorrect conclusions and distortions in data interpretation. Such a level of error is too high for the chart to be considered reliable for precise analysis.

In practice, this means that charts generated with a minimum point spacing of 100 cm may only be useful in situations requiring rapid data orientation or as supporting tools. They can serve for preliminary analysis and for identifying

a) b) c)

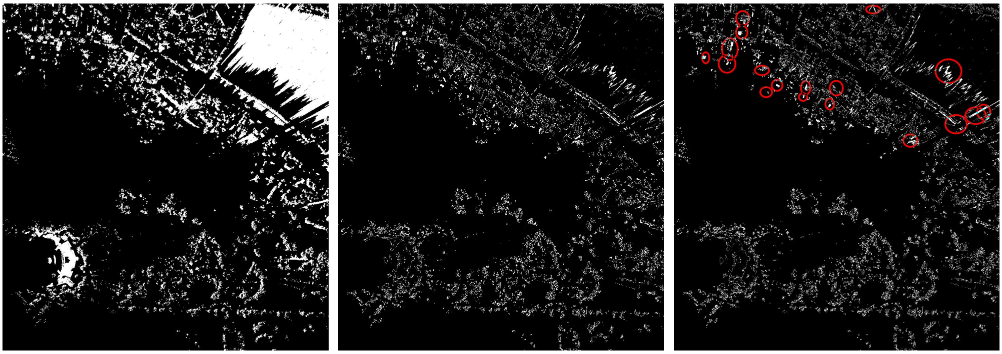

Fig. 11. Comparison of visibility analysis results for the 100 cm simplification threshold: a) viewshed diagram generated with a 100 cm minimum point spacing, b) differences compared to the reference (non-simplified) diagram shown as absolute visibility changes, c) significant differences highlighted in red.

areas that require closer examination, but they should not be used as the primary tool for drawing conclusions.

To ensure accuracy and reliability of analyses, it is necessary to use charts with smaller minimum point spacing. Only then can significant errors be avoided and results guaranteed to be sufficiently precise and representative of the actual state of the analyzed data.

Reducing the minimum distance between points to 200 cm (Fig. 12) leads to extremely fast generation of the viewshed diagram, taking only 12 seconds (Fig. 5). While such a short processing time may seem appealing, it comes with serious compromises in terms of data accuracy and reliability.

a) b) c)

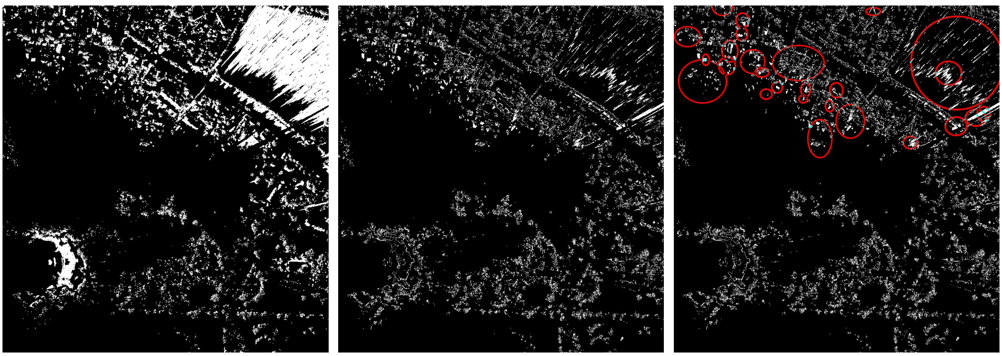

Fig. 12. Comparison of visibility analysis results for the 200 cm simplification threshold: a) viewshed diagram generated with a 200 cm minimum point spacing, b) differences compared to the reference (non-simplified) diagram shown as absolute visibility changes, c) significant differences highlighted in red.

An error level of 7.55 % (Table 2) relative to the reference chart is significant and indicates severe deviations from the actual state. The missing elements on the chart, marked in red, show which data areas were omitted or distorted. This drastically reduces the quality of the presented results, rendering the chart unreliable and unsuitable for analysis.

The absence of visible objects on this chart means that many essential pieces of information are missing, which disqualifies it as an analytical tool. In the context of any precise work, where accuracy and data completeness are critical, such a chart fails to meet the basic requirements.

4. Conclusions

The conducted research demonstrated that the degree of point cloud simplification, achieved by increasing the minimum distance between points, has a direct and measurable impact on both the accuracy of viewshed diagrams and the time required for their generation. The obtained results allow for identifying clear thresholds of analytical usability. For small simplification parameters ($\delta = 20$ cm to 30 cm), differences compared to the reference diagram do not exceed 2.16 % to 2.66 %, while the number of points is reduced to approximately 27 % to 42 % of the original dataset and computation time decreases from about 9600 s to a range of 840 s to 3000 s. This range represents an optimal compromise between accuracy and computational efficiency and can be recommended for reliable visibility analyses. Further increasing the simplification level ($\delta = 40$ cm to 50 cm) leads to errors exceeding 3 % and the emergence of noticeable spatial clusters of differences, which limits the interpretability of results. In such cases, diagrams may serve only as auxiliary or indicative tools. Simplifications of $\delta \geq 80$ cm result in significant distortions (errors of 4.55 % to 7.55 %) and should not be applied in analyses requiring high reliability. Future research should extend the analysis to other point cloud reduction methods, including adaptive approaches that locally decrease point density in areas of lesser importance for visibility while preserving detail in critical zones. Such solutions could enable further reduction of computation time without substantial loss of result quality.

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