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Multi-Criteria Evaluation of Urban 3D Mesh Model Quality Using Three Photogrammetric Software Tools

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Abstract:
Urban 3D models play an increasingly significant role in various domains such as spatial analysis, urban planning, environmental monitoring, and the design and management of smart infrastructure. These models offer a detailed and realistic representation of urban environments, which aids decision-makers and urban developers in evaluating current conditions and predicting future development scenarios more effectively. Due to the growing number and diversity of photogrammetric and reality-capture software available in the market, ensuring the quality and reliability of the generated 3D models is of paramount importance. Precise quality evaluation—both geometrically and visually—is essential for selecting the most appropriate tool for urban applications.In this study, a comprehensive quality assessment was carried out based on four main categories: visual and radiometric quality control, absolute geometric accuracy, length measurement accuracy, and internal consistency (internal accuracy). The performance of three widely-used software tools Pix4D Mapper, Agisoft Metashape, and Itwin Capture Modeler was evaluated using identical input datasets. According to the analysis results, Itwin Capture Modeler outperformed the other two in terms of both geometric precision and visual fidelity. These findings suggest that Itwin is a more reliable and efficient option for professionals engaged in high-quality urban modeling projects.

1.Introduction

Urban 3D models provide a valuable platform for advanced spatial analyses in fields such as disaster management, construction monitoring, infrastructure planning, and smart city development. The advancement of sensors, reconstruction algorithms, and photogrammetric systems has enabled the rapid and relatively automated generation of these models. However, potential errors and deficiencies in the models may lead to inaccurate decisions, highlighting the critical importance of quality assessment. Urban 3D models, as accurate geometric and semantic representations of urban structures, have become vital tools in urban planning, environmental modeling, disaster management, and smart infrastructure development. These models, by enabling visualization and analysis of spatial data in three dimensions, provide a powerful foundation for scientific and engineering decision-making (Biljecki et al., 2015). With the advancement of data acquisition technologies such as remote sensing, airborne LiDAR, drone imagery, and 3D reconstruction algorithms, the automated production of urban models has significantly progressed (Peters et al., 2021). Meanwhile, quality evaluation of these models has become both a scientific and practical necessity, as any errors or inaccuracies can lead to flawed analyses, poor decisions, and even economic or environmental costs (Ennafii et al., 2019).

1.1 Research Background

Recent studies have developed modern approaches for evaluating urban 3D models based on a combination of quantitative and qualitative criteria. Some of the evaluation criteria addressed in this study are classified into the following four categories:

a) Model Quality Control

This includes visual and radiometric assessments to examine the coherence, texture, clarity, and optical distortions of the models (Wagner et al., 2007).

b) Absolute Accuracy Control

Refers to the geometric consistency of the model with reality in both horizontal (planimetric) and vertical (altimetric) dimensions. This is typically analyzed using ground control points (GCPs) and indicators such as RMSE (ISO 19157:2013, 2020).

c) Length Accuracy Control

Performed by comparing measured dimensions in the model whether based on physical targets or known object sizes with reference data (Macay, 2018).

d) Internal Accuracy Control of the Model

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This involves analyzing indicators such as data density, 3D noise, point sparsity, and the spatial resolution of the model in three dimensions. This category supports the structural stability of the model and the feasibility of precise subsequent analyses (Val3dity Tool, ISPRS 2020). In addition, standard frameworks such as CityGML and CityJSON, developed by the OGC, aim to standardize the conceptual, semantic, and geometric structure of 3D models and facilitate data evaluation and interoperability (Gröger et al., 2012). Global initiatives such as 3D BAG (Netherlands) and Virtual Singapore have successfully employed these frameworks to produce and evaluate national-scale 3D models. This article focuses on these four evaluation domains and assesses the quality of 3D mesh models using different software tools.

2. Proposed Method

This section outlines the evaluation workflow of 3D mesh models using three widely recognized photogrammetric software tools: Pix4D Mapper (version 4.5), Agisoft Metashape (version 2.2.1), and Itwin Capture Modeler (version 2024). The 3D models were generated for an urban area using rendered images captured from

- Detection of texture seams, color inconsistencies, or distortions
- Overall assessment of object integrity (e.g., does the model of a building visually resemble a real building?)

b) Radiometric Quality Control:

In textured models, radiometric quality plays a crucial role. The texture evaluation criteria in this study include:

- Texture sharpness: the image resolution relative to the surface area, expressed in pixels per meter
- Color and lighting uniformity: absence of unnatural lighting, undesirable shadows, or inconsistent color across the same surface
- Signal-to-noise ratio (SNR).

2.2 Absolute Accuracy Control (Vertical and Horizontal)

Absolute accuracy was assessed in two ways: vertical (elevation) and horizontal (planimetric), each explained below.

a) Vertical Absolute Accuracy

Elevation data from DEMs/DSMs or 3D models should be consistent with real ground data such as GPS, GNSS, or terrestrial LiDAR. For this purpose:

- Elevation control points are measured on the ground or rooftops
- Error at each point is calculated, and indicators such as vertical RMSE or NMAD are reported
- Sometimes, the "percentage of points with error less than ±1 meter" is used as a criterion

b) Horizontal Absolute Accuracy

In this part, the horizontal location of features in the model is compared using the estimated coordinates of ground control points after bundle adjustment. Planimetric and vertical discrepancies between the model and the reference are assessed accordingly.

2.3 Length Accuracy Control

20 identical viewpoints. The evaluation was conducted based on criteria such as visual quality control, as well as geometric criteria, including absolute accuracy, length accuracy control, and internal accuracy of the 3D model, each of which is described in detail in the following sections.

2.1. Quality Control (Visual and Radiometric):

In this study, quality control was examined from two aspects: visual and radiometric.

a) Visual Quality Control:

Visual evaluation is the primary and most common method for assessing the quality of 3D models. In this method, experts use software such as Pix4D Mapper Enterprise, Agisoft Metashape, and Itwin Capture Modeler to inspect visual defects in the model. The following items must be considered during visual inspection:

- Presence of open edges or defective surfaces
- Errors in surface vertex sequencing (e.g., surface twisting or self-intersection

Length accuracy was assessed using two criteria: target-based and object-based, described as follows:

a) Target-Based Length Accuracy

In this method:

- Accurate reference points with known distances (e.g., between two geodetic nails or building corners) are used
- The distance is measured in the 3D model and compared with the actual value
- This method is highly precise and lab-oriented, it has limitations in large urban environments

b) Object-Based Length Accuracy

In this method:

- Known dimensions of urban features (e.g., street width, wall length, or building height) are compared with values from the model.
- Accuracy in this method often depends on the model's level of detail (LoD) and visual clarity

2.4 Internal Accuracy Control of the 3D Model

Internal model control includes:

- 2D point density
- Mesh uniformity index
- Point distribution (sparsity) in the final model

These factors contribute to structural stability of the model and its feasibility for further precise analyses.

3. Results

3.1. Software Selection

In this section, the most suitable software for geometric and visual evaluation of urban 3D mesh models were identified and utilized. These include:

- Pix4D Mapper Enterprise 4.5-2013
- Agisoft Metashape 2.2.1-2025
- Itwin Capture Modeler-2024

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3.1.1 Geometric Evaluations

Based on the available data and the study area, the following three geometric evaluations were implemented:

a) Geometric Accuracy:

Defined as the perpendicular error of ground control points estimated from the 3D mesh. Estimated coordinates were used rather than field-surveyed ones to isolate mesh reconstruction errors from bundle adjustment errors in each software. Therefore, the reconstruction error is assessed independently in each software using post-bundle adjustment estimated coordinates. This evaluation highlighted the superiority of Itwin software over the other platforms. Table 1 presents the results obtained from the different software packages.

Software	Z- estimated (m)	Z- mesh (m)	Sign distance (m)
Pix4d mapper	1541.725	1541.88	-0.155
Agisoft Metashape	1541.938	1542.035	-0.097
Itwin capture	1541.7	1541.692	0.008

Table 1: Results of Geometric Accuracy Assessment

b) 2D Density:

2D density refers to the number of faces present per unit area. The results obtained for 2D density are presented in Table 2.

Software	2D density (face/m^2)
Pix4d mapper	0.4
Agisoft Metashape	4.77
Itwin capture	2.38

Table 2: Results of 2D Density Assessment

It should be noted that a high 2D density value alone does not necessarily indicate a high-quality 3D mesh model. All three software programs utilize mesh simplification techniques during mesh reconstruction to optimize and re-present the mesh. In this process, the number of faces is reduced in flat areas and increased in more complex or uneven surfaces. Therefore, the impact of this factor should be interpreted in combination with other geometric and visual evaluation metrics to gain meaningful insight. Among the tested software, Agisoft produced the highest density with 4.77 faces/m², while Pix4D showed the lowest with 0.4 faces/m². Nevertheless, higher density does not always correlate with better quality and must be assessed alongside other indicators.

c) Mesh Homogeneity:

This section evaluates the distribution of triangle size and shape within the mesh. Non-uniform meshes may indicate noise or reconstruction errors. A normalized metric is used to assess triangle uniformity:

- The closer the value is to 1, the more homogeneous the triangles are (closer to equilateral).
- Values closer to 0 indicate greater irregularity in the triangles forming each face.

Equation 1 was used to assess this characteristic.

$$\text{Quality Metric}=\frac{4.A.\sqrt{3}}{\sum_{i=1}^{3} side_i^2} \quad (1)$$

In this equation, A represents the area of each triangle, and side denotes the length of each edge. In Table 3, the mean and standard deviation of this normalized index are calculated and presented. The last column shows the percentage of triangles in the entire 3D mesh with a uniformity score less than 0.5. A lower percentage in this column indicates greater mesh homogeneity. Using this normalized metric, Itwin had the lowest uniformity, with a mean value of 0.74 and a lower percentage of irregular triangles. This result may be attributed to the mesh simplification algorithm or local reconstruction errors.

Software	Mean	Std	Lower than (0.5) percentage
Pix4d mapper	0.87	0.12	1.6 %
Agisoft Metashape	0.84	0.16	4.5 %
Itwin capture	0.74	0.20	13.9 %

Table 3: Results Derived from Equation 1

3.1.2. Visual Evaluation:

For the visual evaluation, 20 identical viewpoints of each of the three textured 3D mesh models were generated and images were saved. Based on expert judgment, the following criteria were used for scoring the models. In Table 4, a score of 1 represents poor quality, and 5 represents excellent quality. Human scoring indicated that Itwin, with an average score of 5, outperformed in all visual criteria, while Pix4D showed the weakest performance in most criteria.

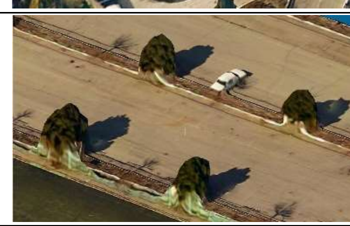
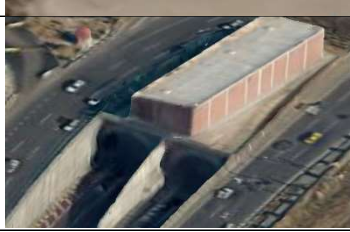
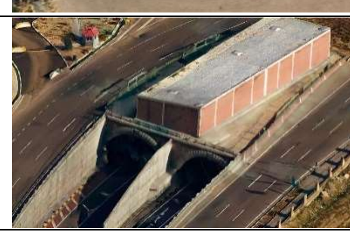
Table 5 visually presents the image results from the different software. According to the displayed images, the visualization in the Itwin software is better and of higher quality compared to the other two software programs.

Criterion	Itwin Capture	Agisoft Metashape	Pix4d Mapper
Sharpness	5	3	1
Noise	5	4	1
Color Fidelity	5	4	3
Contrast	5	4	4
Artifacts	5	3	1
[1] SSIM	5	3	2
Naturalness	5	4	1

[1] Structural Similarity Index

detail preserving	5	3	1
Average Score	5	3.5	1.75

Table 4: Results of Visual Evaluation

meta	pix	twin	Criterion
			Color Fidelity
			SSIM
			SSIM
			Naturalness
			Noise
			Sharpness
			Sharpness

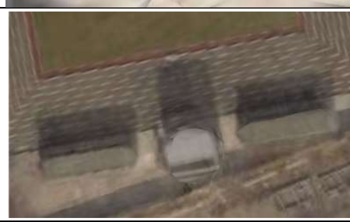
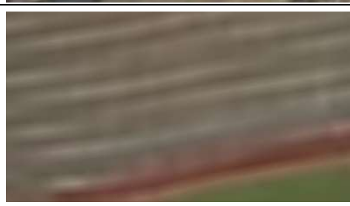
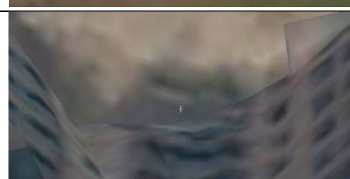
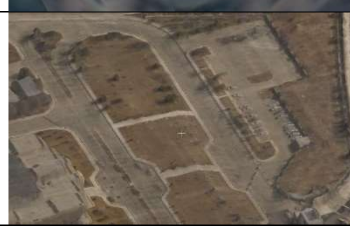
meta	pix	twin	Criterion
			detail preserving
			Artifacts
			Sharpness
			Color Fidelity
			Artifacts
			Contrast

Table 5: Visual Display in Different Software

4. Conclusion

The quality assessment of urban 3D models is of great importance due to their wide applications in urban planning, infrastructure management, and the development of smart cities. In this study, three prominent software packages for generating 3D models—Pix4D Mapper, Agisoft Metashape, and Itwin Capture Modeler—were evaluated based on four main criteria: quality control (visual and radiometric), absolute accuracy, length accuracy, and internal accuracy. The results from geometric and visual analyses showed that Itwin Capture Modeler outperformed the other software in most indicators, particularly in geometric accuracy, mesh homogeneity, and visual quality of the models. On the other hand, although software such as Agisoft Metashape performed well in certain parameters, such as data density, it had overall lower quality compared to Itwin when considering the combined evaluation criteria. Ultimately, it can be concluded that selecting the appropriate software for producing urban 3D models should be based on a comprehensive set of technical and practical criteria. Using a multi-criteria approach for quality assessment provides a holistic view of each software's strengths and weaknesses and greatly aids decision-makers and urban modeling specialists in choosing the optimal tool.

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