BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 74(1), 2026, Article number: e156770
DOI: 10.24425/bpasts.2025.156770

CIVIL ENGINEERING

Evaluating geometric quality and accuracy of 3D building models: a concept of 3D model evaluation method

Przemysław KLAPA *

Department of Geodesy, University of Agriculture in Krakow, al. Mickiewicza 21, 31-120 Krakow, Poland

Abstract. Evaluation of 3D building model quality is central to civil engineering, geodesy, architecture and the construction industry as it facilitates the assessment of the model's accuracy, completeness and interoperability. The article presents a concept of a versatile method for evaluating the quality of 3D building models, the 3D model evaluation method. It can compare models regardless of their data sources, modelling techniques, visualization and file format. The method covers key quality aspects such as completeness, which reflects the degree to which object components are represented; accuracy, which concerns geometric and positioning integrity; and interoperability, which includes the model's compliance with standards, editability and reusability. The author investigated a range of 3D modelling approaches, including mesh, solid and parametric models derived from a variety of data sources. The proposed evaluation method is founded on analyzing model attribute values for selected criteria followed by visualization of these values on a radar chart. The model quality index, normalized to [0; 1], quantifies the 3D model quality. The results demonstrate the method's effectiveness for 3D model evaluation regarding both geometric and non-geometric aspects. The method can be applied in GIS, BIM, spatial analyses, civil engineering and environmental engineering. It provides a single pipeline for classifying and comparing different types of models. The 3D model evaluation method provides a universal, structured and practical basis for comparing 3D models across sources and techniques, ensuring result comparability and consistent quality reporting.

Keywords: 3D modelling; model quality evaluation; solid model; mesh model; parametric model.

1. INTRODUCTION

1.1. Foundations of 3D building modelling

A 3D model is a digital representation of an object or scene in a three-dimensional space generated by a structure of points, lines and faces [1]. It is used to represent shapes, textures and other properties of objects exactly and quantifiably [2]. It can also cover a detailed representation of space, including basic structural elements of the building, such as walls and ceilings, or complex details such as doors and windows [3]. Moreover, 3D models can incorporate information on colors, materials and physical properties for realistic renders and simulations [2–4]. Modelling is an extensive process, starting with data acquisition all the way to visualizing a model of a 3D object [1]. Three-dimensional models are employed in a variety of fields, like the visualization of sites and objects, cultural heritage archiving, technical inspections, navigation, virtual reality (VR) and augmented reality (AR) design, animation, or virtual tourism. They are used for precise rendition of objects to protect them from damage and as virtual reconstructions for educational and research purposes. The models can also double as realistic and interactive visualizations of complex structures [1, 5]. Three-dimensional modelling is critical for civil engineering, geodesy, cartography, cultural heritage protection, medicine, animation and video games. It helps with precise object archiving, design and simulation, driving innovation in a multitude of sectors [2]. In architecture, 3D models are used to plan emergency evacuation, manage crises, analyze energy needs and complete environmental simulations. By streamlining the visualization of virtual spaces, they support design processes and infrastructure management. Route planning and safety assessments also benefit from 3D models [3]. Cultural heritage protection makes use of HBIM (Heritage Building Information Modelling) to generate parametric models from survey and historical data for precise representation and documentation of heritage objects. This process integrates data acquired with multiple platforms, like laser scanning and photogrammetry [6].

Three-dimensional modelling is a digital visual reconstruction technique for generating 3D models of existing objects and spaces. The process includes data acquisition, geometry reconstruction and visualization [3, 5]. It involves transforming collected multi-platform (geo)spatial datasets into a digital rendition with points, vertices, lines, edges, planes and solids, or mathematical (parametric) equations and notations. Three-dimensional modelling requires precise input and sophisticated computing [1].

1.2. Data sources for 3D modelling

Data sources are critical in modelling, i.e. rendering digital representations of spaces and objects. The data determine the most significant model attributes: accuracy, precision, completeness and reliability. They also affect the level of detail. Input accuracy

*e-mail: przemyslaw.klapa@urk.edu.pl

Manuscript submitted 2025-07-07, revised 2025-08-28, initially accepted for publication 2025-10-14, published in January 2026.

and completeness set the limits for the potential final outcome while also defining the modelling process [7–11]. Apart from numerous types of data that can be used to generate 3D models, the process also involves multiple tools and programming environments for modelling and visualization [9, 12–14].

The usual data sources for 3D modelling include physical measurements, laser scanning (LiDAR), photogrammetry and other spatial data, including technical files [7, 11, 15]. Operators can use diverse spatial datasets, including topographic raster maps, cadastral databases, digital landscape models (DLM), 3D city models as well as cartographic service and automated mapping data, so they can build 2D and 3D models of variable levels of detail [15]. A specific type of models, 2.5D models, makes use primarily of raster maps and cadastral databases. They reproduce building footprints and their primary geometric features. Conversely, 3D models from digital landscape models and spatial databases provide information on building heights, roof shapes and building layouts. Multi-platform integration empowers more inclusive and interoperational models for urban study analyses, spatial planning and geovisualization [15]. Technical files are another critical data source for modelling. This category includes scanned building plans with floor plans, elevations and section views. However, height and spatial structure are usually not covered. Reconstruction of 3D models from 2D plans remains a challenge, and the resulting models often need to be complemented with auxiliary sources, such as laser 3D scanning, to improve accuracy and completeness [16]. Another important addition to spatial data is land surveys, which contribute precise information on the locations and dimensions of objects. This can provide a matrix for integrating scanning outputs with spatial models [15]. Aerial photographs and GIS geospatial data are also an important part of the 3D model generation suite, facilitating precise rendition of buildings and their surroundings [8]. Aerial photogrammetry provides high-resolution images suitable for 3D reconstructions. Still, they cannot be used on their own because of complex processing and missing data on building heights. By integrating aerial photographs and GIS data, one can generate more accurate models, combining details from images with geodetic information, significantly improving 3D model quality [8].

The advent of laser scanning (LiDAR), with its high geometric accuracy, revolutionized data acquisition for 3D modelling of cities and single objects. Aerial laser scanning (ALS) has become the primary source of data for building modelling because it offers complete and precise information on building height and relief. Integrating LiDAR and photogrammetry yields more comprehensive models that combine geometric precision and elaborate visual textures [7]. That is why ALS is prevalent in urban studies, spatial planning and engineering analyses, where the urban fabric has to be fully rendered [8]. On the other hand, mobile laser scanning (MLS) allows for rapid and effective spatial data acquisition, especially in a dynamic urban environment. Mobile laser scanning point clouds from sensors on vehicles or other mobile platforms can reconstruct building geometry, road infrastructure and street objects. Moreover, the integration of MLS into an existing 3D mesh and data fusion algorithms can improve building model accuracy and integrity, which makes the technology highly relevant in civil engineering and urban infrastructure management. With MLS, operators can quickly reproduce objects in real time. However, the method offers accuracy below that of aerial or terrestrial laser scanning, so it often requires additional data sources [17]. Still, terrestrial laser scanning (TLS) remains the central technique for reconstructing objects with the highest possible precision, in architectural heritage, industrial infrastructure and complex built structures. Terrestrial laser scanning generates detailed point clouds with which one can analyze building geometry, detect structural deformations and evaluate the building's condition. Thanks to its high resolution capabilities, TLS is preferred in projects where details have to be reproduced very accurately, such as heritage conservation and structural analyses [18]. The technology helps identify damage, monitor changes over time, and precisely model complex shapes. Even though TLS is a source of very accurate data, it is limited to non-mobile applications, so the acquisition times are longer, and it may prove more challenging to use in urban environments.

Today's 3D modelling methods increasingly turn to artificial intelligence (AI), machine learning (ML) and deep learning (DL), which significantly streamline reconstruction. These techniques enable operators to automatically generate 3D models from various geospatial data sources, such as aerial images, LiDAR point clouds, satellite data and GIS. Thanks to sophisticated segmentation, classification and spatial analysis algorithms, it is possible to reproduce terrain and building geometry rapidly and accurately. They also facilitate an automated Level of Detail (LoD) optimization and elevate reconstruction precision [19].

1.3. Structure of 3D models

One can identify three types of 3D model structures, depending on the specific civil engineering approach: solid models, surface models and parametric models.

The most common civil engineering 3D modelling method is solid modelling. It employs basic 2D and 3D shapes (primitives), such as cubes, spheres and cylinders, which are modified to attain the desired shape. The process involves structural manipulations and often subdivision until the intended result is achieved and the final shape is obtained [20]. Solid models are generated using 2D profiles that are building blocks of 3D shapes. Flat contours can be transformed into 3D solids by extruding, cutting, revolving, etc. Then, the final shape is achieved with a plethora of geometric and logical operations for modifying, combining or subtracting model components. This way, the operator can generate multiplex spatial structures representing simple structural elements and complex architectural compositions. This process is the foundation of modelling in CAD and BIM systems, where precise geometry and editability are central for further analyses and design applications [21, 22].

Surface modelling comes in three subtypes, exhibiting different approaches to how the external surface of 3D objects is described. Surface models are often combined with solid and parametric models to provide high-fidelity representation. Surface modelling makes use of profiles, but its chief functional component is control points for defining 2D and 3D curves.

Surface modelling is employed when the target shape is too complex to be represented with traditional solid modelling techniques [22]. Mesh models are the most popular and common ones. Mesh 3D models are represented with a polygonal network, typically of triangles or quadrangles, consisting of nodes, edges and faces. This approach is most common in computer graphic design, 3D modelling and engineering [23].

Parametric modelling offers dynamic control over object geometry with a set of parameters and links between them. With this method, one can automatically adapt the building's structure by modifying the input parameters. This makes it popular in civil engineering, architecture and BIM, where it contributes to the effective generation of multiplex forms and structural optimization. Parametric modelling is a pivotal tool for architecture and engineering today thanks to its capability to rapidly adapt projects to complex environmental, technical and functional conditions [24]. This approach helps precisely reproduce building and element geometry in Building Information Modelling, which is highly relevant for archiving architectural heritage and traditional building methods [25]. Parametric models are founded on relationships between structural elements and mathematical equations that define their shape and properties, which means design flexibility and easy modifications without remodelling [26]. Architecture and civil engineering liberally employ parametric modelling, particularly for projects where diverse structural elements need to be precisely optimized and integrated. Parametric modelling is a state-of-the-art design approach. It offers rapid iterating and automatic synchronization of changes across the model, eliminating project reprocessing after each modification. As opposed to traditional design methods, parametric modelling offers dynamic editing and real-time optimization, contributing to process efficiency. It is also critical for archiving architectural heritage and traditional construction methods, facilitating reproducing and analyzing heritage building systems [25]. Parametric modelling is commonly used in architecture, engineering and design, allowing for precise adaptation of buildings to environmental conditions and functional requirements [24].

Solid, surface and parametric modelling are often combined into many derivative forms. NURBS models describe surfaces with mathematical curves and splines and are used mainly to create smooth free-form, edgeless objects. The model contains no edges or vertices, preserving object smoothness [20, 27]. In SubD models (subdivision surfaces), the surface emerges from the subdivision of a polygon mesh into smaller pieces, leading to smoother shapes. This 3D modelling technique combines polygon and NURBS approaches for virtually total control over the mesh to obtain sophisticated shapes. Then there are CAD models, often generated from sections, where precision and accuracy of visualization and ease of transformation into engineering drawings are paramount. This method combines the mesh and solid approaches [20, 28].

1.4. Purpose and scope of research

The study aims to develop criteria for the qualitative evaluation of 3D models of built structures and to conceptualize a versatile method for evaluating the quality of such models (3D model evaluation method). Its focal point is an analysis of 3D modelling methods from diverse (geo)spatial data, including point clouds from laser scanning and photogrammetry. The study objective is to evaluate the quality of 3D models in the context of civil engineering requirements in architecture, construction and geodesy. An attempt is made to propose criteria encompassing solid, mesh and BIM models. The evaluation criteria are universal and can be applied to all types of built structures regardless of the data source, methods and tools used for 3D modelling. The evaluation involves a set of qualitative attributes of 3D models, such as interoperability, completeness, integrity and geometric accuracy, including element positioning, object spatial occupancy consistency, detail reproduction accuracy and potential for sharing and editing the model.

2. METHODS AND CRITERIA FOR EVALUATING 3D MODELS

The available 3D modelling methods can yield objects of diverse levels of detail and accuracy, depending on the intent. When choosing the method, one should take into account limitations in data availability and processing tool performance [29]. Effective management of the level of the model's detail requires elasticity to adapt the Level of Detail (LoD) and Level of Information (LoI) to individual elements or their groups instead of defining one universal detail level for the entire model. This way, project resources can concentrate on elements critical at a specific stage, which prevents model overload. The diversification of LoD rules out unnecessary modelling of all elements with the maximum detail, which could extend lead times, complicate model management and hinder data processing. Effective LoD management significantly streamlines model modifications, limiting the need for editing over-detailed elements that are not critical at a specific stage [30].

According to the CityGML standards, Levels of Detail of 3D models vary in terms of how detailed 3D building models are. Level of Detail 0 is the most straightforward approach. It represents buildings as 2D footprints with optional height information. Level of Detail 1 is a solid block building model with a flat roof that is the footprint extruded to a uniform height. Level of Detail 2 includes simplified roof shapes and a basic representation of details, such as walls and roofs. Level of Detail 3 is a detailed model with windows, doors, balconies, and more sophisticated roof details (Fig. 1) [31–33].

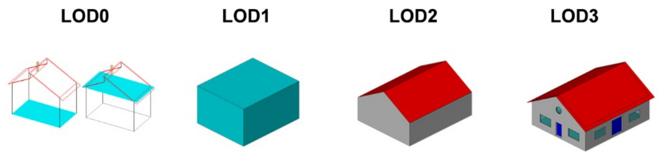

Fig. 1. Representation of a building using LoD 0–3 [31]

The information load is more extensive in more complex 3D models, such as BIM models, which are still based on the same CityGML aspects but may include additional non-geometric information. Level of Detail 1 represents overall structural geometry in the form of a simplified solid shape. It does not include material properties, thicknesses, or construction joints. At LoD 2, basic building components such as walls, ceilings and roofs are correctly positioned, and their dimensions are consistent with the assumptions of a static model, understood here as a fixed geometric representation without mechanical or dynamic properties. Details such as joints or steps are not included at this level. LoD 3 provides more detailed representations, where roofs, walls and stairs are accurately positioned, and basic features like steps and beams are included. Structural materials are also distinguished. LoD 4 extends the model to include all details of structural elements, and LoD 5 offers the highest level of geometric precision, representing even minor construction details such as nails and rebar [30].

Level of Information (LoI) concerns how much detailed information is assigned to model elements for building and infrastructure management processes. It is linked directly to LoD regarding the detail of information provided [34]. Level of Information 1 offers general information. It contains the minimal data tier, such as element name, type and general purpose. Level of Information 2 is simple geometric and material information. It provides basic object dimensions and approximate material data. Level of Information 3 provides technical details. It covers accurate material properties and basic condition data, such as strength and wear. Level of Information 4 provides elaborate data on the element's condition. It contains diagnostic details such as damage, wear analysis, or repairs. Level of Detail 5 means complete information. It offers any possible piece of information, such as element history, complete technical analyses, maintenance plan and management information [30].

Level of Geometry (LoG) concerns the geometric detail reflected in 3D models. Level of Geometry covers all geometric information of the model, both for general shapes and structural elements [35]. Level of Geometry is divided into five tiers of increasing detail. Level of Geometry 100 is a concept model with a general building footprint and no detailed representation of shapes or geometry. Level of Geometry 200 is the approximate representation of building geometry, with only a basic spatial extent. Level of Geometry 300 entails precise geometry, accurately representing shapes, attributes and types of structural elements. Level of Geometry 350 can be used to draft detailed structural documentation from the model. Level of Geometry 400 is a very detailed representation of elements and joints, with full insight into individual components. Level of Geometry 500 offers a perfect representation, verified in the field through surveys [34,35]. Level of Accuracy (LoA) defines the dimensional precision of the model as compared to the actual object [34]. This parameter indicates the accuracy applied to the acquisition, processing and use of survey data when building BIM models. The model precision is evaluated at specific accuracy levels. Level of Accuracy 10 means a deviation above 5 cm as compared to the actual object. Level of Accuracy 20 stands for accuracies between 5 cm and 15 mm. Level of Accuracy 30 represents accuracies from 15 to 5 mm. Level of Accuracy 40 is assigned to models accurate at 5 to 1 mm [34].

Such detail levels in BIM as LoD, LoI, and LoG are central for precise representation of the building's geometry and integration of non-geometric information in building documentation and management. Each level precisely defines the geometric and informational scope of models, supporting interoperability and facilitating accurate analyses at various project stages [36].

3. CONCEPT OF THE 3D MODEL EVALUATION METHOD

3.1. Attributes and criteria for model evaluation

Evaluation of 3D building model quality for civil engineering purposes should cover multiple attributes that describe completeness, accuracy and applicability. A systemic model evaluation requires a set of quality attributes and criteria with which one can objectively analyze the model's usability and compliance with standards. The evaluation should address fundamental questions of the model's quality and functionality. First, one has to determine whether the model is comprehensive, containing all relevant object elements. The next aspect is integrity or cohesion of information within a scheme, format and data structure. Model geometry should conform to specific accuracy standards that include positioning precision, shape reproduction and spatial occupancy of individual components such as beams and walls. Another relevant evaluation criterion is the model's interoperability. It covers software compatibility, exportability and importability, and optimization through size reduction, elimination of redundant data and textures compression, which improves its performance and downstream usability [30–36].

3.2. 3D model evaluation method

There are three critical evaluation criteria among the multitude of model quality attributes:

a) **COMPLETENESS**, which defines whether and to what degree all of an object's elements are presented. It can be described with the model's detail level and completeness according to the CityGML standard, which defines several LoDs (Table 1).
b) **ACCURACY**, which concerns how correctly details are represented and how much the model is consistent with the actual geometry. This attribute can be evaluated with LoG and LoA standards, which provide methods for analyzing the model's geometry and object positioning accuracy (Table 2).
c) **INTEROPERABILITY**, which is the model's potential for collaboration and reuse in various software environments. There are five dominant attributes of interoperability (Table 3):
   - integrity (cohesion of data within a standard, scheme, or format),
   - reusability (software compatibility, including visualizations),
   - standard compliance (or compatibility with general principles for generating, processing and sharing 3D models),
   - editability (compatible format, export and import compatibility),
   - model optimization (optimal file size and data redundancy).

Table 1
Criterion a) Model completeness: attributes and their values, based on: [30, 31]

COMPLETENESS		
Value	Attribute	Description
1	LoD 1	A simple solid. Building represented as a block without details.
2	LoD 2	A building with represented roof and primary elements: walls, roof and ground.
3	LoD 3	A detailed building model with windows, doors, and more specific surface and roof geometry.
4	LoD 4	A detailed building model containing the geometry of all components, detailed dimensions and structural elements.
5	LoD 5	A sophisticated model with architectural details, structural elements and services.

Table 2
Criterion b) Model accuracy: attributes and their Levels of Accuracy, based on: [30, 33–36]

ACCURACY		
Value	Attribute	Level of Accuracy
1	LoA 0	> 30 cm
2	LoA 10	30 cm–5 cm
3	LoA 20	5 cm–15 mm
4	LoA 30	15 mm–5 mm
5	LoA 40	< 5 mm

Table 3
Criterion c) Model interoperability, based on: [30–36]

INTEROPERABILITY		
Attribute*	Conformity	Assigned value
integrity	yes/no	1/0
reusability	yes/no	1/0
compliance with standards	yes/no	1/0
editability	yes/no	1/0
optimization	yes/no	1/0
	Criterion value:	Total score

* where the attributes represent the following concepts:
1. integrity – consistency and completeness of the presented data; uniform representation throughout the entire model;
2. reusability – the model's applicability for practical purposes such as visualization, analysis, simulation, or design;
3. compliance with standards – conformity with applicable norms or standards (e.g. national, industry-specific);
4. editability – the ability to further work on the model, including editing, improvement, or expansion;
5. optimization – adaptation of the model to its intended use by simplifying its structure and improving performance, while preserving required functionality

As is the case for CityGML 3.0, external and internal elements are analyzed for each LoD because all object types can contain internal and external components in line with LoD [31, 37].

The Level of Accuracy range is defined according to the applicable LoA standards. Additional LoA 0 is used to accommodate a value critical for civil engineering specified in technical standards for the mean error of 3D coordinates [38].

The model quality score under the present research design can be visualized as a radar chart with variables representing the three criteria: a) completeness, b) accuracy, and c) interoperability. The criteria are shown as radial axes with relevant values on each axis (Fig. 2).

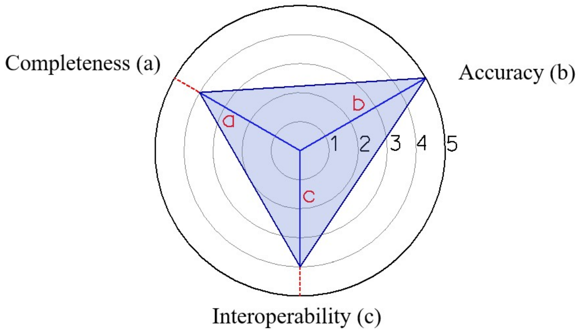

Fig. 2. Radar chart method

A 3D model's quality evaluation involves the determination of the 3D model score area (A) calculated from the area of the triangle identified on the radar chart and the law of sines (Fig. 3), where the axes reflect the criteria and values represent variables a, b and c.

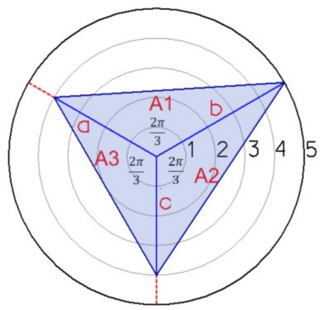

Fig. 3. Triangle area

The area of triangle A is a sum of triangle areas A1, A2 and A3:

$$A = A_1 + A_2 + A_3 \,. \tag{1}$$

Employing the law of sines and the known lengths of sides a, b and c and the angle between the respective sides of:

$$\alpha = \frac{2\pi}{n}, \tag{2}$$

where $n = 3$ is the number of criteria and axes on which the vertices lie.

According to the law of sines, the area of triangle A is:

$$\mathrm{A} = \frac{1}{2}ab\sin\left(\frac{2\pi}{3}\right) + \frac{1}{2}bc\sin\left(\frac{2\pi}{3}\right) + \frac{1}{2}ac\sin\left(\frac{2\pi}{3}\right). \tag{3}$$

When simplified, (3) yields:

$$A = \frac{1}{2}(ab + bc + ac)\sin\frac{2\pi}{3}. \tag{4}$$

The value of the standard 3D model evaluation method score (S) is obtained by normalization of value A calculated from attribute values for each criterion, taking into account the maximum value of $A_{\max}$ (which is 5 for a, b and c), as per (4):

$$S = \frac{A}{A_{\max}}. \tag{5}$$

The normalization yields 3D model quality evaluation values of $S \in [0; 1]$, where $S = 1$ means the perfect model with all structural elements, services and architectural details, reproduced at high accuracy of geometry and shape that is completely interoperable and can be edited and employed in spatial analyses.

4. 3D MODEL EVALUATION METHOD TEST

The performance and versatility of the model evaluation method were assessed through tests on 3D models available online and using data for generating the models. The tests aimed to verify whether the model quality can be evaluated and compared despite the different origins, structures and applicabilities of the models.

4.1. Parametric BIM model from TLS and UAV data

This 3D BIM model was generated from open-access research data [39]. The building shown in Fig. 4 was scanned using a Leica ScanStation P40 terrestrial laser scanner, covering both the interior and exterior parts. Missing fragments of the exterior were supplemented using data acquired from a DJI Phantom 4 Pro drone. The resulting model integrates data from both terrestrial laser scanning (TLS) and unmanned aerial vehicle (UAV) photogrammetry. It offers high geometric accuracy in the range of 2–3 cm, corresponding to Level of Accuracy 20 (LoA 20), and is classified at Level of Detail 4 (LoD 4). The model demonstrates high interoperability and compliance with BIM standards, making it suitable for advanced engineering and spatial analyses [6].

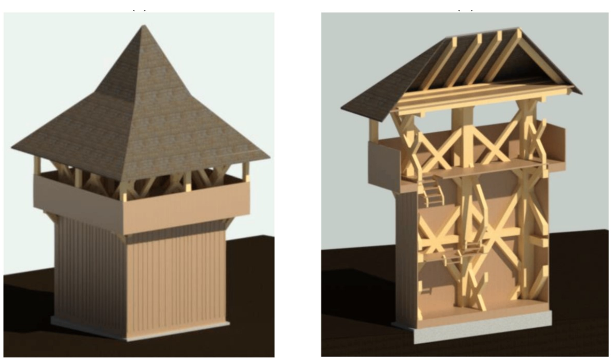

Fig. 4. BIM models of the building [6]

Model quality evaluation according to the 3D model evaluation method:

a) Completeness value: 4 (LoD 4)
b) Accuracy value: 3 (LoA 20)
c) Interoperability value: 5 (integrity, reusability, standard compliance, editability, optimization).

Index value (acc. to (4) and (5)) $S = 0.63$ (Fig. 5).

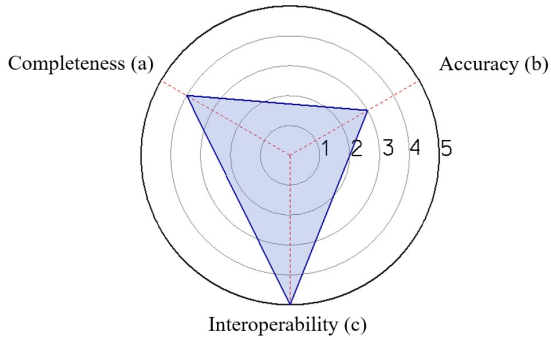

Fig. 5. Model quality visualization acc. to the 3D model evaluation method (4-3-5)

4.2. Mesh surface model from satellite imaging – photogrammetric modelling

Google Earth [40] has 3D building models (Fig. 6) for many global cities generated using sophisticated photogrammetric techniques. The process involves the analysis of satellite and aerial images that are then converted into realistic 3D models. These are surface mesh models, which means they are unified spatial representations of buildings instead of individual solids. Its strengths include global reach, easy availability and optimization, which streamlines urban exploration and analysis. However, the user faces certain challenges using the system. The satellite-based model accuracy is limited, and it is impossible to download the models to edit them in alternative software environments [41].

Fig. 6. City 3D model – New York (USA) [40]

Model quality evaluation according to the 3D model evaluation method:

a) Completeness value: 3 (LoD 3)
b) Accuracy value: 1 (LoA 0)
c) Interoperability value: 2 (integrity, reusability).

Index value (acc. to (4) and (5)) $S = 0.15$ (Fig. 7).

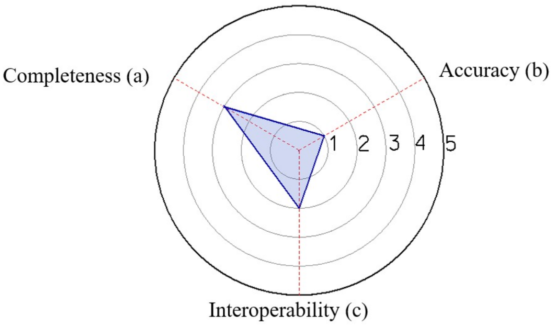

Fig. 7. Model quality visualization acc. to the 3D model evaluation method (3-1-2)

4.3. Solid model from ALS data

These 3D building models (Fig. 8) come from the official Polish geoportal at Geoportal.gov.pl. They are available free of charge as part of the National Geodetic and Cartographic Resources. The solid 3D models were generated from three data sources: 2D footprints from the database of topographic objects, LiDAR (ALS) scans, and a digital terrain model. The models conform to the CityGML standards at LoD 2 [42].

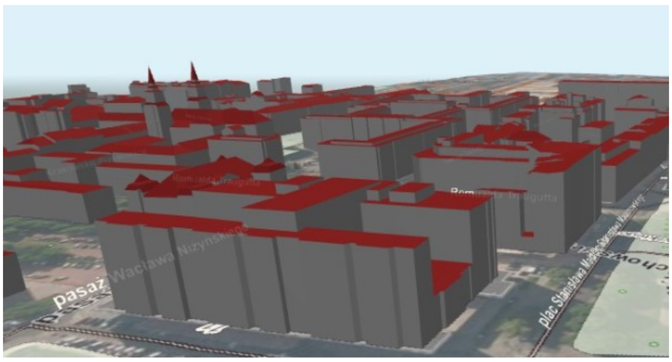

Fig. 8. 3D model of a city [42]

Model quality evaluation according to the 3D model evaluation method:

a) Completeness value: 2 (LoD 2)
b) Accuracy value: 2 (LoA 10)
c) Interoperability value: 5 (integrity, reusability, standard compliance, editability, optimization).

Index value (acc. to (4) and (5)) $S = 0.32$ (Fig. 9).

Although the evaluation criteria for completeness (a), accuracy (b) and interoperability (c) are clearly defined in Tables 1–3, the only realistic source of error in applying the method lies in the potential misclassification of parameter values by ±1 point. A sensitivity analysis was performed to determine how such

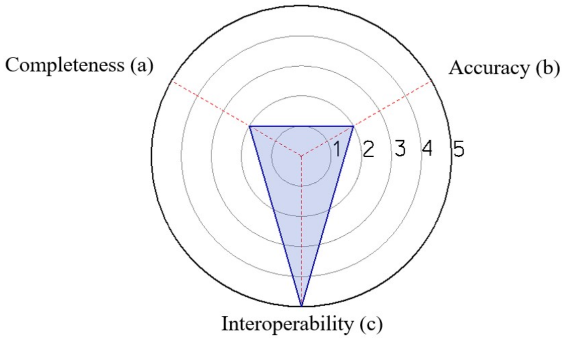

Fig. 9. Model quality visualization acc. to the 3D model evaluation method (2-2-5)

input errors affect the calculated evaluation result ((4), (5)). A misassignment of one parameter by a single point results in an error of approximately 13% in the calculated value of the model's evaluation index. In the case of two incorrect parameter assignments, the resulting error increases to around 25%. The most extreme scenario – where all parameters are misclassified by one point – leads to a maximum deviation of about 36% in the computed index value. Importantly, such an error does not reflect a change in the actual quality of the model, but rather a distortion in its quantified evaluation due to incorrect parameter selection. This analysis shows that the proposed method is moderately sensitive to classification errors. While mathematically stable and transparent, it relies on the accurate assignment of input values to ensure that the resulting index reliably reflects the intended evaluation outcome.

The proposed 3D model evaluation method introduces a novel approach to assessing the quality of 3D building models by integrating three key aspects: completeness, geometric accuracy and interoperability. The normalized quality index and radar chart visualization enable objective and efficient comparison of models originating from various data sources and modelling techniques. The literature in the field underscores the need for a comprehensive, systematic, and both qualitative and quantitative evaluation of spatial models, particularly in the context of data quality, reconstruction accuracy and compatibility with target formats [6, 17]. Growing attention is also paid to the importance of combining classical error metrics (e.g. RMSE) with clear visual representations of model quality. An example is the study by Subramaniyam *et al.* (2024) [43], which proposed a method for evaluating 3D models in a VR environment based on both quantitative analyses and user perception. 3D models, increasingly generated from diverse spatial data, constitute an important source of information for VR and AR applications; however, optimization, standardization and performance assurance are necessary [44], which requires standardized quality assessment procedures. It is essential that the quality of 3D building models, regardless of the acquisition method, be assessed in a standardized manner using comparable error indicators [45]. Similar to the 3D model evaluation method concept presented in this study, this approach emphasizes the need for tools that enable the comparison of diverse 3D models – originating from different sources, created in various environments, and intended for different purposes. The quality categories and parameter structure adopted in this work are consistent with established indicators such as completeness and correctness, which remain fundamental methodological components in evaluating the geometry of building models [46]. It should be noted that both the scientific and industry literature indicate limitations of models generated from, among others, UAV data, mobile scanning, or photogrammetry, whose quality may vary considerably and which are often devoid of standardized validation criteria [44, 45, 47].

The literature increasingly emphasizes the need to assess models in the context of the quality and accuracy of 3D building models. A comprehensive assessment should not be limited to geometric correctness but should also include the potential for further use of the model in design, construction and operational processes [48]. Drobnyi *et al.* (2024) [49] point out that geometric accuracy cannot be analyzed in isolation from topology; the lack of correct relationships between elements (e.g. wall connectivity, proper spatial structure) leads to erroneous reconstructions or limits further use of models. This confirms the rationale for including such structural features in quality assessment, which in this study is captured within the aspects of consistency and completeness. In turn, combining exterior and interior geometry within a single model requires an appropriately designed reconstruction process; achieving accuracy, for example in the order of a few centimeters, depends not only on the technique but also on the quality of input data and the complexity of room structures [50]. This confirms the importance of assessing accuracy on the basis of specific numerical values, as well as the need to consider the context of data acquisition and geometric complexity when comparing models. Meanwhile, in the area of interoperability, analyses indicate that the ability to transfer data between environments without losing semantics and spatial relationships is as important as geometry itself [51, 52], which confirms the need for systematic assessment of interoperability on a par with geometric accuracy. The proposed 3D model evaluation method addresses these challenges by offering a universal, structured and implementable tool for the comparative evaluation of 3D models, while ensuring comparability of results across models originating from different sources and modelling techniques, as well as consistent reporting of their quality metrics.

5. CONCLUSIONS

The proposed 3D model evaluation method is a universal and well-structured approach to evaluating 3D building models regardless of the data source, modelling technique, visualization and format. The crux of the method is the quality index (S) calculated based on a triangle area in a radar chart. This approach can partially compensate for any imbalance across the evaluated attributes, facilitating analysis of the model's structure and balance instead of focusing on individual, extreme differences among aspects or criteria. One of the central benefits of this method is a single normalized [0; 1] score value for easier model classification and back-to-back comparison. The standardization ensures all model attributes are evaluated fairly: even if one value is low, the method still takes into account the 'strength' of the other parameters, yielding an objective evaluation of the 3D model's quality.

The method's primary advantage is its versatility and simplicity, so it can be used in many fields such as BIM, civil engineering, VR, spatial analysis and GIS. The method provides easy visualization of results on a radar chart, which makes it clear and intuitive to interpret, in addition to determining the value of the 3D model's quality. The proposed method can be further expanded for special-case scenarios because the evaluation criteria are easy to add. Each new attribute adds another radial axis while the basic design remains unaffected. One can modify not only the list of attributes but also the scale without changing the way the 3D model's quality score is calculated.

The results confirm the effectiveness and universality of the proposed method for evaluating the quality of 3D building models, particularly in terms of geometric accuracy, completeness and interoperability. The normalized quality index enables objective comparison of models regardless of their structure, level of detail, modelling technique, or data source. The unified evaluation approach, based on common criteria, allows for the assessment of models created using various methods of spatial data acquisition, processing and 3D building modelling. Owing to its formalized structure and transparent evaluation criteria, the 3D model evaluation method provides a consistent and practical framework for assessing the quality of 3D models of building objects.

Future research undertaken within the proposed method and framework for qualitative assessment of 3D models of building objects will focus on developing and empirically testing the approach on broader datasets encompassing diverse acquisition sources and modelling techniques. The definition of criteria and the scoring procedure will also be refined to increase assessment repeatability and the unambiguous interpretation of results. The method remains open and scalable: additional criteria can be introduced and the number of axes scaled as needed without altering the underlying construction of the index. Consequently, 3D model evaluation method can be gradually enriched with new aspects arising from advances in science and technology while preserving its flexibility and universality. In particular, it is possible to introduce contextual weights for individual criteria (e.g. prioritization of accuracy in structural diagnostics or interoperability in data-exchange tasks) and to generalize to $n > 3$ axes by adding further, substantively justified dimensions (e.g. semantic richness, consistency/topology, environmental footprint). These extensions do not compromise the structure of the index or interpretability of the result. Although the conceptual assumptions adopt equal weights due to the equivalence of the three primary aspects, the solution remains compatible with weighted variants where required by the application context. The universality of the proposed method means that, although the study presents the evaluation of a single building, the concept is also suitable for analyzing sets of objects – from small ensembles to highly urbanized environments – thus enabling comparison and aggregation of results on different scales without changing the way the index is computed.

ACKNOWLEDGEMENTS

This research was funded by the Ministry of Science and Higher Education with a subsidy for the University of Agriculture in Krakow, Department of Geodesy.

REFERENCES

[1] F. Remondino and S. El-Hakim, "Image-based 3D modelling: A review," *Photogramm. Rec.*, vol. 21, no. 115, pp. 269–291, 2006, doi: 10.1111/j.1477-9730.2006.00383.x.

[2] X.D. Luan, Y.X. Xie, L. Ying, and L.D. Wu, "Research and development of 3D modeling," *Int. J. Comput. Sci. Netw. Secur.*, vol. 8, no. 1, pp. 49–53, 2008.

[3] L. Díaz-Vilariño, K. Khoshelham, J. Martínez-Sánchez, and P. Arias, "3D modeling of building indoor spaces and closed doors from imagery and point clouds," *Sensors*, vol. 15, no. 2, pp. 3491–3512, 2015, doi: 10.3390/s150203491.

[4] P. Klapa, "Standardisation in 3D building modelling: Terrestrial and mobile laser scanning level of detail," *Adv. Sci. Technol. Res. J.*, vol. 19, no. 3, pp. 237–250, 2025, doi: 10.12913/22998624/199381.

[5] F. Remondino, "Heritage recording and 3D modeling with photogrammetry and 3D scanning," *Remote Sens.*, vol. 3, no. 6, pp. 1104–1138, 2011, doi: 10.3390/rs3061104.

[6] P. Klapa and P. Gawronek, "Synergy of geospatial data from TLS and UAV for heritage building information modeling (HBIM)," *Remote Sens.*, vol. 15, no. 1, p. 128, 2023, doi: 10.3390/rs15010128.

[7] R. Wang, "3D building modeling using images and LiDAR: A review," *Int. J. Image Data Fusion*, vol. 4, no. 3, pp. 273–292, 2013, doi: 10.1080/19479832.2013.811124.

[8] I. Suveg and G. Vosselman, "Reconstruction of 3D building models from aerial images and maps," *ISPRS J. Photogramm. Remote Sens.*, vol. 58, no. 3–4, pp. 202–224, 2004, doi: 10.1016/j.isprsjprs.2003.09.006.

[9] A. Scianna, "Building 3D GIS data models using open source software," *Appl. Geomatics*, vol. 5, no. 2, pp. 119–132, 2013, doi: 10.1007/s12518-013-0099-3.

[10] E. Głowienka *et al.*, *Photogrammetry and Laser Scanning in 3D Modeling*, Rzeszów, Poland: Wyższa Szkoła Inżynieryjno-Ekonomiczna w Rzeszowie, 2015.

[11] P. Klapa and B. Mitka, "Edge effect and its impact upon the accuracy of 2D and 3D modelling using laser scanning," *Geomatics Landmanage. Landscape*, vol. 1, pp. 25–33, 2017, doi: 10.15576/GLL/2017.1.25.

[12] J. Montusiewicz, "Methods of visualisation of the interior of 3D objects in the AutoCAD program," *Postępy Nauki i Techniki*, vol. 2, pp. 5–15, 2008.

[13] A. Janowski, P. Sawicki, and J. Szulwic, "The 3D visualization method of close range objects in the OpenGL standard," *Arch. Photogramm., Cartogr. Remote Sens.*, vol. 16, pp. 239–247, 2006.

[14] M. Christen and S. Nebiker, "Visualisation of complex 3D city models on mobile web browsers using cloud-based image provisioning," *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.*, vol. II-3/W5, 2015, doi: 10.5194/isprsannals-II-3-W5-517-2015.

[15] R. Hecht, G. Meinel, and M. Buchroithner, "Automatic identification of building types based on topographic databases – a comparison of different data sources," *Int. J. Cartogr.*, vol. 1, no. 1, pp. 18–31, 2015, doi: 10.1080/23729333.2015.1055644.

[16] L. Gimenez, J.-L. Hippolyte, S. Robert, F. Suard, and K. Zreik, "Reconstruction of 3D building information models from 2D scanned plans," *J. Build. Eng.*, vol. 2, pp. 24–35, 2015, doi: 10.1016/j.jobe.2015.04.002.

[17] W. Liu *et al.*, "3D building model generation from MLS point cloud and 3D mesh using multi-source data fusion," *Int. J. Appl. Earth Obs. Geoinf.*, vol. 116, p. 103171, 2023, doi: 10.1016/j.jag.2022.103171.

[18] P. Klapa, B. Mitka, and M. Zygmunt, "Study into point cloud geometric rigidity and accuracy of TLS-based identification of geometric bodies," *IOP Conf. Ser.-Earth Environ. Sci.*, vol. 95, no. 3, p. 032008, 2017, doi: 10.1088/1755-1315/95/3/032008.

[19] D. Yu, S. Ji, J. Liu, and S. Wei, "Automatic 3D building reconstruction from multi-view aerial images with deep learning," *ISPRS J. Photogramm. Remote Sens.*, vol. 171, pp. 155–170, 2021, doi: 10.1016/j.isprsjprs.2020.11.011.

[20] A. Molga and P. Krawczyk, "Three-dimensional modeling," *Dydaktyka Informatyki*, vol. 16, 2021, doi: 10.15584/di.2021.16.16.

[21] P. Rubinowicz, "Visualisation of DSM as 3D-Mesh for Urban Analyses," *ICGG 2018 – Proceedings of the 18th International Conference on Geometry and Graphics, Advances in Intelligent Systems and Computing*, 2019, vol. 809, pp. 1013–1022, doi: 10.1007/978-3-319-95588-9_87.

[22] P. Penkala and T. Gorecki, "Solid and surface modeling in CAD/CAM systems," *Postępy Nauki i Techniki*, vol. 4, pp. 75–84, 2010.

[23] K. Polakowski and J. Sikora, "Mesh Modeling of Planar and Spatial Objects Using Computer Techniques," *Prz. Elektrotechn.* vol. 90, no. 3, pp. 143–146, 2014.

[24] A. Eltaweel and Y. Su, "Parametric design and daylighting: A literature review," *Renewable Sustainable Energy Rev.*, vol. 73, pp. 1086–1103, 2017, doi: 10.1016/j.rser.2017.02.011.

[25] S. Fai, M. Filippi, and S. Paliaga, "Parametric modelling (BIM) for the documentation of vernacular construction methods: A BIM model for the Commissariat Building, Ottawa, Canada," *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.*, vol. II-5/W1, 2013, doi: 10.5194/isprsannals-II-5-W1-115-2013.

[26] R. Białozor, " Parametric Design as a Support for the Structural Design Process," in *Nowoczesne projektowanie i realizacja konstrukcji budowlanych 2017*, M. Kijania-Kontak, Ed., Kraków, Poland: SKNKŻ CONKRET, 2017, pp. 111–117.

[27] K. Januszkiewicz and K. Kowlaski, "Building information modeling in BIM technology – the role of the parametric model," *Architecturae et Artibus*, vol. 12, no. 4, 2020, doi: 10.24427/aea-2020-vol12-no4-02.

[28] "DC Design – Don College Design Wiki." [Online]. Available: http://dcdesign.wikidot.com/subdivision-modelling [Accessed: 15. Jan. 2025].

[29] A. Struś, "Procedural modelling of 3D cities," *Arch. Photogramm., Cartogr. Remote Sens.*, vol. 30, pp. 107–122, 2018, doi: 10.14681/afkit.2018.008.

[30] R. Bednarczyk *et al.*, *BIM Standard PL*. Warszawa, Polska: Polish Association of Construction Employers, 2020.

[31] C. Heazel, "Open Geospatial Consortium, OGC City Geography Markup Language (CityGML) 3.0 Conceptual Model Users Guide," 2021. [Online]. Available: http://www.opengis.net/doc/UG/CityGML-user-guide/3.0 [Accessed: 13. Jan. 2025].

[32] F. Biljecki, H. Ledoux, and J. Stoter, "Generation of multi-LOD 3D city models in CityGML with the procedural modelling engine Random3DCity," *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.*, vol. IV-4/W1, 2016, doi: 10.5194/isprs-annals-IV-4-W1-51-2016.

[33] R. Akmalia, H. Setan, Z. Majid, D. Suwardhi, and A. Chong, "TLS for generating multi-LOD of 3D building model," *8th International Symposium of the Digital Earth (ISDE8), IOP Conf. Ser.-Earth Environ. Sci.*, vol. 18, p. 012064, 2014, doi: 10.1088/1755-1315/18/1/012064.

[34] R. Brumana *et al*., "Generative HBIM modelling to embody complexity (LOD, LOG, LOA, LOI): surveying, preservation, site intervention – the Basilica di Collemaggio (L'Aquila)," *Appl. Geomatics*, vol. 10, no. 4, pp. 545–567, 2018, doi: 10.1007/s12518-018-0233-3.

[35] J. Abualdenien and A. Borrmann, "Ensemble-learning approach for the classification of Levels Of Geometry (LOG) of building 605 elements," *Adv. Eng. Inf.*, vol. 51, p. 101497, 2022, doi: 10.1016/j.aei.2021.101497.

[36] A. Rossi and U. Palmieri, "Experimentation of an Information Model," *Vitruvio-Int. J. Archit. Technol. Sustainability*, vol. 5, no. 1, pp. 37–46, 2020. doi: 10.4995/vitruvio-ijats.2020.13639.

[37] M.-O. Löwner, G. Gröger, J. Benner, F. Biljecki, and C. Nagel, "Proposal for a new LOD and multi-representation concept for CityGML," in *Proceedings of the 11th 3D Geoinfo Conference 2016, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.*, vol. IV-2/W1, pp. 3–12, 2016, doi: 10.5194/isprs-annals-IV-2-W1-3-2016.

[38] Polish regulation of the Minister of Development and Technology of December 16, 2022, "On databases concerning aerial and satellite imagery, as well as orthophotomaps and the digital terrain model," *Polish Journal of Laws*, item 89, 2023, (Dz.U. 2023 poz. 89).

[39] P. Klapa, "Open Research Data." [Online]. Available: https://pliki.urk.edu.pl/index.php/s/iu2cr6pV0EZn6Em, doi: 10.15576/REPOURK/2024.1.03 [Accessed: 13. Feb. 2025].

[40] "Google Earth – Program," earth.google.com/web. [Online]. Available: https://earth.google.com/web/@40.68588184,-73.98159903,24.29610208a,46.70828337d,35y,47.91640253h,66.98259386t,0r/data=CgRCAggBMikKJwolCiExNjVDQmkxY01uVkFqeEZoUkI5VXFaYWJDaWJrMTR6cEggATwDCgEwQgIIAEoICNf4udMBEAE [Accessed: 13. Feb. 2025].

[41] "Google Earth – Technical Description of Technology," [Online]. Available: https://npseo.pl/google-earth/# budynki-3d-i-widoki-terenu [Accessed: 13. Feb. 2025].

[42] "3D Models of buildings," [Online]. Available: https://www.geoportal.gov.pl/pl/dane/inne-dane/modele-3d-budynkow/ [Accessed: 13. Feb. 2025].

[43] S. Subramaniyam, M. Pramanik, T. Horanont, and M. Shibasaki, "Towards Perceptual Quality Assessment of 3D Building Models in Virtual Environments Using Point Cloud Data," *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.*, vol. X-4-2024, pp. 333–340, 2024, doi: 10.5194/isprs-annals-X-4-2024-333-2024.

[44] R. Grande, J. Albusac, D. Vallejo, C. Glez-Morcillo, and J.J. Castro-Schez, "Performance Evaluation and Optimization of 3D Models from Low-Cost 3D Scanning Technologies for Virtual Reality and Metaverse E-Commerce," *Appl. Sciences*, vol. 14, p. 6037, 2024, doi: 10.3390/app14146037.

[45] R. Kontrimovicius, M. Juszczyk, A. Leśniak, L. Ustinovicius, and C. Miedziałowski, "Photogrammetry-based approach for collecting and processing information about an existing building," *Bull. Pol. Acad. Sci. Tech. Sci.*, vol. 71, no. 1, p. e144453, 2023, doi: 10.24425/bpasts.2023.144453.

[46] H. Tran, A. Kolbe, and P. Löwner, "Quality Assessment of 3D Building Models Using Extended Completeness and Correctness Metrics," *ISPRS J. Photogramm. Remote Sens.*, vol. 149, pp. 66–81, 2019. doi: 10.1016/j.isprsjprs.2019.01.010.

[47] A. Krystek, A. Kwinta, and M. Michnik, "Assessment of the Accuracy of Low-Cost 3D Models Generated from UAV and Mobile Devices," *Appl. Sciences*, vol. 14, no. 6, p. 6037, 2024. doi: 10.3390/app14066037.

[48] H. Abdolpour and M. Marut, "Parametric design for sustainable marine infrastructure," *Bull. Pol. Acad. Sci. Tech. Sci.*, vol. 73, no. 5, p. e154289, 2025, doi: 10.24425/bpasts.2025.154289.

[49] V. Drobnyi, S. Li, and I. Brilakis, "Connectivity detection for automatic construction of building geometric digital twins," *Autom. Constr.*, vol. 159, p. 105281, 2024, doi: 10.1016/j.autcon.2024.105281.

[50] B.G. Pantoja-Rosero, A. Rusnak, F. Kaplan, and K. Beyer, "Generation of LOD4 models for buildings towards the automated 3D modeling of BIMs and digital twins," *Autom. Constr.*, vol. 168 (Part A), p. 105822, 2024, doi: 10.1016/j.autcon.2024.105822.

[51] P.-D. Lam, B.-H. Gu, H.-K. Lam, S.-Y. Ok, and S.-H. Lee, "Digital Twin Smart City: Integrating IFC and CityGML with Semantic Graph for Advanced 3D City Model Visualization," *Sensors*, vol. 24, p. 3761, 2024, doi: 10.3390/s24123761.

[52] H.İ. Senol and T. Gökgöz, "Integration of Building Information Modeling (BIM) and Geographic Information System (GIS): a new approach for IFC to CityJSON conversion," *Earth Sci. Inf.*, vol. 17, pp. 3437–3454, 2024, doi: 10.1007/s12145-024-01343-1.