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CREATION OF A DIGITAL TWIN OF THE URBAN ENVIRONMENT USING UAV PHOTOGRAMMETRY AND GIS

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Abstract. *The article presents a methodology for creating a basic digital twin of the urban environment based on the integration of unmanned aerial vehicles (UAVs), photogrammetry, high-precision GNSS measurements, and geographic information*

systems (GIS). The aim of the study is to develop a methodology for creating a digital twin of the urban environment using UAV photogrammetry and geospatial technologies and to validate the proposed approach through a real-world case study. To achieve this objective, a comprehensive six-phase technological workflow was developed, including flight mission planning, field data acquisition with RTK positioning, photogrammetric processing in Agisoft Metashape, vectorization of spatial objects in QGIS with the creation of a GeoPackage database, spatial analysis, and three-dimensional visualization. The key outcome of the study is the development of an LOD1 digital model of the urban environment corresponding to the Digital Mirror concept, which can be considered the initial stage of digital transformation for territorial communities. Unlike a full-scale digital twin, a Digital Mirror reproduces the current state of the physical environment but does not provide automated bidirectional real-time data exchange. The proposed methodology was validated on a 42-hectare urban area in Rivne, Ukraine. Optimal flight parameters were determined, the required number of ground control points was established, and the achieved positional accuracy was confirmed to comply with the specified requirements. The spatial accuracy of the generated datasets was assessed, the building coverage ratio and the Visible Atmospherically Resistant Index (VARI) were calculated, and an LOD1 model was created and published in a web environment. The research findings demonstrate that the proposed methodology enables the development of a digital urban model suitable for building inventory, updating cartographic data, spatial planning, and supporting decision-making processes for post-war reconstruction and sustainable territorial development.

Keywords: digital twin; UAV photogrammetry; geographic information systems (GIS); digital city model; orthophoto; spatial data; LOD1; territorial community; digital modeling.

Problem Statement. The digital transformation of urban spatial management systems is a global trend that is increasingly becoming a strategic necessity. As a result of Russia's armed aggression, Ukraine's infrastructure has suffered extensive direct

damage, with a significant number of buildings damaged or completely destroyed. Effective recovery planning requires accurate, up-to-date, and standardized spatial data, including orthophotoplans, digital terrain models, and 3D building models, which constitute an important information basis for developing digital twins of territories. Digital twins themselves are regarded as comprehensive dynamic models of spatial objects, processes, and infrastructure integrated into decision-making systems.

Advances in Earth observation technologies, unmanned aerial systems, terrestrial and mobile laser scanning, high-precision GNSS measurements, and cloud-based geographic information platforms have created the conditions for a transition from traditional mapping to comprehensive digital modelling of territories [1]. One of the key outcomes of this process has been the implementation of digital twins, which enable the integration, analysis, visualization, and continuous updating of spatial data and are considered an important tool for decision support [2].

Analysis of recent research and publications. In contemporary scientific research, digital twins of urban environments are regarded as a promising tool for integrating spatial data, three-dimensional modelling, and geoinformation technologies to support decision-making and sustainable territorial development. In particular, M. Grieves and J. Vickers [3] elaborated on the concept of a digital twin as a combination of a physical object or system and its digital representation, which are interconnected through iterative and reciprocal exchange of data and information. Fundamental principles for developing digital twins are defined in the Gemini Principles, which state that such models should be oriented toward public good, value creation, and the provision of trustworthy information, while also meeting the requirements of security, openness, quality, interoperability, and extensibility [4].

R. Kitchin and U. Dawkins [5] presented their experience in developing a three-dimensional city information model of Dublin designed to integrate, visualize, and interpret spatial data. The authors noted that the developed Dublin City Information Model (CIM), in terms of its functional characteristics, was more of a digital mirror of the urban environment than a fully-fledged digital twin, as it primarily represented the

state of the city but did not provide a complete bidirectional data exchange with the physical environment.

Yakovenko et al. were the first in Ukraine to apply geodetic deformation monitoring methods to refine the boundary conditions of a digital twin of a building at 6-A Lobanovskoho Street in Kyiv, which was damaged by a missile strike on February 26, 2022 [6]. It was established that the deviation of the slab on the 25th floor from the horizontal level reached 241 mm, while the relative differential settlement of 0,0448 exceeded the regulatory limit of 0,005 by a factor of nine. These data were integrated into the BIM model and the building's digital twin as boundary conditions for finite element modelling. The study represents a unique example of applying geodetic measurements to verify a digital twin under conditions of an ongoing armed conflict.

Modern information technologies for urban environment modelling were investigated by T. Honcharenko [7]. The researcher proposed a conceptual IT framework for urban spatial management based on the integration of three components: an artificial intelligence (AI) system, Big Data technologies, and the CIM methodological platform. Study [8] examines the potential of a mobile platform for using a digital twin of meteorological forecasting processes. The authors emphasize that the use of a digital twin in weather forecasting can significantly improve forecast accuracy and provide rapid access to up-to-date weather information. O. Chertkov's research highlights the importance of geographic information systems (GIS), BIM modelling, Earth observation technologies, and automated monitoring systems in improving forecasting accuracy, optimizing design solutions, and ensuring the operational management of urban engineering infrastructure [9].

The aim of the article is to develop and validate a methodology for creating a digital twin of the urban environment using UAV photogrammetry and geographic information systems. The methodology encompasses sequential stages of flight mission planning, geospatial data acquisition and processing, development of a Level of Detail 1 (LOD1) City Information Model (CIM), and assessment of the technical and economic efficiency of its implementation for the needs of urban territorial communities.

Materials and Methods. The methodological framework of the study is based on a combination of systemic, comparative, geoinformation, photogrammetric, and cartographic approaches. The study is based on publications by Ukrainian and international authors addressing digital twins and city information models, the provisions of the international standards OGC CityGML 3.0 [4] and ISO 19152 [10], regulatory documents in the field of geospatial data, as well as UAV imagery and open spatial datasets. The study systematizes the types of digital models of the urban environment, determines an appropriate level of detail, substantiates the sequence of geospatial data acquisition and processing, and develops a City Information Model (CIM) for the needs of territorial communities.

At the initial stage of the study, the digital models of the urban environment were typologized and their functional differences were identified. In accordance with the classifications proposed by M. Grieves and J. Vickers [3], A. Bolton et al. [4], and R. Kitchen and U. Dawkins [5], digital representations of the urban environment were considered according to the level of interaction between a physical object and its digital model, the completeness of information exchange, and functional purpose. CIM is implemented at three functional levels (Table 1).

1. Typology of Digital Twins of the Urban Environment

Type	Name	Characteristics	LOD	Platform	Examples	Note
Digital Mirror	Static CIM	Accurate geometry + semantics. No real-time connection with the physical object	LOD1–LOD2	QGIS + GeoPackage + Cesium	Initial projects, first-cycle MTT	Recommended as a starting point in Ukraine
Digital Shadow	Shadow	One-way update: sensors → model. No feedback loop for management	LOD2	PostGIS + Sensor Feed	Utility monitoring, network auditing	Medium level of complexity
Digital Twin	Full Digital Twin	Bidirectional connection: model changes → management actions in the real city	LOD2–LOD3	CityEngine + IoT + AI	Singapore, Helsinki, Dubai	High cost; requires IoT

Type	Name	Characteristics	LOD	Platform	Examples	Note
CIM	City Information Model	Semantic 3D + simulation + real-time data. Corresponds to a Digital Mirror or Digital Twin depending on implementation	LOD2–LOD3	FME + CityGML + Unity	Dublin BCD (Kitchin, 2024)	Flexible architecture

Source: developed by the authors based on [3-5; 11-12].

At the same time, the OGC CityGML 3.0 standard [11;12] defines five geometric Levels of Detail, LOD0–LOD4 (Fig. 1).

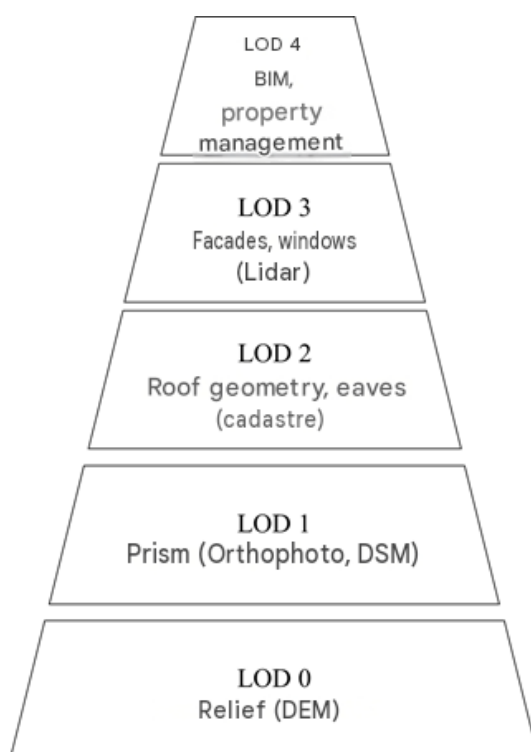


Fig. 1. Pyramid of Levels of Detail LOD0–LOD4 according to OGC CityGML 3.0. Source: developed by the authors based on [11;12].

For most urban territorial communities in Ukraine, the Digital Mirror / LOD1 level can be considered an appropriate initial stage for creating a digital representation of the territory. Given the balance between the level of detail, cost, complexity of development, and availability of source data, the Digital Mirror / LOD1 level was selected as the baseline for the initial validation of the methodology under the conditions of urban territorial communities in Ukraine.

To substantiate the selection of the data acquisition method, a comparative analysis of seven approaches was conducted using the following criteria: productivity, horizontal and vertical accuracy (mXY, mH), achievable Level of Detail (LOD), spatial coverage characteristics, cost, and recommended application area (Table 2). The input data for the comparison were compiled based on the research results of Ľ.Kovanič [13], V. Tarnavskiy et al. [14], and the authors' own calculations.

2. Comparative Analysis of Geospatial Data Acquisition Methods

Method	Productivity	mXY	mH	LOD	Coverage	Cost per 1 km ²	Applications
Total station survey	0,5–2 km ² /day	2–5 mm	5–10 mm	LOD3	Partial	45–80 thousand UAH/km ²	Detailed cadastral, BIM, facades
RTK-GNSS survey	1–3 km ² /day	8–12 mm	15–18 mm	LOD2	Partial	30–50 thousand UAH/km ²	GCP, land boundaries, control network
UAV photogrammetry (RTK)	10–50 km ² /day	< 2–5 cm	< 5–8 cm	LOD1–2	Full	8–15 thousand UAH/km ²	Orthophoto, DTM, mass cadastre, DT
Terrestrial laser scanning (TLS)	0,1–20 ha/day	0,1–1 mm	1–2 mm	LOD3	Full	Very high	Facades, LOD3, monuments, BIM
Airborne LS (ALS/LiDAR)	≤ 800 km ² /day	5–8 cm	10–15 cm	LOD1	Full	High (aviation)	Large-scale, DTM, forests
Mobile LS (MLS)	≤ 500 km ² /day	5–8 cm	8–12 cm	LOD2	Full	High	City streets, DSM, tunnels
Satellite imagery (comm.)	Global	0,3–0,5 m	—	LOD0	Full	Low	Monitoring, archive data, background

Source: developed by the authors

Based on the combination of the selected criteria, UAV photogrammetry with RTK positioning was chosen for the validation of the methodology. Compared with ground-based methods, it provides continuous spatial coverage, high productivity, sufficient accuracy for an LOD1 model, and the ability to simultaneously generate an orthophotomap, a digital surface model, and a dense point cloud.

The mathematical framework of the study comprises a system of calculation formulas that formalize the main stages of the workflow, from flight mission planning to the assessment of the efficiency of digital twin implementation.

Ground Sample Distance (GSD, cm/pixel) [13]:

$$GSD = \frac{H \times d}{f \times 1000}, \quad (1)$$

where: H – is the flight altitude (m); d is the matrix pixel size (mu m); f – is the focal length (mm). Initial data for DJI P4 RTK (d = 2,41 mkm, f = 8,8 mm, H = 120, m).

Number of flight lines (n, strip) [13]:

$$n = \left\lceil \frac{W}{(Sw \times (1 - By))} \right\rceil + 1, \quad (2)$$

where: W – width of the area of interest (AOI), m; Sw = GSD × Nw – ground footprint width, m; Nw – number of pixels of the digital image along the frame width, pix.; By – lateral overlap.

Base distance between photographs (B_{photo}) and total number of photographs (N) [13]:

$$B_{photo} = Sh \times (1 - Bx), \quad (3)$$

$$N = n \times \left\lceil \frac{L}{B_{photo}} \right\rceil, \quad (4)$$

where: Sh – length of the frame on the ground along the flight direction, m; Bx – photogrammetric base along the flight direction, i.e., the distance between the centers of two consecutive photographs on the ground, m; L – length of the study area along the flight route, m.

Accuracy of the orthophoto (mXY, cm) [13]:

$$mXY \approx 1,5 \times GSD; \quad mH \approx 2,0 \times GSD \quad (5)$$

Accuracy without GCP in PPK mode (mXYppk, cm) [10]:

$$mXYppk \approx GSD \times 1,2 + C_{sys}, \quad (6)$$

where, C_{sys} = 2-5 cm is the systematic error of camera RTK positioning without ground control. Optimal number of ground control points with known planimetric and elevation coordinates (nGCP) [13]:

$$nGCP = \left\lceil \sqrt{\frac{S}{S_0}} \right\rceil \times k, \quad (7)$$

де S – area of the study territory (AOI)(km²); $S_0 = 0,5$ km² – standard area per 1 GCP; k – correction coefficient accounting for the territory configuration, corner sections, and required overlap, $k=1,5-2,0$.

The number and placement of GCPs were determined taking into account the area, territory configuration, relief, and accuracy requirements.

Building density coefficient [13]:

$$K_Z = \left(\frac{S_b}{S_{AOI}} \right) \times 100\%, \quad (8)$$

VARI- vegetation index for an RGB camera [13]:

$$VARI = \frac{G-R}{G+R-B}, \quad (9)$$

NDVI for multispectral cameras (DJI Multispectral, MicaSense RedEdge) [10]:

$$NDVI = \frac{NIR - R}{NIR + R}, \quad (10)$$

where, NIR – is the near-infrared band. Classification: $< 0,1$ – bare soil/asphalt; $0,1-0,25$ – sparse vegetation; $> 0,25$ – dense vegetation.

Relative savings compared to the traditional method (E_s , %) [13] :

$$E_s = \frac{E_{trad} - E_{uav}}{E_{trad}} \times 100\% \quad (11)$$

where, E_{trad} – cost of traditional surveying of the same area (thousand UAH); E_{uav} – cost of UAV surveying. For an area of 1km²: $E_{trad} \approx 62$ thousand UAH (tachymetry), $E_{uav} \approx 13$ thousand UAH $\rightarrow$ relative savings compared to the traditional method is 79,0%. Relative economic efficiency coefficient (K_e) [13]:

$$K_e = \frac{E_{trad}}{E_{uav}}, \quad (12)$$

The calculated coefficient demonstrated a 4,77-fold reduction in costs.

The proposed six-phase technological workflow covers the complete cycle of CIM model development, from the preparation of input data to its publication (Fig. 2). Each phase produces a separate information product that is subsequently used as input data for the next stage.

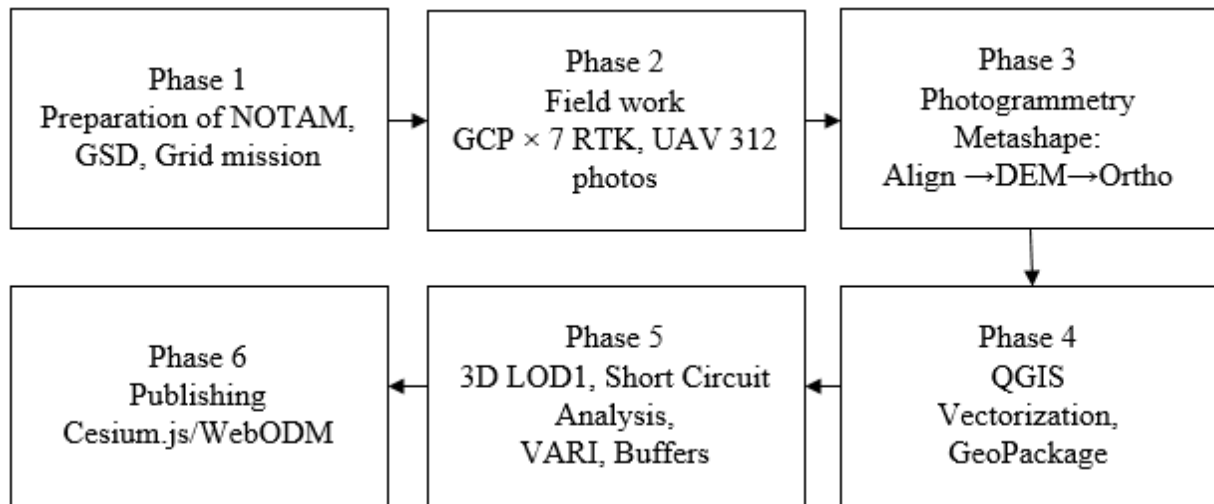


Fig. 2. 6-phase methodical chain for constructing a digital twin of the MTG

Notation: → sequential product transfer; ← reverse transition (Phase 5→4 upon detection of topological errors). Source: developed by the authors [13–16].

A comparative analysis of specialized software products was conducted to select the software required for photogrammetric processing of UAV imagery, spatial analysis, geospatial data storage, three-dimensional modelling, and workflow automation. The evaluation was based on functional purpose, license type, supported operating systems, key capabilities, and suitability for specific stages of CIM model development (Table 3).

3. Comparative characteristics of software tools for creating a CIM (City Information Modeling) model of the urban environment

Software Product	Category	License	OS	Key Features	Suitability Assessment
Agisoft Metashape Pro 2.x	Photogrammetry	Commercial	Win/Mac/Linux	SfM+MVS, RTK/PPK, auto GCP, LOD1–3 products, quality report	high
OpenDroneMap (ODM)	Photogrammetry	Open Source	Docker/CLI	SfM without GUI, WebODM interface, batch processing	auxiliary
Pix4Dmapper	Photogrammetry	Commercial	Windows	Rapid Check, real-time quality, LOD3 point cloud	medium
QGIS 3.34 LTR	GIS analysis, 3D	Open Source (GPL)	Cross-platform	Vectorization, GeoPackage, 3D View, 100+ plugins, NDVI	high

Software Product	Category	License	OS	Key Features	Suitability Assessment
PostGIS / PostgreSQL	Spatial DB	Open Source	Cross-platform	SQL+geometry, LADM-UA, mass appraisal, CityGML	medium
Delta/Digitals Pro XE	GIS / topography	Commercial (UA)	Windows	DXF/XML, cadastral plans, remote sensing integration	medium
Python (GeoPandas, Rasterio)	Automation	Open Source	Cross-platform	NDVI, deep learning, batch raster processing	medium
CityEngine (Esri)	3D planning	Commercial	Win/Mac	CGA-rules, LOD2–3, CityGML, procedural modeling	auxiliary
Cesium.js / Ion	3D publishing	Open Source / SaaS	Web (WebGL)	3D Tiles, CZML, public API, open cloud environment	medium
DJI Pilot 2 / Terra	UAV missions	Free	Android/iOS/Win	Grid/Waypoint, RTH, auto GSD, 2D/3D missions	medium

Source: developed by the authors [15;16]

Presentation of the main research material. The methodology was tested through practical validation by developing a Digital Mirror. A Digital Mirror is a digital representation of a physical object or urban environment that reflects its current state based on the available data but does not provide a fully automated bidirectional exchange with the real-world object [5;15]. In general, an urban digital twin is based on two fundamental principles: learning and decision-making. It provides an opportunity to learn from interactions between urban elements and, consequently, to make more informed decisions that improve the efficiency of urban management and the performance of individual urban components. The results of implementing an urban digital twin include data management, visualization, situational awareness, planning and forecasting, integration, and collaboration [16].

The digital environment was represented by a fragment of the urban territory of Rivne, with an Area of Interest (AOI) of 42,0 ha (Fig. 3).



Fig. 3. Object of study: Land plot in Rivne: a – topographic base scale 1:2000; b – base map (ESRI Online Imagery). Source: Open Data Geoportal of Rivne

Input parameters of the DJI Phantom 4 RTK mission: $h = 120$ m, $GSD = 3,02$ cm, $B_x = 80\%$, $B_y = 70\%$, $n = 12$ strips, $N = 322$ images, the estimated duration of the flight mission was 22 min 41 s. (Fig. 4).

Geodetic support: $nGCP = 7$ (formula 7: $S = 0,42\text{km}^2$, $S_0 = 0,5\text{km}^2$, $k = 2,0 \rightarrow n = 6 + 1 = 7$), evenly distributed along the perimeter of the area, measured by the RTK method (Leica GS18 T / ZAKPOS NRTK network): $m_{XY} = \pm 9\text{-}14$ mm, $m_H = \pm 14\text{-}20$ mm.

Processing was performed in the Agisoft Metashape Pro 2.1 environment (High accuracy, GCP referencing, Medium Dense Cloud): 5793412 points, DSM 6 cm, orthophoto $GSD = 3,29$ cm/pixel. Residual error for GCP: $m_{XY} = 0,014$ m (standard $< 1,5 \times GSD = 0,049$ m). In the QGIS 3.34 LTR environment, a geospatial database city.gpkg was generated in GeoPackage format using the coordinate system EPSG:5562.



Fig. 4. Planned aerial survey route using the DroneDeploy Flight App.

Source: developed by the authors

The database contained five thematic layers: buildings – 248 polygons, roads – 187 linear segments, green spaces – 34 polygons, ground control points – 7 points, and the study area boundary – 1 polygon. The labor intensity of manual vectorization was about 2,5 h/ha (Fig. 5).

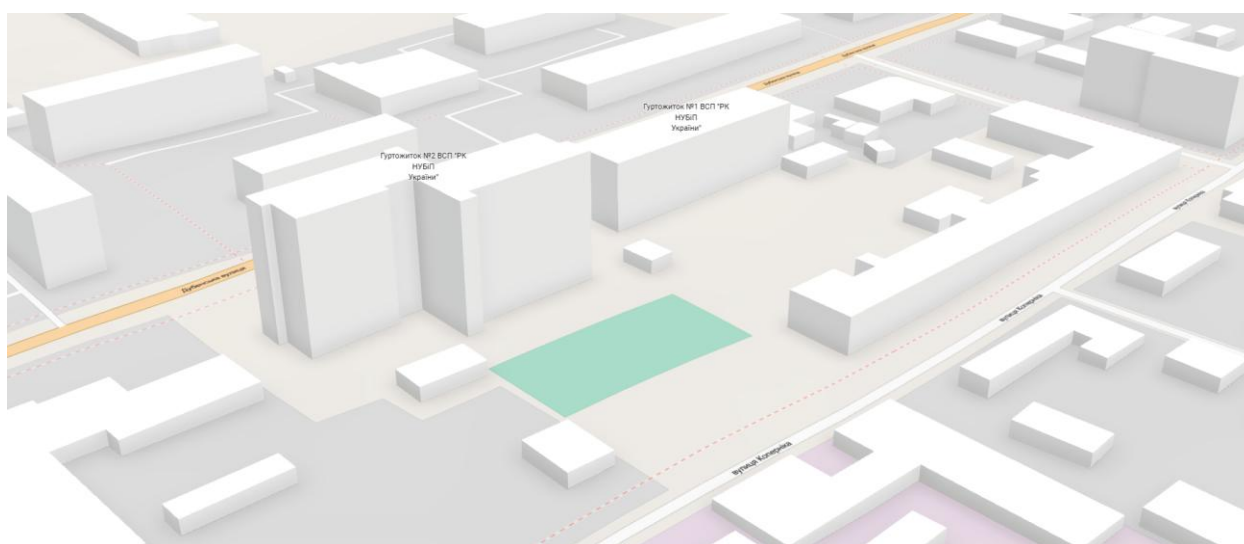


Fig. 5. Three-dimensional LOD1 model of an urban environment fragment in the city of Rivne. Source: developed by the authors

The spatial analysis of the study area included the determination of the building coverage ratio, assessment of the condition of green vegetation using the VARI index, delineation of pedestrian accessibility zones, and calculation of the economic efficiency of the applied approach. The building coverage ratio was 12,9%, while the

mean VARI value was approximately 0,22, indicating a satisfactory condition of the vegetation cover. To assess the accessibility of facilities, buffer zones with a radius of 500 m were generated. The calculated Return on Investment (ROI) was approximately 4,77 times. During the development of the LOD1 model, building heights were automatically determined from the Digital Surface Model (DSM) for 87% of the buildings, while the height characteristics of the remaining 13% of the objects were manually refined. The summarized results of the methodology validation are presented in Table 4.

4. Consolidated results of the practical validation of the methodology

Indicator	Value	Comment
Number of DNG images	322 pcs.	20 MP, with EXIF-RTK coordinates, RAW format
Flight height (AGL)	120 m	According to APU-UAS; optimum GSD/time
GSD (calculated)	3,29 cm/pixel	Formula (1): $d=2,41 \text{ mkm}$, $f=8,8 \text{ mm}$, $H=120 \text{ m}$
Longitudinal / lateral overlap	80% / 70%	Regulatory requirement $> 60\%$ / 55%
Number of flight strips	12 strips	Formula (2): $W=577 \text{ m}$, $Sw \approx 165\text{m}$, $By = 0,70\%$
Mission duration (calculated)	22 min 41 s	According to the flight mission planner.
Number of GCPs	7 points (101–107)	Uniform distribution; distance between GCPs $\leq 350 \text{ m}$
GCP accuracy (mXY)	$\pm 0,009\text{--}0,014 \text{ m}$	RTK Leica GS18 T / ZAKPOS NRTK network
GCP accuracy (mH)	$\pm 0,014\text{--}0,020 \text{ m}$	Baltic 1977 height system
Dense point cloud	5793412 points	Agisoft Metashape, Medium quality
Orthophoto GSD	3,02 cm/pixel	GeoTIFF, RGB 8-bit, EPSG:5562, seamless
DSM resolution	6,0 cm/pixel	GeoTIFF float32, EPSG:5562
Residual GCP error (mXY)	0.014 m (avg.)	Meets $< 1,5 \times \text{GSD} = 0,049 \text{ m}$
Number of vector features: buildings	248 polygons	Average area $218,5 \text{ m}^2$; manual digitization
Number of features: roads	187 segments	Centerlines, surface/width_m attribute
Number of features: greenery	34 polygons	Area $\approx 8.46 \text{ ha}$ (20.1% AOI)

Indicator	Value	Comment
Building density coefficient (K3)	12,9%	Formula (8): $S_{build} = 54200 / SAOI = 420000 \text{ m}^2$
Vegetation index (VARI)	≈ 0.22	Formula (6): green zone – satisfactory condition
Vectorization time per 1 ha	$\approx 2.5 \text{ h}$	Manual digitization in QGIS 3.34, scale 1:500
Relative economic efficiency coefficient (Ke)	≈ 4.8 times higher than the costs associated with UAV use	Formula (12): $E_{trad} = 62 \text{ thousand UAH}$ / $E_{uav} = 13 \text{ thousand UAH}$

Source: developed by the authors; calculations were performed using Equations (1)–(12); QGIS Field Calculator

For the 42,00 ha study area, seven Ground Control Points (GCPs) were established, distributed along the perimeter and in the central part of the survey block. The number of points was determined considering the configuration of the study area, image overlap parameters, the RTK-based camera positioning method, and the need for spatial control of the photogrammetric model. The mean VARI value within the delineated green vegetation areas was approximately 0,22, which, according to the adopted classification, corresponds to a predominance of sparse and moderately dense vegetation.

The validation results confirmed the practical suitability of the proposed technological workflow for developing a basic digital representation of an urban territory at the LOD1 level. The application of UAV photogrammetry enabled the simultaneous generation of an orthophotomap with a spatial resolution of 3,02 cm/pixel, a Digital Surface Model (DSM) with a resolution of 6 cm/pixel, and a dense point cloud containing more than 5,79 million points. The residual horizontal error was 0,014 m, which was below the adopted threshold value of $1,5 \times \text{GSD}$. The resulting datasets provided a sufficient geometric basis for vectorizing buildings, the road network, and green vegetation, as well as for subsequent development of a three-dimensional building model.

An important advantage of the proposed approach is the integration of photogrammetric products with a semantically structured geospatial database. The

resulting GeoPackage database contained 248 building polygons, 187 road network segments, 34 green vegetation polygons, Ground Control Points, and the boundary of the study area. This structure makes it possible to move beyond visual representation of the territory toward the execution of spatial queries, calculation of building coverage indicators, analysis of green vegetation, and preparation of data for three-dimensional visualization. At the same time, the workload associated with manual vectorization, which amounted to approximately 2,5 hours per hectare, indicates the need for further automation of the object recognition process.

The comparison of geospatial data acquisition methods demonstrated that UAV photogrammetry occupies an intermediate position between highly accurate but relatively low-productivity ground-based methods and wide-area satellite and airborne technologies, which generally provide less detailed spatial information [15]. For the development of an LOD1 model, its main advantage lies in the balance between spatial detail, continuous coverage, productivity, and cost. Terrestrial laser scanning provides higher accuracy and greater façade detail; however, it is more appropriate for LOD3 models, detailed documentation of individual buildings, and the recording of architectural heritage sites [16]. Satellite imagery can be used as background and archival data, but its spatial resolution is insufficient for detailed modelling of individual urban objects [17].

In terms of its functional characteristics, the developed model represents the geometric and semantic state of the territory at the time of data acquisition, but it does not maintain a permanent connection with sensors and does not provide automated bidirectional data exchange. This does not diminish its practical value for territorial communities, since the Digital Mirror / LOD1 level can serve as a realistic initial stage of spatial management digitalization [18]. A model at this level can be used for building inventory, updating the cartographic base [19], land-use analysis, assessment of green areas, urban improvement planning, and preliminary substantiation of urban planning decisions [20]. The gradual integration of utility network data, municipal registers, sensor data, and information on changes in physical objects will enable the digital representation to be progressively transformed into a Digital Shadow and subsequently

into a fully functional Digital Twin. The classification-based distinction between these levels has already been established in the methodological section of the article.

Conclusions. The study substantiates a methodology for creating a basic digital representation of the urban environment based on the integration of UAV photogrammetry, high-precision GNSS measurements, and geographic information systems. The proposed six-phase technological workflow encompasses flight mission preparation, field data acquisition, photogrammetric processing, development of a geospatial database, spatial analysis, three-dimensional modelling, and publication of the results. The results of the comparative analysis demonstrate that UAV photogrammetry is an appropriate method for developing a Level of Detail 1 (LOD1) City Information Model (CIM). It provides continuous spatial coverage, enables the generation of an orthophotomap, Digital Surface Model (DSM), and point cloud, delivers sufficient accuracy for the defined tasks, and offers lower costs compared with traditional ground-based surveying. The developed model corresponds to the Digital Mirror / LOD1 functional level rather than a fully-fledged digital twin, as it does not provide automated bidirectional data exchange with the physical environment. At the same time, it can be regarded as a foundational stage in the development of a territorial community digital twin and can be used for object inventory, updating the cartographic base, analysis of built-up areas and green vegetation, spatial planning, and information support for decision-making.

Further development of the methodology should focus on automating vectorization, assessing accuracy using independent check points, progressing to the LOD2 level, integrating cadastral and urban planning data, establishing mechanisms for regular data updating, and incorporating sensor information. These developments will enable a gradual transition from a static Digital Mirror to a dynamic Digital Twin of the urban environment.

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СТВОРЕННЯ ЦИФРОВОГО ДВІЙНИКА МІСЬКОГО СЕРЕДОВИЩА ЗАСОБАМИ БПЛА-ФОТОГРАММЕТРІЇ ТА ГІС

***Анотація.** У статті розглянуто методологію створення базового цифрового двійника міського середовища на основі інтеграції безпілотних літальних апаратів (БПЛА), фотограмметрії, високоточних GNSS-вимірювань і геоінформаційних систем (ГІС). Метою дослідження є розробка методології створення цифрового двійника міського середовища із застосуванням БПЛА-фотограмметрії та геоінформаційних технологій, а також її апробація на реальному об'єкті дослідження. Для досягнення поставленої мети застосовано комплексний шестифазний технологічний ланцюг, що охоплює планування знімальної місії, виконання польових робіт із RTK-позиціонуванням, фотограмметричне опрацювання матеріалів у середовищі Agisoft Metashape, векторизацію просторових об'єктів у QGIS з формуванням бази даних*

GeoPackage, просторовий аналіз та тривимірну візуалізацію. Ключовим результатом є створення цифрової моделі міського середовища рівня LOD1, яка відповідає концепції Digital Mirror і може розглядатися як початковий етап цифровізації територіальних громад. На відміну від повноцінного цифрового двійника, цифрове дзеркало відтворює поточний стан фізичного середовища, але не забезпечує автоматизованого двостороннього обміну даними в режимі реального часу. Методичний підхід апробовано на фрагменті міської території м. Рівне площею 42 га. Розраховано оптимальні параметри аерознімання, визначено необхідну кількість наземних опорних точок та підтверджено відповідність отриманої точності встановленим вимогам. Виконано оцінювання просторової точності отриманих матеріалів, розраховано коефіцієнт забудови, індекс рослинності VARI та сформовано модель рівня LOD1 із подальшою публікацією у вебсередовищі. Результати дослідження підтвердили, що запропонована методологія забезпечує формування цифрової моделі міського середовища, придатної для інвентаризації забудови, актуалізації картографічної основи, просторового планування та інформаційної підтримки прийняття управлінських рішень у процесі відбудови й розвитку територій..

Ключові слова: *цифровий двійник, БПЛА-фотограмметрія, геоінформаційні системи, цифрова модель міста, LOD1, просторові дані, територіальна громада, цифрове моделювання.*