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TERRESTRIAL LASER SCANNING FOR 3D CADASTRE: A CASE STUDY OF ROAD INFRASTRUCTURE IN THE REPUBLIC OF MOLDOVA

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Abstract. Accelerated urban development and infrastructure expansion require the modernization of the cadastral system in the Republic of Moldova through the integration of the three-dimensional component. This article analyzes the possibility of implementing 3D cadastre, starting from the limitations of the current two-dimensional cadastre and the need for alignment with international standards, particularly ISO 19152 (LADM - Land Administration Domain Model). The case study focuses on the three-dimensional modeling of a complex infrastructural object – a road bridge in Criuleni district, located at the intersection of Hrușova, Ciopleni, and Goian villages. Using terrestrial laser scanning technology (Leica BLK360), high-precision spatial data were obtained (RMS <10 mm, density >800 points/m²), which were processed and integrated into a functional 3D model. The results demonstrate that three-dimensional modeling provides a more accurate representation of reality, facilitates engineering analysis, and enables correct description of overlapping objects or those with complex geometry. The article proposes a hybrid implementation model, in which the 2D cadastre remains the legal basis, while 3D models serve as technical and decision-making support. The conclusions highlight the need for developing a specific regulatory framework, standardizing data acquisition processes, and creating an integrated GIS (Geographic Information Systems) platform for efficient management of three-dimensional spatial information.

Keywords: *3D cadastre, terrestrial laser scanning, three-dimensional modeling, road infrastructure, GIS, LADM.*

Rezumat. Dezvoltarea urbană accelerată și extinderea infrastructurii impun necesitatea modernizării sistemului cadastral din Republica Moldova prin integrarea componentei tridimensionale. Prezentul articol analizează posibilitatea implementării cadastrului 3D, pornind de la limitele cadastrului bidimensional actual și necesitatea alinierii la standardele internaționale, în special ISO 19152 (LADM - Land Administration Domain Model). Studiul de caz se concentrează asupra modelării tridimensionale a unui obiect infrastructural complex – un pod rutier din raionul Criuleni, situat la intersecția satelor Hrușova, Ciopleni și Goian.

Utilizând tehnologia de scanare laser terestră (Leica BLK360), au fost obținute date spațiale de înaltă precizie (RMS <10 mm, densitate >800 puncte/m²), care au fost procesate și integrate într-un model 3D funcțional. Rezultatele demonstrează că modelarea tridimensională oferă o reprezentare mai exactă a realității, facilitează analiza inginerească și permite descrierea corectă a obiectelor suprapuse sau cu geometrie complexă. Articolul propune un model hibrid de implementare, în care cadastrul 2D rămâne baza juridică, iar modelele 3D servesc ca suport tehnic și decizional. Concluziile evidențiază necesitatea dezvoltării unui cadru normativ specific, standardizarea proceselor de achiziție a datelor și crearea unei platforme GIS (Sisteme informaționale geografice) integrate pentru gestionarea eficientă a informațiilor spațiale tridimensionale.

Cuvinte cheie: *cadastru 3D, scanare laser terestră, modelare tridimensională, infrastructură rutieră, GIS, LADM.*

1. Introduction

The cadastral system represents the fundamental infrastructure for real estate administration, playing an essential role in ensuring legal security of property rights and in territorial development planning [1, 2]. In the Republic of Moldova, the cadastre currently operates based on a two-dimensional model [3], in which real estate properties are represented through planar projections, without reflecting the vertical complexity of modern constructions and infrastructure [4].

Rapid urban development, the expansion of underground infrastructure (utility networks and underground transportation systems), and the growing number of buildings with complex multi-level uses have highlighted the limitations of two-dimensional representation [5, 6]. In such situations, the 2D cadastre cannot accurately describe the spatial relationships between overlapping objects, which generates legal and technical ambiguities [7]. For example, in the case of road overpasses, tunnels, mines and quarries, or multi-story buildings owned by different proprietors, the delineation of spaces and the establishment of property rights becomes problematic in the absence of a clear vertical component [8, 9, 10]. Rethinking the legal and economic aspects of urban society by transitioning from the traditional two-dimensional paradigm to a three-dimensional (3D) approach to property and space use represents a current necessity in the development, implementation, and monitoring of urban land policies (social, economic, ecological) [11]. The 3D cadastre is one of the instruments that can facilitate this process through spatial databases and representations.

The International Organization for Standardization (ISO) has recognized the necessity of a three-dimensional approach through the development of the ISO 19152 standard, also known as the Land Administration Domain Model (LADM) [1, 2]. This standard provides a conceptual framework for representing cadastral objects in three-dimensional space, enabling the correct description of legal volumes, vertical boundaries, and complex spatial relationships [12].

In this context, the Republic of Moldova faces the challenge of developing its cadastral system to meet current requirements and align with European and international standards [12, 13]. The implementation of 3D cadastre represents not only a technological modernization but also a practical necessity for ensuring efficient territorial administration and facilitating sustainable development [6, 8, 14].

This article aims to analyze the feasibility of implementing 3D cadastre in the Republic of Moldova through a concrete case study of complex road infrastructure. The purpose is to demonstrate, through practical application, the advantages of three-dimensional modeling and to propose a methodological framework for integrating these technologies into the national cadastral system.

2. Materials and Methods

2.1. Study area

The area selected for the case study is located in Criuleni district, at the administrative boundary between the villages of Hrușova, Ciopleni, and Goian. The analyzed sector is part of the national road network, classified as a category M road (main/expressway) on the principal section, while the intersection area includes connections with a republican road (category R), local roads, and a watercourse (Figure 1). This classification confers strategic regional importance to the site, with the road serving as a link between localities and ensuring regional traffic continuity [15, 16].

a) b)

Figure 1. Location of the study area: a) Source: *cadastru.md/ecadastru*; b). Source: *andsa.md/harta-interactiva* [15, 16].

The main infrastructural element analyzed is a road bridge that crosses an area with significant altitude differences. The three-dimensional configuration of the road junction is characterized by: the bridge deck located at the upper elevation, the lower roadway (local road) at the intermediate elevation, the watercourse bed at the lowest elevation, access ramps with significant level differences, and embankments and structural support zones.

The geometric complexity of the structure – which includes the roadway at the upper level, the abutment system, and lateral embankments – fully justifies the selection of this object for demonstrating the advantages of three-dimensional modeling. In classical two-dimensional cadastral representation, such structures are reduced to simple planar projections, which eliminates essential information about the vertical component and the actual spatial relationships between constructive elements.

The development of the three-dimensional model of the road infrastructure required the use of a complex dataset, structured into two main categories: existing (archival) data and data acquired through direct precision geodetic measurements. This combined approach allows for the creation of a coherent and accurate model while ensuring its integration into the legal and administrative framework specific to the Republic of Moldova. Topographic maps at scales of 1:10,000 and 1:50,000 played an important role in the initial analysis, used for understanding the geographical position of the study area, the relief configuration, and the relationship between the road infrastructure and the surrounding terrain (Figure 2). This enabled the identification of contour lines, main relief forms, the road network, and land use boundaries.

a) b)

Figure 2. Topographic maps: a) scale 1:10,000; b) scale 1:50,000 [17].

To evaluate the evolution of road infrastructure and changes occurring in the study area, a comparative analysis was performed based on available orthophotoplans for different time periods, through the overlay and comparison of photogrammetric (aerial) images acquired during 2011–2021 [17].

The land within the studied area is registered in the Real Estate Registry (RER) and identified by a cadastral number, in accordance with current legislation. This cadastral registration ensures legal recognition of the site and enables the correlation of cadastral data with the actual situation on the ground. The cadastral data available in the e-Cadastre platform [15] provide information regarding cadastral parcel boundaries and the general location of the object, however, they do not reflect the vertical spatial relationships between constructive elements. The orthophotoplan – the primary visual support of the system – graphically overlays all components of the bridge without altimetric separation, which represents precisely the limitation that terrestrial laser scanning technology modeling aims to overcome.

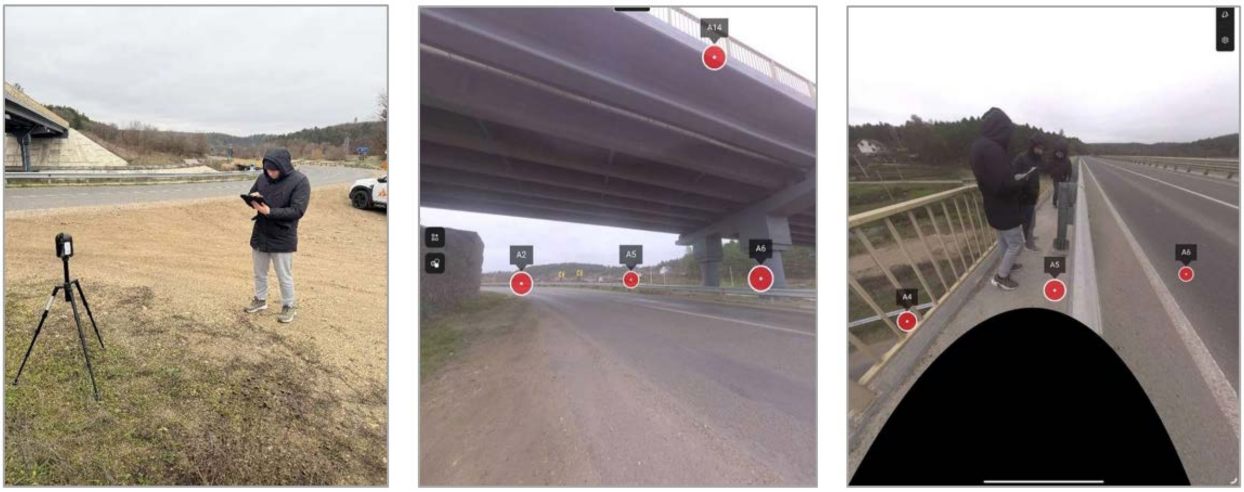
Following the analysis of available data – topographic maps, orthophotoplans, cadastral data from the RER, and information regarding infrastructure and relief – it was determined that the study area is characterized by a complex spatial structure. The overlay of road elements with the relief and adjacent areas cannot be accurately represented through a two-dimensional representation, which limits the understanding of vertical relationships between objects. For this reason, the use of a three-dimensional approach is required, capable of faithfully reflecting the actual structure of the terrain and the analyzed infrastructure.

2.2. Data acquisition

For the acquisition of three-dimensional data, the Leica BLK360 (BLK Edition) terrestrial laser scanner was used, a high-precision equipment designed for rapid and detailed documentation of built and natural environments. It operates using LiDAR (Light Detection and Ranging) technology: emitting laser pulses and recording their return time, calculating the distance to reflective objects in the scanning field [18].

The combination of high precision, portability, and scanning speed makes the BLK360 a suitable instrument for documenting road infrastructure, including in areas with limited access (under the bridge deck, at the base of abutments, on embankments).

To ensure complete coverage of the studied area and to obtain a coherent three-dimensional model, the positioning of scanning stations was performed strategically, based on the road infrastructure configuration and field conditions (Figure 3).

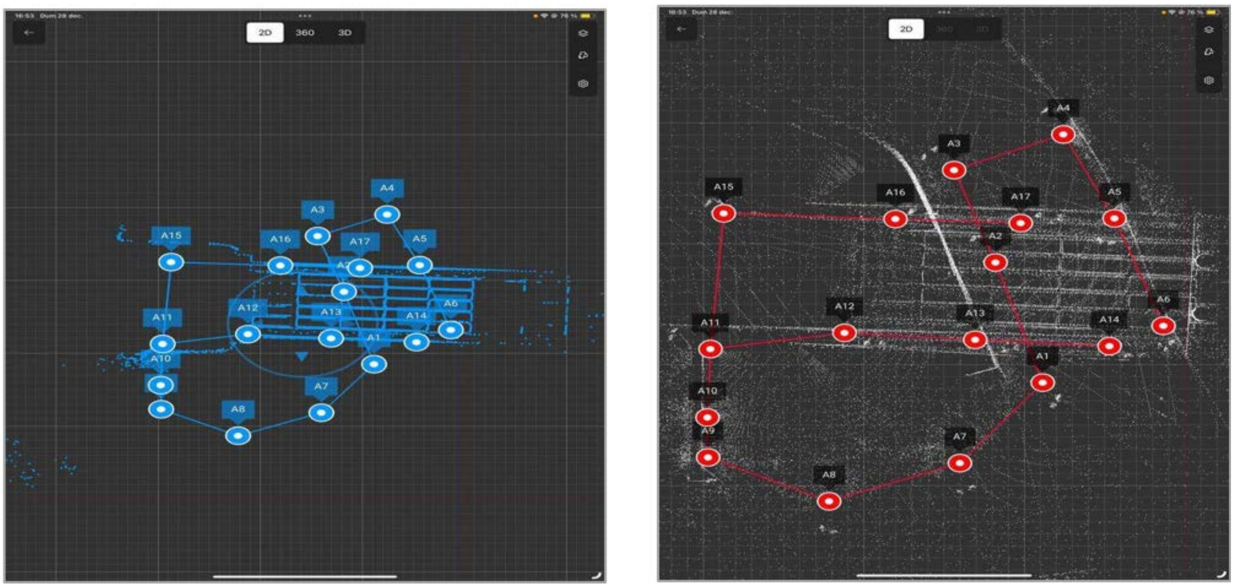


a) b) c)

Figure 3. Data acquisition: a) Terrestrial laser scanning using the BLK360; b) Positioning of scanning stations under the overpass; c) Positioning of scanning stations on the roadway [19].

The stations were positioned in two main configurations: on the bridge deck (for scanning the deck and parapets) and under the crossing structure (for scanning the support infrastructure and vertical constructive elements). Positioning under the deck involved special visibility conditions and required station placement both axially and laterally relative to the travel lane.

During the data acquisition process, the scans were initially correlated using the automatic pre-alignment method (Pre-alignment). Pre-alignment of the scans played an essential role in the coherent organization of the measurement campaign, as it enabled real-time evaluation of spatial continuity between successive scanning positions (Figure 4).



a) b)

Figure 4. Scan pre-alignment process: a) Pre-alignment scheme of scanning stations; b) Result of scan pre-alignment.

Through this stage, it was immediately verified whether the areas of interest were adequately covered and whether sufficient overlaps existed between scans for subsequent correct integration. An important advantage of pre-alignment is the ability to rapidly identify any discontinuities or coverage gaps, which could be remedied by adding supplementary stations.

2.3. Data processing

The processing of the acquired data followed a structured workflow in successive stages, performed in Cyclone REGISTER 360 (BLK Edition) software, an application dedicated to processing data from Leica BLK terrestrial laser scanners [20]. The processing workflow aimed to transform the raw data into usable three-dimensional models while ensuring quality control and geometric accuracy of the results (Figure 5).

a) b)

Figure 5. Data processing in Cyclone REGISTER 360: a) Point cloud processing interface; b) Final integrated point cloud.

The process included several essential stages: (1) importing and organizing raw data from all scanning stations; (2) registering the scans into a common coordinate system through cloud-to-cloud and target-based alignment methods, achieving sub-centimeter alignment accuracy; (3) global optimization (bundle adjustment) to minimize accumulated errors and ensure geometric consistency; (4) point cloud cleaning by removing temporary elements, outliers, and noise; (5) georeferencing to the national MOLDREF 99 system [21, 22] for compatibility with cadastral data from the Real Estate Registry.

Following the import, alignment, and optimization stages, a coherent, cleaned, and correctly positioned point cloud in the national coordinate system was obtained. This result represents the final form of the field acquisition and constitutes the basis for all subsequent analyses.

An important advantage is the ability to export and use the data in specialized 3D modeling applications, geographic information systems (GIS), or engineering software without significant precision losses [23]. Additionally, the point cloud enables the generation of a coherent three-dimensional model, usable for both geometric analysis and functional evaluation of the infrastructure, providing an accurate representation of the vertical relationships specific to bridge-type works, overpasses, or overlapping roads (Figure 6) [19].

Thus, the processing stage consolidates the metric foundation of the entire experimental approach, ensuring the necessary conditions for the coherent integration of three-dimensional information within an extended cadastral model.

a) b) c) d)

Figure 6. 3D representation of infrastructure after data processing: a) 3D visualization of bridge superstructure; b) 3D model of the bridge deck; c) Representation of piers and infrastructure; d) 3D model of the roadway.

3. Results and Discussion

3.1. Characteristics of the obtained 3D model

Following the data acquisition and processing, a three-dimensional point cloud was obtained, completely covering the analyzed road infrastructure and including all main components: the bridge deck, support abutments, lateral embankments, the lower local road, and the watercourse bed. The final model exhibits geometric precision evaluated through root mean square error (RMS) below 10 mm, which corresponds to the requirements for engineering analysis applications and high-precision cadastral modeling. The high density of the point cloud, exceeding 800 points per square meter, enabled detailed representation of all constructive elements, including fine details such as structural joints, parapets, and surface textures.

The three-dimensional model provides a complete representation of the spatial configuration of the road junction, highlighting the altimetric relationships between infrastructure components. The level difference between the upper deck and the lower local road roadway reaches approximately 4.20 meters, an aspect that cannot be accurately represented in two-dimensional cadastral representation. The bridge abutments have heights of approximately 5.67 meters, while the embankments have variable slopes ranging from 15° to 30°, depending on the terrain configuration [19].

Georeferencing to the national MOLDREF 99 system ensures complete compatibility with data from the Real Estate Registry and enables direct integration into the existing cadastral system. This aspect is essential for the practical valorization of the model within territorial administration and for facilitating its use by institutions involved in infrastructure management.

3.2. Comparative analysis: 3D model vs. 2D cadastral representation

The comparison between the obtained three-dimensional model and the existing two-dimensional cadastral representation in the e-Cadastre platform [15] highlights a series of significant advantages of the 3D approach, both from a technical perspective and in terms of the clarity of the information provided.

In the 2D cadastral representation, the road infrastructure appears as a simple area delineated on the horizontal plane, without clear indications about the vertical component. The e-Cadastre platform displays the bridge as a flat surface, graphically overlaying all components (deck, abutments, lower road, watercourse bed) in a single projection, without altimetric separation. The user cannot distinguish between the different levels of the infrastructure, which hinders understanding of the actual configuration. The graphic overlay of all elements creates uncertainty in spatial delineation and in establishing property or administrative rights [24].

The three-dimensional representation volumetrically delimits each component: the volume occupied by the bridge deck and protective parapets (public road domain - category M national road), the volume used by the lower local road (public road domain - local road), the volume of the watercourse bed (public water domain). This clear separation facilitates appropriate administration of each domain and eliminates potential disputes regarding space use.

The 3D model obtained through laser scanning provides exact measurements of all dimensions [25], with sub-centimeter precision: bridge deck length, roadway width, abutment heights, embankment slopes, level differences between infrastructure components. These data are integral to the geometric model and can be extracted directly, without requiring additional measurements.

The 2D representation does not allow volumetric analyses, stability calculations, or clearance verifications. Any technical analysis requires the creation of additional models, which fragments the process and increases the risk of errors.

The three-dimensional model would enable the direct performance of complex analyses in the 3D GIS environment (volumetric calculations, embankment stability, clearance verifications, hydrological simulations), ensuring data coherence and reducing decision-making time.

3.3. Implementation proposal for the Republic of Moldova

Based on the obtained results and the conducted analysis, a hybrid implementation model for 3D cadastre in the Republic of Moldova is proposed, which combines the advantages of the existing two-dimensional cadastre with the extended capabilities of three-dimensional representation.

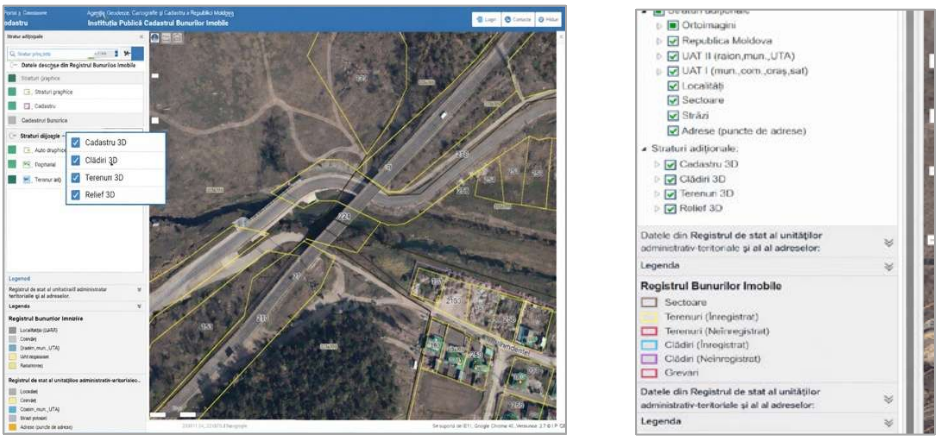
The case study demonstrates that modern spatial data acquisition technologies, particularly terrestrial laser scanning, are perfectly compatible with the requirements of the ISO 19152 standard (LADM - Land Administration Domain Model) [23] for defining three-dimensional spatial units. The obtained model can be structured according to LADM, defining the legal volumes of different infrastructure components.

The LADM standard provides four fundamental packages for land administration: Party (legal entities holding rights), Administrative (rights, restrictions, and responsibilities), Spatial Unit (spatial units that delimit the extent of rights), and Surveying (geodetic measurements). In the case of the analyzed infrastructure, the 3D model enables precise definition of spatial units (the bridge deck as a distinct volume, the lower road as another volume, the riverbed space as a third volume), each having specific legal attributes (public road domain, public water domain).

Continuously evolving 3D technology is changing the paradigms of urban planning and land policy, as it influences not only how the city is viewed, but also how property rights and other restrictions are described in space. The implementation of 3D cadastre in the Republic of Moldova should not involve replacing the existing system, but rather a gradual extension of its capabilities. A hybrid model is proposed in which the 2D cadastre remains the legal basis for real estate registration, while three-dimensional models function as complementary technical and decision-making support.

This approach enables: maintaining the stability of the existing legal framework, avoiding disruption of the current rights registration system, gradual and realistic transition without systemic ruptures, using 3D models in complex situations (overlapping infrastructure, multi-level buildings, underground networks), improving the quality of cadastral services by providing detailed visualizations, grounding urban planning decisions on actual geometry. In practice, this means that property ownership of land and buildings will continue to be recorded in the traditional two-dimensional cadastral registry, however, for complex objects (bridges, overpasses, high-rise buildings, underground parking facilities), associated 3D models will be created and maintained, serving as technical reference for analysis, design, and administration.

The integration of three-dimensional models into existing GIS systems represents an essential component of the proposed model. By analogy with platforms such as Google Earth, which visualizes terrain and buildings three-dimensionally, the cadastral system in the Republic of Moldova can be extended to include a 3D layer that correlates legal information with the actual geometry of constructions (Figure 7).



a) b)

Figure 7. Conceptual integration of 3D cadastral layers: a) Proposed implementation in the e-Cadastre platform; b) Layered structure of the cadastral information system.

The development of 3D functionality within the e-Cadastre platform is proposed, which would enable: three-dimensional visualization of complex cadastral objects, interactive navigation in 3D space (rotation, zoom, sectioning), querying object attributes directly from the visualization, overlaying 3D models with existing 2D cadastral data, differentiated access for public authorities (full functionality) and citizens (visualization and consultation). To illustrate the potential integration of the three-dimensional model into the e-Cadastre platform, Figure 8 was developed, presenting a conceptual visualization of the 3D model obtained through laser scanning overlaid on existing two-dimensional cadastral data. The final graphic representation was generated using AI-assisted visualization tools [26], based on geometric parameters extracted from the actual model and the current cadastral configuration. This approach demonstrates how three-dimensional information can be coherently integrated into the cadastral platform user interface, providing a clear perspective on the spatial relationships between different infrastructure levels.

This integrated platform would enable unified visualization of land and buildings in three-dimensional space, analysis of relationships between overlapping or adjacent objects, grounding of urban planning decisions on actual geometry, alignment of the national cadastre with European trends in 3D cadastre, and increased transparency and quality of information provided by the cadastral system.

Currently, the cadastral legislation in the Republic of Moldova does not contain explicit provisions regarding the registration and management of three-dimensional objects. The development and adoption of a specific regulatory framework is necessary, harmonized with the ISO 19152 standard, which would define: concepts of 3D spatial unit, volumetric delimitation, and three-dimensional cadastral registration; procedures for collecting, processing, and validating 3D data; precision and quality standards accepted for different object categories; institutional responsibilities in 3D cadastre management.

Figure 8. Conceptual visualization of the integration of the 3D model into the e-Cadastre platform.

The storage and processing of point clouds and volumetric models require adequate IT infrastructure. The development of an integrated GIS platform is recommended, which would enable: efficient data exchange between cadastral institutions, public authorities, and infrastructure administrators; long-term storage and archiving of 3D models; efficient data processing and updating; secure and controlled access to information, based on user type.

The establishment of clear and uniform requirements is necessary regarding: spatial data acquisition methods (laser scanning, photogrammetry, GNSS); measurement precision for different object categories (critical infrastructure - millimeter precision, buildings - centimeter precision, land - decimeter precision); point cloud resolution and density; data storage and exchange formats; georeferencing procedures.

The implementation of 3D technologies necessitates continuous training of specialists in the fields of cadastre and geodesy. Training programs must cover: technical aspects (use of scanning equipment, data processing in specialized software, GIS-BIM integration); conceptual aspects (LADM, 3D modeling, volumetric property administration); legal aspects (interpretation and application of new regulations, legal validation of 3D data).

A phased approach is recommended, starting with priority objects: critical infrastructure (bridges, overpasses, tunnels); dense urban areas (Chișinău, Bălți); new complex constructions (high-rise buildings, underground parking facilities); progressive extension to other object categories (public buildings, industrial zones, utility networks). The implementation of 3D cadastre in the Republic of Moldova represents not only a technological modernization but also a practical necessity for ensuring efficient territorial administration.

4. Conclusions and recommendations

Despite the significant potential of three-dimensional (3D) technologies as advanced urban planning tools, as well as the substantial progress achieved at both theoretical and practical levels, currently no country has implemented a fully functional 3D cadastre completely integrated into national legal and administrative systems. Most existing initiatives are either in pilot phases or in partial stages of operationalization, highlighting the complexity of the transition from the traditional two-dimensional paradigm to a coherent three-dimensional framework. The evolving concepts involved in this new process should be based on the ISO 19152 Land Administration Domain Model (LADM), which provides support for 3D representations.

This study has demonstrated the viability and advantages of implementing 3D cadastre in the Republic of Moldova through a concrete case study of complex road infrastructure. The obtained results confirm that modern spatial data acquisition technologies, particularly terrestrial laser scanning, can provide the high-precision information necessary for three-dimensional representation of cadastral objects.

The 3D model generated for the road bridge in Criuleni district, with geometric precision below 10 mm and a density exceeding 800 points/m^2, provides a faithful representation of ground reality, significantly superior to traditional two-dimensional representations. The comparative analysis highlights that three-dimensional modeling eliminates ambiguities related to overlapping objects, provides enhanced geometric clarity, and enables detailed engineering analyses.

In the context of accelerated urban development and infrastructure expansion, 3D cadastre no longer represents an option but a necessity for efficient territorial administration. Alignment with the international standard ISO 19152 (LADM) provides a solid framework for implementing these technologies in a consistent and interoperable manner.

Based on the obtained results and the conducted analysis, the following recommendations are formulated for the implementation of 3D cadastre in the Republic of Moldova:

– Development of the regulatory framework. Adoption of a specific legislative framework for 3D cadastre, harmonized with ISO 19152, to define concepts, procedures, and institutional responsibilities.
– Standardization of technical processes. Establishment of clear requirements regarding data acquisition methods, measurement precision, and storage formats, to ensure uniformity and interoperability.
– Development of an integrated GIS platform. Creation of a modern technological infrastructure that enables efficient management of three-dimensional data and information exchange between institutions.
– Investment in infrastructure and equipment. Allocation of necessary resources for acquiring scanning equipment and developing data storage and processing capabilities.
– Continuous professional training. Organization of training programs for specialists in the field, covering both technical and conceptual aspects of 3D cadastre.
– Phased implementation. Adoption of a gradual approach, starting with priority objects (critical infrastructure, complex urban areas) and progressive extension to other categories.

The consolidation of a three-dimensional cadastre capable of explicitly recording and modeling the interaction between 3D real estate units and applicable legal norms (urban planning regulations, easements, protection zones, environmental restrictions, etc.) would constitute an essential tool for increasing the effectiveness of urban and environmental planning. By correlating spatial volumes with their regulatory regime, such a system would enable coherent evaluation of the conformity of proposed developments with the existing legal framework.

The implementation of these recommendations will enable the Republic of Moldova to take an important step toward modernizing the cadastral system, ensuring more precise, transparent, and efficient territorial administration, in accordance with international best practices.

Research Data Availability Statement: The original contributions presented in the study are included in the article. The authors can provide the data upon request.

Declaration of generative AI use: During the preparation of this manuscript, the author(s) used DALL-E 3 (via ChatGPT) to generate the image presented in Figure 8. The authors have reviewed and revised the output and accept full responsibility for the content of this publication.

Contribution of authors

Ana Vlasenco: Supervision, resources, writing – original draft, writing—review & editing
Livia Nistor-Lopatenco: Supervision, writing—review & editing, validation, project administration.
Efim Zubco: Conceptualization, investigation, methodology, data curation.
Alexandru Fărîmă: Conceptualization, investigation, methodology, data curation, software.

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