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Integration of Historical Cadastral Plans into GIS: A Workflow for Data Enhancement and Building Footprint Extraction

Integrarea planurilor cadastrale istorice în GIS: un flux de lucru pentru îmbunătățirea datelor și extragerea amprentelor clădirilor

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Abstract. *This paper explores the methodology and implications of transforming traditional cadastral plans into three-dimensional digital models using complementary software tools such as GIMP, ArcGIS Pro, ArcGIS CityEngine, and Python. The research addresses the growing need for digitization in Romania's cadastral system, highlighting both technological opportunities and legislative challenges. A step-by-step workflow is proposed, from preprocessing scanned cadastral maps to generating realistic 3D city models. The study demonstrates the added value of 3D models for urban planning, heritage conservation, infrastructure design, and public consultation. Recommendations are made for standardizing practices and aligning Romania's approach with European and international best practices.*

Key words: *GIS, 3D models, cadastral plans*

1. Introduction

The accelerated pace of urbanization, globalization, and the increasing pressure on spatial resources have generated an urgent demand for modern tools capable of managing territorial information more efficiently. In this context, the digitization of cadastral plans and their integration into Geographic Information Systems (GIS) represent not only a technological innovation but also a strategic necessity for national administrations, municipalities, and private stakeholders. Cadastral systems, as foundational infrastructures for land administration, provide security of property rights, support the functioning of real estate markets, and ensure transparent taxation

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systems. In addition, they play a vital role in urban and regional planning, environmental protection, and disaster risk management.

Historically, cadastral plans were drawn on paper, serving as static representations of property parcels and ownership information. Although these analogue records were functional in their time, they present serious limitations today: they are difficult to update, prone to deterioration, and require significant effort to integrate with digital workflows. As modern cities face rapid demographic changes and complex spatial transformations, the lack of digitally integrated cadastral data creates inefficiencies in planning processes, legal disputes, and administrative bottlenecks.

The concept of transforming cadastral plans into three-dimensional (3D) digital models aligns with broader global trends such as the creation of digital twins for cities, the push toward smart city governance, and the integration of geospatial data into decision-making platforms. By shifting from two-dimensional (2D) maps to immersive 3D environments, planners, architects, engineers, and citizens can visualize and analyze urban realities in ways previously unavailable.

Despite progress in Romania, the country continues to face challenges: the lack of uniform digitization standards, inconsistent technical requirements across regions, gaps in legislation, and low interoperability between agencies. Furthermore, public access to cadastral information remains limited compared to other European states. These obstacles reduce the efficiency of land management and delay Romania's alignment with European Union directives.

The main objective of this paper is to provide a comprehensive methodology for converting traditional cadastral plans into 3D digital models, while also exploring the practical applications, limitations, and opportunities associated with this transformation. The study contributes to both the academic literature and professional practice by offering a replicable workflow, contextualizing the Romanian situation within international best practices, and identifying future directions for policy and technology.

2. Theoretical background and conceptual framework

Cadaster constitutes a fundamental pillar of land administration, combining both legal and technical dimensions that shape the management, governance and development of territorial resources. Legally, it ensures the publicity and security of property rights, facilitates real estate transactions and supports the stability of land markets. Technically, it provides an essential geospatial foundation for urban planning, infrastructure development, density analysis and heritage protection. In Romania, the importance of cadaster is amplified by ongoing processes of rapid urbanization and increasing spatial pressures, which require modern digital tools capable of managing detailed and accurate spatial information.

Recent technological developments have profoundly transformed the way cadastral data are produced, managed and analyzed. While traditionally based on two-dimensional representations, cadastral systems are increasingly integrated into advanced geospatial infrastructures built upon Geographic Information Systems (GIS). GIS enables the storage, visualization and analysis of spatial information while supporting the integration of multiple thematic datasets—ranging from cadastral parcels to infrastructure, utilities, demographic indicators and mobility networks. This integration facilitates coherent data management and enhances the analytical capabilities of urban planners, engineers and local authorities, who can now examine spatial relationships that were previously difficult or impossible to evaluate using analogue maps.

Incorporating cadastral datasets into GIS is therefore an essential step in the modernization of land administration systems. The ability to import, georeferenced and structure historical cadastral plans within a GIS environment offers substantial advantages, such as improved spatial accuracy, rapid access to information, enhanced interoperability with other geospatial datasets and the possibility of performing complex spatial analyses. Moreover, GIS platforms provide the computational framework necessary for transitioning from 2D to 3D representations, a domain that is increasingly central to urban analysis and planning.

The shift from two-dimensional to three-dimensional cadastral modelling represents one of the most significant conceptual and methodological advances in recent decades. While 2D cadaster can describe parcel boundaries and surface extents, it cannot capture the volumetric characteristics of the built environment—such as building height, roof geometry or the relationship between overlapping structures, technical corridors or underground utilities[1]. In dense urban areas, where vertical complexity is substantial, relying solely on 2D data leads to interpretative ambiguities and limits the potential for accurate planning and legal analysis. In contrast, 3D cadastral models provide volumetric representations that more closely reflect the spatial reality of cities. These models enable detailed assessments of urban density, morphological patterns, visibility, shadow casting, and volumetric use of space. They also help clarify complex property situations such as condominiums, multi-level underground infrastructure or shared technical spaces. Through their increased realism, 3D models greatly support communication with non-expert stakeholders and enhance transparency in planning processes.

A decisive factor in achieving high-quality digital cadastral models is the quality of the input data, particularly the resolution of scanned cadastral plans. In Romania, historical cadastral maps are frequently digitized at relatively low resolutions—often around 150 DPI—which generate blurred lines, insufficient contrast and numerous graphical artefacts. Such limitations negatively affect subsequent digital processing stages, especially contour detection, vectorization and the separation of relevant features from background noise. Without nationally regulated scanning standards, considerable discrepancies exist between institutions, resulting in heterogeneous datasets and inconsistent outputs during vectorization. Establishing a minimum scan resolution (e.g., 300 DPI or higher) would significantly improve the accuracy and efficiency of digital workflows and reduce the need for extensive manual corrections.

Digital preprocessing therefore becomes a critical stage in ensuring the reliability of vector extraction. Operations such as contrast enhancement, background normalization, noise removal and the elimination of irrelevant graphical elements help produce clean raster inputs suitable for automated or semi-automated detection algorithms. The research demonstrates that such preprocessing not only optimizes contour recognition but also reduces total processing time and improves the consistency of the resulting datasets.

Within this conceptual framework, cadaster evolves from a static registry of land parcels into a dynamic component of an integrated spatial information system. The methodology described in this study must be understood in the context of global advancements in 3D cadaster, digital cartography and smart city technologies, where geospatial infrastructures increasingly incorporate three-dimensional visualizations, simulation tools and analytical models. The emergence of 3D city models, CityGML standards and digital twins confirms that cadastral information is no longer solely a basis for legal documentation, but also a strategic resource for urban modelling, scenario testing and long-term territorial management. The transition towards 3D and the adoption of advanced digital tools are thus interconnected processes aimed at modernizing urban governance and fostering sustainable development.

In conclusion, the theoretical foundation of this research demonstrates that the digitization of cadastral plans, their integration into GIS platforms and the development of 3D representations constitute synergistic steps toward the modernization of Romania's cadastral infrastructure. These processes enhance the analytical capacity of urban planners, support the protection of architectural heritage, enable more transparent public communication and align national practices with international standards for spatial data management.

3. Legislative and institutional framework

Romania's cadastral system is regulated by the Law on Cadaster and Real Estate Publicity (Law no. 7/1996[2]), which defines the responsibilities of the National Agency for Cadaster and Land Registration (ANCPI). While the law establishes the principles of cadastral organization and integration with land registry data, practical implementation remains uneven. Technical regulations, such as ANCPI Order no. 600/2023[3], detail requirements for digital documentation formats and integration procedures, but gaps persist—particularly regarding standards for scanned maps, automated vectorization, and quality control[4].

By contrast, other European states such as Germany, the Netherlands, and France have established robust standards ensuring high-quality digital cadastral data. Germany enforces strict regulations on resolution and national integration, while the Netherlands ensures broad public accessibility through its Kadaster. France integrates cadastral data into a national geospatial infrastructure (BDTOPO®), frequently used for planning. These examples highlight Romania's need for clearer technical guidelines and harmonization with EU standards, such as those mandated by the

INSPIRE Directive (2007/2/EC). Despite Romania's obligation to align with INSPIRE, the lack of detailed national norms continues to hinder progress[5].

4. Software and technology used

The methodological framework developed in this research relies on an integrated suite of software tools and technologies designed to address the full spectrum of tasks required for transforming historical cadastral plans into accurate three-dimensional digital models. Each application contributes distinct functionalities that, when combined, form a coherent workflow capable of supporting both the preprocessing of analogue documents and the generation of advanced spatial representations. The complementary use of image editing software, geographic information systems, programming libraries, and procedural modelling environments reflects the multifaceted nature of cadastral digitization and the necessity of combining multiple disciplines to achieve reliable results.

ArcGIS Pro serves as the central geospatial platform within this workflow, providing robust capabilities for importing, visualizing and managing both raster and vector datasets. Its advanced tools for georeferencing, topological correction, attribute management and spatial analysis make it indispensable for integrating preprocessed cadastral plans into a spatially coherent geodatabase. The software further enables the extrusion of building footprints into simple three-dimensional forms, allowing an initial layer of volumetric representation that supports urban analysis and the subsequent transition to more detailed modelling. A significant advantage of ArcGIS Pro is its native compatibility with Python through the ArcPy library, which allows tasks such as geoprocessing, data cleaning or bulk attribute updates to be automated efficiently, thus reducing human error and processing time.

While ArcGIS Pro provides the analytical foundation, ArcGIS CityEngine [6] introduces the capacity for advanced procedural modelling, expanding the possibilities of 3D representation far beyond simple extrusion. CityEngine employs rule-based generation through the CGA (Computer Generated Architecture) language, enabling the creation of detailed architectural features such as roof shapes, façade elements, textures and building typologies. This procedural approach allows entire neighborhoods or historical urban areas to be modelled quickly and consistently, significantly enhancing the visual realism and interpretive quality of the resulting 3D models. In the context of this research, CityEngine played a crucial role in transforming simple building footprints into more realistic volumetric representations that capture the morphological diversity and architectural character of the study area.

Prior to the geospatial analysis and 3D modelling stages, it was essential to preprocess the scanned cadastral plans to ensure that the raster images were suitable for automated or semi-automated vectorization. For this purpose, GIMP (GNU Image Manipulation Program) was employed as an open-source image editing tool capable of performing sophisticated adjustments such as contrast enhancement, noise removal and background homogenization. These preprocessing steps proved critical for improving the legibility of lines and reducing the presence of undesirable graphical artefacts, which would otherwise interfere with contour detection algorithms. The research demonstrates that the quality of preprocessing directly affects the efficiency and accuracy of subsequent vector extraction, making this stage indispensable for the overall workflow.

Python, paired with the OpenCV library, provided the computational backbone for the semi-automated extraction of building footprints from the preprocessed raster images. OpenCV's advanced image-processing capabilities—such as thresholding, Canny edge detection, contour extraction and geometric filtering—enabled the identification and isolation of relevant elements within the cadastral plan. Through the development of custom scripts, the workflow achieved a significant reduction in manual digitization time while maintaining a high degree of accuracy. The reproducibility and flexibility of this scripting approach also make it particularly suitable for scaling the methodology to larger datasets or different urban contexts.

Although the workflow relies primarily on Esri's proprietary software, the research acknowledges the importance of open-source alternatives, particularly for institutions or projects with limited financial resources. Tools such as QGIS offer a wide range of GIS functionalities comparable to those of ArcGIS Pro, including georeferencing, spatial analysis and plugin-based automation. Blender, a powerful open-source 3D modelling suite, may also serve as an alternative to CityEngine for producing detailed architectural models, although it typically requires a higher level of technical skill and does not natively support procedural urban modelling. The existence of these alternatives demonstrates that the proposed methodology can be adapted to different technological ecosystems, albeit with variations in workflow complexity and user expertise.

Together, these software tools form a comprehensive technological ecosystem that supports the full workflow of cadastral digitization—from image cleaning and georeferencing to automated footprint extraction and 3D model generation. Their integration reflects the interdisciplinary nature of the research, combining principles from geoinformatics, computer vision, cartography and urban modelling. The success of the methodology is therefore grounded not only in the capabilities of each individual tool, but also in the coherent orchestration of their functions within a unified digital environment.

5. Methodology

The proposed methodology follows a structured workflow: (1) preprocessing cadastral maps in GIMP[7], including contrast correction and background cleaning (Fig. 1.)

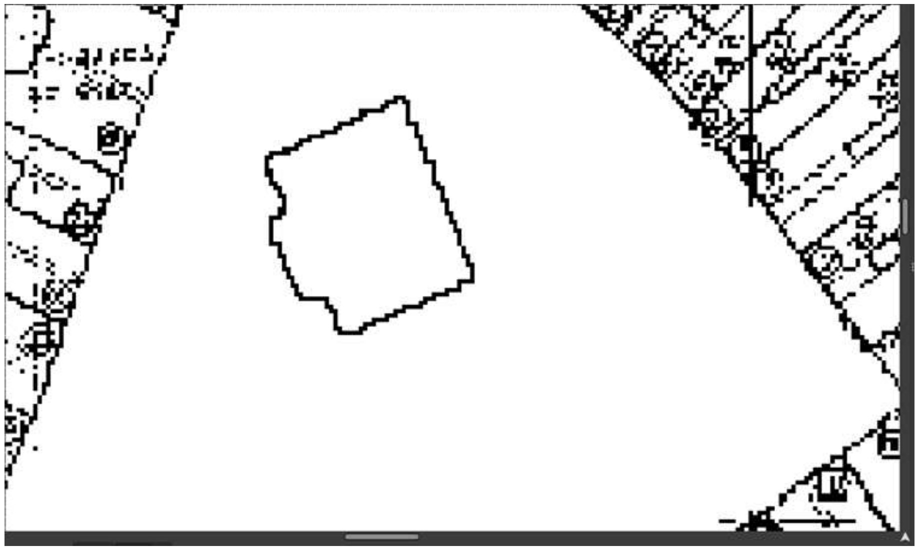

Fig. 1. Preprocessed image

(2) importing and georeferencing in ArcGIS Pro, (3) extracting building footprints through Python and OpenCV scripts (Fig. 2.)

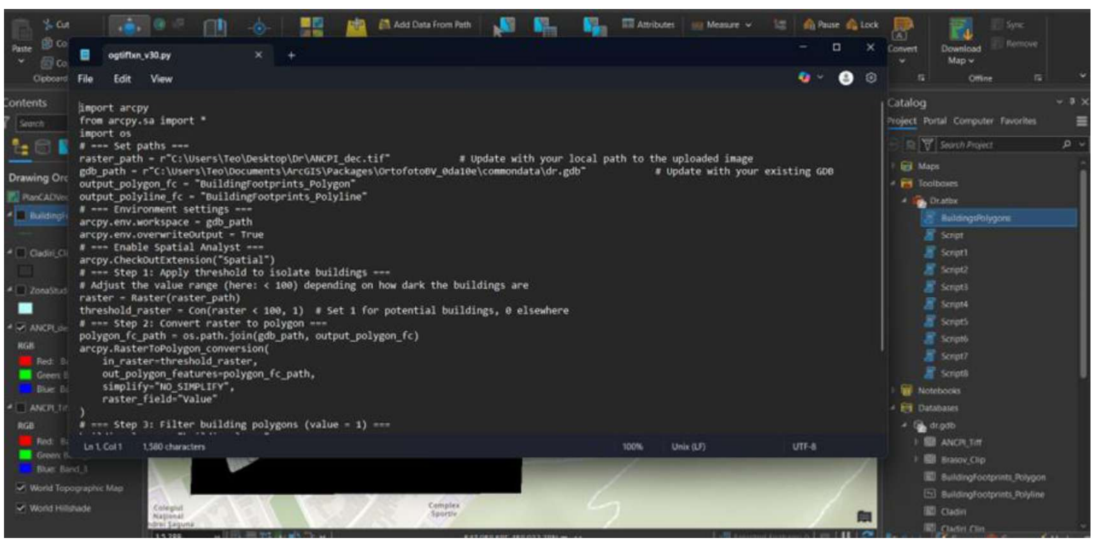

Fig. 2. The Python script

(4) generating 3D building models by extrusion in ArcGIS Pro (Fig. 3.)

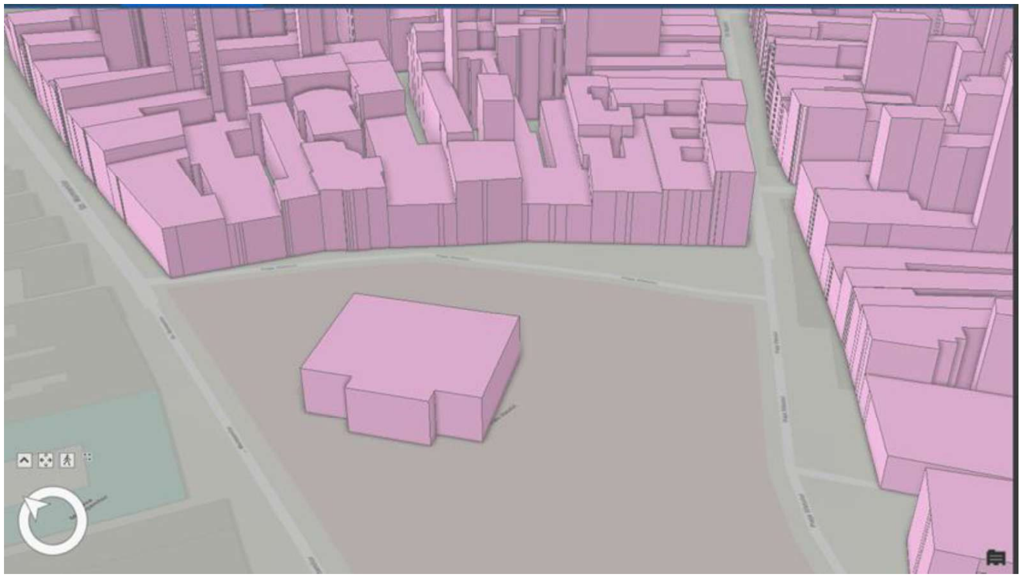

Fig. 3. 3D buildings in ArcGIS Pro

(5) refining models procedurally in CityEngine (Fig. 4.) and (6) analyzing results and addressing limitations.

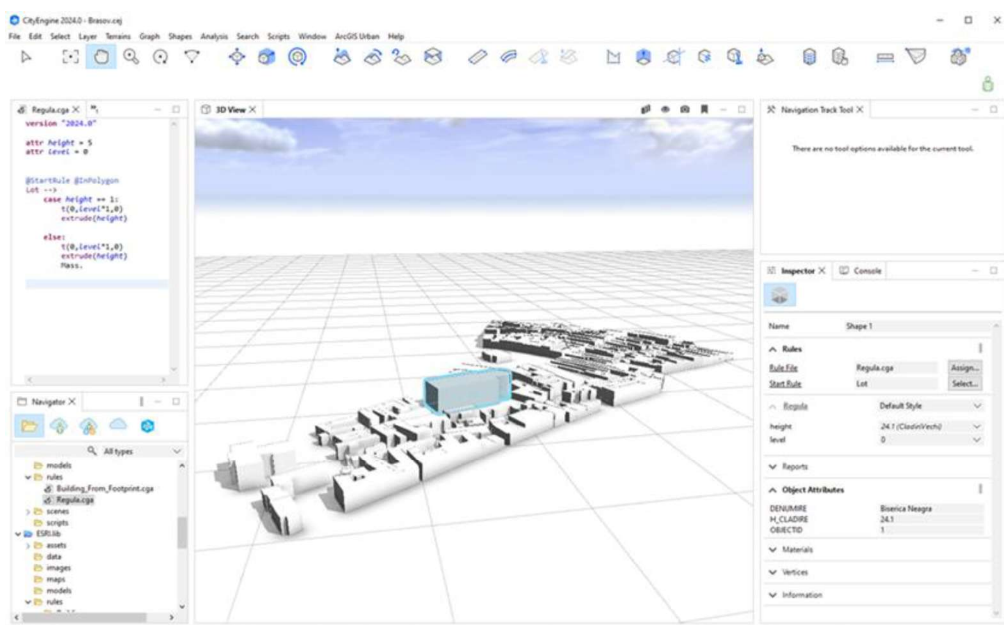

Fig. 4. 3D buildings in CityEngine

This semi-automated workflow balances efficiency with accuracy. Preprocessing improves input quality, Python scripts automate contour detection, and GIS tools enable spatial integration. Extrusion produces simple volumetric models, while procedural modeling generates more realistic 3D representations. Challenges encountered include low-resolution scans, noise in vectorization, and absence of height data, which were addressed through filters, assumptions, and supplementary data sources.

6. Results and discussion

The results obtained through the proposed methodology demonstrate the feasibility, efficiency, and practical relevance of transforming historical cadastral plans into three-dimensional digital models. The experimentation carried out throughout this research highlights several key findings related to scan resolution, semi-automated building footprint extraction, 3D modelling accuracy, and the comparative performance of the different software environments used. These findings collectively validate the methodological approach and reveal both its strengths and its limitations.

One of the most influential factors identified in the workflow is the resolution of the scanned cadastral plans. The comparison between plans scanned at 150 DPI and those preprocessed or originally scanned at 300 DPI or higher demonstrates a clear correlation between resolution and extraction performance. Lower-resolution scans showed blurred or partially broken linework, heterogeneous backgrounds, and significant visual noise, all of which hindered the capacity of automated and semi-automated tools to correctly detect edges (Fig. 5.).

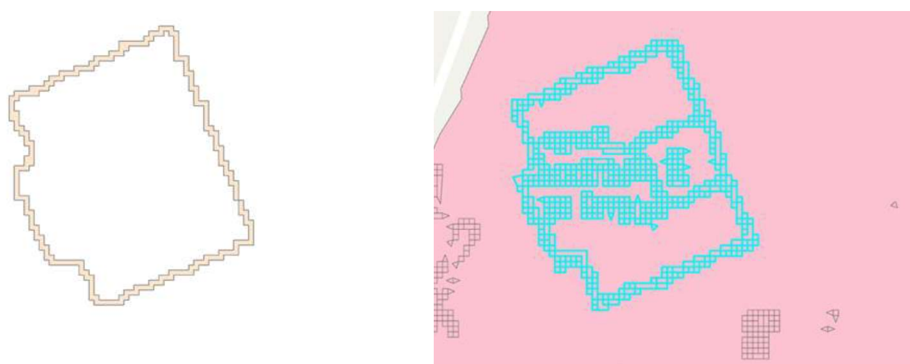

Fig. 5. The difference between the results of the two cadastral plans used as inputs

As the research indicates, these deficiencies required substantial manual corrections and additional preprocessing steps, thereby increasing the overall processing time. In contrast, higher-resolution scans produced well-defined contours and provided much more reliable inputs for Python-based contour detection and vectorization. This demonstrates that adopting a standard minimum resolution would not only streamline digitization practices but also significantly enhance the accuracy of the resulting digital cadastral datasets.

The semi-automated extraction of building footprints using Python and OpenCV proved to be one of the most effective components of the workflow. The contour detection algorithm successfully identified over 80% of the building outlines present in the tested cadastral plans, requiring only minor manual adjustments for the remaining geometries. This level of automation represents a substantial improvement over entirely manual digitization, which is labor-intensive and prone to human error. Quantitatively, the method reduced digitization time by more than 60%, while simultaneously increasing consistency across the generated vector datasets. These results confirm that semi-automated vectorization is a viable approach for large-scale digitization projects, provided that input scans undergo proper preprocessing to ensure sufficient clarity for the detection algorithms.

The subsequent generation of 3D models in ArcGIS Pro reinforced the value of integrating extracted footprints into a volumetric framework. The extruded models, while simple in geometry, provided spatially accurate representations of building massing and proved highly useful for analytical tasks such as sunlight analysis, shadow projections, built density studies and visibility assessments. Their simplicity ensures that computational requirements remain moderate, enabling efficient manipulation even on mid-range hardware. However, the limitations of simple extrusion become evident when more detailed architectural analysis or visualization is required. The extruded volumes do not include architectural elements such as roof forms, façade structures or stylistic characteristics, which are essential for heritage conservation, public presentation, and immersive simulation.

These limitations were addressed through the use of ArcGIS CityEngine, which introduced a level of detail unattainable through extrusion alone. By applying procedural rules that define architectural features, CityEngine generated realistic and visually rich 3D models capable of capturing the diversity and complexity of urban environments. In the case study, the procedural models accurately reflected variations in roof shapes, building heights and general architectural patterns, creating an engaging and interpretable representation of the built environment. The contrast between the simple extruded models and the detailed procedural ones highlights the complementary nature of the two approaches: extrusion serves analytical efficiency, while procedural modelling supports visual realism and communicative clarity. Together, they provide a flexible modelling framework adaptable to a variety of urban applications.

Nevertheless, several limitations and sources of error were identified throughout the workflow. The absence of reliable height data required the use of estimated values or heuristic rules, which inevitably reduced the accuracy of the resulting 3D models. Although the procedural modelling environment allowed for the integration of average height values or typological assumptions, these approaches cannot fully replace precise field measurements or LiDAR data. Similarly, inconsistencies in the quality and structure of cadastral documentation across municipalities introduce variability in the digitization results, particularly when the input plans differ significantly in resolution or graphic conventions. The research also notes the considerable hardware requirements associated with handling high-detail 3D models in CityEngine, which may pose challenges for smaller institutions or municipalities with limited access to advanced computing resources.

Despite these limitations, the overall results demonstrate that the workflow is robust, adaptable, and capable of producing high-quality spatial datasets from historical cadastral resources. The semi-automated extraction method significantly enhances efficiency, and the combination of GIS and procedural modelling tools allows users to transition smoothly from analytical representations to visually detailed urban models. The methodology supports a wide array of practical applications, from urban planning and infrastructure design to heritage conservation and public engagement, confirming its relevance within contemporary urban management practices. The research ultimately shows that the transformation of analogue cadastral plans into 3D digital models is not merely a technical exercise but a strategic process that improves spatial understanding, supports data-driven decision-making, and contributes to the broader digital modernization of cadastral systems in Romania.

7. Case study and practical applications

The historical center of Brașov serves as an illustrative case study for applying the methodology developed in this research, demonstrating both the practical utility and the analytical depth afforded by the digital transformation of cadastral plans into three-dimensional city models. Brașov's central district is characterized by a dense medieval urban fabric, irregular parcel configurations, narrow streets, and a heterogeneous architectural landscape. These features render traditional two-dimensional cadastral representations insufficient for capturing the spatial intricacies of the area. By applying the complete workflow—from raster preprocessing and automated contour extraction to GIS integration and procedural modelling—the study reveals the considerable advantages of 3D cadastral modelling in complex heritage environments.

The digitization of the cadastral plan for the historic center exposed several challenges specific to old urban cores. Parcels are often irregular and tightly interlocked, and many buildings share party walls or display non-standard geometric configurations. Such conditions complicate boundary delineation and can hinder the interpretability of traditional cadastral documents. The extraction of building footprints using the semi-automated Python and OpenCV workflow proved highly effective in this context, as it allowed for the consistent identification of structures even in areas where linework was degraded or visually ambiguous. Once integrated into ArcGIS Pro, the vectorized footprints enabled spatial analyses related to built density, volumetric distribution, and the relationship between constructed and unconstructed areas. These analyses would be significantly more laborious—if not impossible—using the original analogue maps alone.

The transition to three-dimensional modelling further enhanced the interpretive value of the cadastral dataset. ArcGIS Pro's extrusion tools produced simplified volumetric representations that accurately conveyed the massing of Brașov's historic built environment. These 3D volumes serve as a basis for various spatial analyses, such as sunlight and shadow modelling, visibility studies, and evaluations of morphological patterns within the urban core. Although these extruded models lack architectural detail, they provide an essential structural framework on which more refined analyses can be built.

The application of procedural modelling in ArcGIS CityEngine elevated the case study to a more advanced level of visual and analytical sophistication. By applying CGA rules tailored to the architectural characteristics of historical European urban centers, the resulting models displayed realistic roof geometries, façade structures, building heights, and overall morphological coherence. This enhanced level of detail is particularly valuable in heritage zones such as Brașov's historic center, where precision in architectural representation is critical for conservation planning, restoration simulations, and cultural documentation. The resulting 3D urban model not only captures the geometry of the historic core but also conveys its aesthetic and cultural identity, offering a powerful tool for both experts and the general public.

Beyond the specific case of Brașov, the study demonstrates the broad applicability of the proposed methodology to various domains of urban planning and territorial management. Three-dimensional cadastral models can contribute significantly to infrastructure design by facilitating the integration of built structures with underground utilities, mobility networks, or environmental constraints. In urban planning, they support scenario-based evaluations, enabling planners to test the impact of new developments on density, visual corridors, or public space configurations. For heritage conservation, the models offer a means of digitally documenting vulnerable architectural elements and simulating restoration strategies without physical intervention.

The communicative power of 3D models also plays an essential role in public participation processes. Unlike traditional 2D plans, which require technical literacy to interpret, three-dimensional visualizations provide intuitive representations that citizens can easily understand. Municipalities can thus employ such models during public consultations to explain proposed interventions, assess visual impacts, or facilitate collaborative decision-making. The research underscores that improved visual accessibility can reduce conflicts, foster transparency and strengthen public trust in planning institutions.

International examples further highlight the strategic importance of integrating cadastral data into 3D urban models. Cities such as Vienna use 3D models to support energy performance simulations and climate adaptation planning, while Singapore has developed a comprehensive digital twin that integrates real-time data for land-use regulation, mobility, and environmental monitoring. The Netherlands' Kadaster provides publicly accessible 3D datasets that enhance urban planning and civic engagement. These examples illustrate that Romania's progress toward a modern and interoperable cadastral system would benefit greatly from adopting similar 3D modelling strategies, particularly in heritage-rich urban centers like Brașov.

Overall, the Brașov case study confirms that the integration of historical cadastral plans into GIS-based 3D modelling offers substantial advantages for urban planning, heritage management, infrastructure design, public communication, and smart city development. The methodology proposed in this research—supported by image processing, automation, GIS workflows and procedural modelling—proves viable, scalable, and adaptable to a variety of territorial contexts. Its application in Brașov not only validates the workflow technically but also illustrates the transformative potential of 3D cadastral models as strategic tools for contemporary urban governance.

8. Future perspectives

Looking forward, Romania has significant opportunities to advance its cadastral digitization agenda. Several strategic directions emerge from this study:

1. Standardization and Regulation – Establishing mandatory minimum standards for scan quality (e.g., 300 DPI), uniform file formats, and database structures will ensure consistency across regions and institutions. These standards should be harmonized with EU guidelines to facilitate interoperability.
2. Integration with Emerging Technologies – Drone photogrammetry and LiDAR scanning can provide highly accurate and up-to-date data for both cadastral and urban planning purposes. Artificial intelligence and machine learning algorithms can further automate building detection, parcel delineation, and attribute extraction.
3. Digital Twins and Smart Cities – Integrating cadastral 3D models into digital twins of cities will enable holistic simulations combining geospatial data with real-time IoT inputs, mobility flows, and environmental monitoring. This integration can revolutionize governance by supporting predictive analytics and scenario planning.
4. Public Accessibility and Participatory Governance – Expanding open access to cadastral data and developing interactive visualization platforms will empower citizens to engage with urban development projects more effectively. Such initiatives can also reduce disputes, build trust, and foster participatory democracy.
5. Capacity Building and Education – Universities and professional associations should incorporate training modules on 3D cadaster and geospatial technologies, ensuring a skilled workforce to sustain digitization efforts.

By embracing these directions, Romania can not only modernize its cadastral infrastructure but also position itself as a regional leader in the field of 3D land administration.

9. Conclusions

This research demonstrates that transforming traditional cadastral maps into 3D digital models is both feasible and valuable for urban management. The study emphasizes the critical role of input data quality, the efficiency of semi-automated vectorization, and the added value of 3D models in planning, heritage conservation, and citizen engagement. Romania must address technical and legislative gaps by adopting minimum standards, ensuring interoperability, and aligning with EU practices. Broader adoption of these methods will contribute to sustainable urban development, smart city strategies, and participatory governance.

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