3D Surface Models for Urban Planning and Land Value Capture: A Case Study of Rio de Janeiro's Cadastral System

Luiz Carlos TEIXEIRA COELHO, Leandro GOMES SOUZA and Felipe CERBELLA MANDARINO, Brazil

Key words: Multipurpose Cadastre, 3D model, digital surface model, LiDAR, photogrammetry

SUMMARY

This study examines Rio de Janeiro's pioneering use of repeat airborne LiDAR surveys (2019 and 2024) to address the critical challenge of maintaining an up-to-date physical cadastre a foundational element of the Multipurpose Land Cadastre (MLC). By generating differential elevation models, the research quantifies vertical growth across the city, categorizing changes with a 3-meter threshold to reliably identify new construction floors, particularly informal additions. The analysis demonstrates that LiDAR technology is vital not only for topographic mapping but for enabling cross-checks of construction permits, identifying tax evasion, and informing land-use policies. The findings underscore that the long-term effectiveness of such geospatial tools hinges on sustained institutional commitment to regular data updates, interoperability, and systemic coordination across government agencies. Ultimately, the integration of LiDAR with the MLC represents a transformative step toward smarter, more equitable urban governance, where accurate spatial data can support fairer taxation and fund inclusive development.

Palavras-chave: Cadastro Territorial Multifinalitário, modelo 3D, modelo digital de superfície, LiDAR, fotogrametria

RESUMO

Este estudo examina a utilização pioneira do Rio de Janeiro de levantamentos LiDAR aerotransportados repetidos (2019 e 2024) para enfrentar o desafio crítico de manter um cadastro físico atualizado — um elemento fundamental do Cadastro Territorial Multifinalitário (CTM). Através da geração de modelos digitais de elevação diferencial, a pesquisa quantifica o crescimento vertical em toda a cidade, categorizando as alterações com um limiar de 3 metros para identificar de forma fiável novos pisos de construção, particularmente acréscimos informais. A análise demonstra que a tecnologia LiDAR é vital não apenas para o mapeamento topográfico, mas também para permitir a conferência de licenças de construção, identificar a evasão fiscal e fundamentar políticas de uso do solo. As conclusões sublinham que a eficácia a longo prazo destas ferramentas geoespaciais depende de um compromisso institucional sustentado com atualizações regulares de dados, interoperabilidade e coordenação sistémica entre as agências governamentais. Em última análise, a integração do LiDAR com o CTM representa um passo transformador em direção a uma governança urbana mais inteligente e

equitativa, na qual dados espaciais precisos podem suportar uma tributação mais justa e financiar um desenvolvimento inclusivo.

3D Surface Models for Urban Planning and Land Value Capture: A Case Study of Rio de Janeiro's Cadastral System

Luiz Carlos TEIXEIRA COELHO, Leandro GOMES SOUZA and Felipe CERBELLA MANDARINO, Brazil

1. INTRODUCTION

The informal city in Latin America is often perceived as confined to shantytowns—favelas, barrios, or villas—yet it extends far beyond, infiltrating even upper-class neighborhoods. In cities like Rio de Janeiro, informality persists not only through unauthorized settlements but also through unrecorded modifications to legally permitted buildings (Figure 1). This phenomenon stems from fragmented databases, outdated tax systems, and bureaucratic inefficiencies that prevent cities from tracking urban growth accurately. The result is a dual crisis: weakened urban planning and significant losses in municipal revenue. Addressing these challenges requires an integrated approach, with the Multipurpose Land Cadastre (MLC) serving as a foundational tool (Erba et al., 2005; Cowen & Craig, 2003).

Figure 1. Example of informal construction in Rio de Janeiro (source: O Globo)

The MLC is a parcel-based geographic information system designed to unify diverse data layers—property boundaries, zoning regulations, taxation records, and infrastructure networks—into a single, interoperable platform. Its effectiveness, however, hinges on two critical factors: first, the active collaboration of public and private stakeholders at the parcel level, and second, an up-to-date physical cadastre that serves as the cartographic backbone for all other data. In

rapidly growing Latin American cities, maintaining this spatial foundation is a persistent challenge (Magarotto et al., 2016), leaving urban policies—from taxation to housing—vulnerable to inefficiency and evasion.
The city of Rio de Janeiro is characterized by a highly complex dynamic in its formal and informal real estate markets. Composed of a mosaic of valleys and mountains, the plains have historically been privileged as areas of high-status occupation, while irregular constructions have proliferated in areas of lower real estate interest, such as mountain slopes, marshlands, and territories farther from the center.
In recent years, this dynamic has become even more complex, as limitations on the horizontal expansion of favelas, subdivisions, and occupations have led to more pronounced verticalization—either through the addition of floors to existing buildings or through the irregular construction of multi-family buildings.
It is of essential importance for the management of the city of Rio de Janeiro to understand how and where this verticalization is occurring, with the aim of proposing public policies that meet the needs of the population residing in areas of strong population dynamics. Until recently, the Pereira Passos Municipal Institute of Urban Planning only had planimetric cartographic bases, such as orthoimage mosaics, which only allowed for monitoring the city's horizontal expansion.
However, in 2019, a planialtimetric survey of the entire municipal area was carried out using high-resolution LiDAR technology, generating a portrait not only of the natural topography but also of the engineering structures and buildings of all types existing in the municipality of Rio de Janeiro. In 2024, a similar survey was conducted, again covering the entire municipal territory, allowing for the creation of three-dimensional surface models of the same nature. This article describes the main procedures used to compare two building models from distinct time periods and the results of vertical variation between different time frames, emphasizing their applicability in different land use scenarios.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Digital Elevation Model from LiDAR, referenced to the 2019 flight

In 2019, a contract provided LiDAR (Light Detection and Ranging) coverage of the entire city at a resolution of 8 points per m². This survey generated not only digital terrain models but also digital surface models. In other words, the data was capable of capturing tree canopies, buildings, overpasses, and other features that reflected the pulsed laser light. The winning contractor (Topocart Aerolevantamentos) used a Trimble Harrier system to conduct the survey. The final product, exemplified in Figure 2, was delivered in both .LAS (point cloud) and raster (pixel matrix) formats. The accuracy meets the PEC-PCD Class A standard for a 1:5000 scale (with a standard error of 0.34 m for spot heights and models).

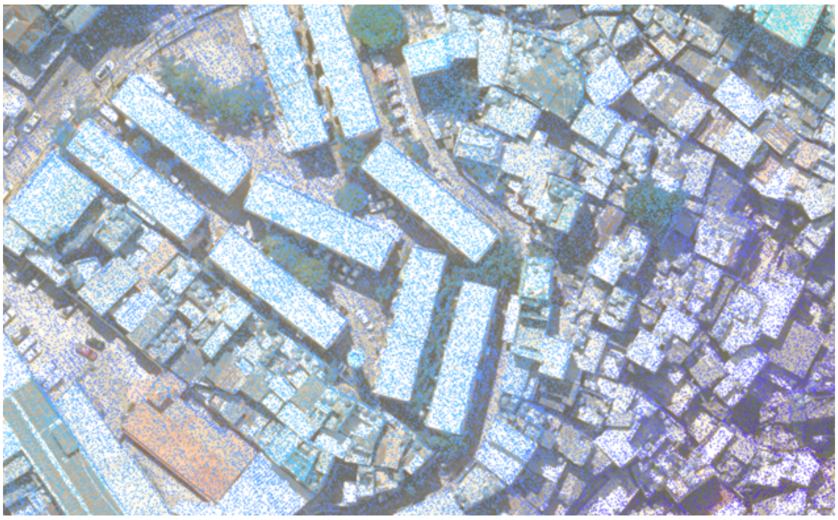

Figure 2. LiDAR point cloud (8 points/m²) over an orthomosaic – both from the 2019 flight and covering an area of Rocinha, Rio de Janeiro

2.1.2 Digital Elevation Model from LiDAR, referenced to the 2049 flight

In 2024, a similar contract also provided LiDAR (Light Detection and Ranging) coverage of the entire city at a resolution of 8 points per m². As in 2019, the survey generated both digital terrain models and digital surface models. The winning contractor was again Topocart Aerolevantamentos, which this time used an Optech Galaxy Prime+ system. The final product, exemplified in Figure 3, was delivered in both .LAS (point cloud) and raster (pixel matrix) formats. Its accuracy also conforms to the PEC-PCD Class A standard for a 1:5000 scale (with a standard error of 0.34 m for spot heights and models), ensuring compatibility between the two models.

Figure 3. LiDAR point cloud (8 points/m²) over an orthomosaic – both from the 2024 flight and covering an area of Rocinha, Rio de Janeiro

2.1.3 Building Footprints

The analysis also incorporated a building footprint vector layer. Originally digitized from a 2013 aerial survey, the layer was updated against the 2019 data and comprises 2D polygons, each with a height attribute.

2.2 Methods

Based on the available data, this study aims to detect changes in the vertical growth of buildings across the city between 2019 and 2024. This was achieved by performing map algebra on the Digital Elevation Models (DEMs) from both years, following these steps:

2.2.1 Point Cloud Filtering

The LiDAR point clouds were filtered to include only returns classified as ground (1), low vegetation (2), and building (6) (ASPRS). This ensures the resulting models represented exposed ground and buildings, excluding trees and other features irrelevant to analyzing vertical construction growth.

2.2.2 Raster Generation

The filtered point clouds were then converted into raster files with a 0.5-meter spatial resolution. The elevation value for each pixel was rounded to the nearest integer.

2.2.3 Change Detection via Subtraction

A pixel-by-pixel subtraction of the 2019 model from the 2024 model will be performed. This operation will generate a synthetic raster image (a Digital Difference Model) where positive values indicate vertical addition (new floors/structures), a value of zero indicates no change and negative values indicate demolition. Figure 4 provides a simplified diagram of this procedure.

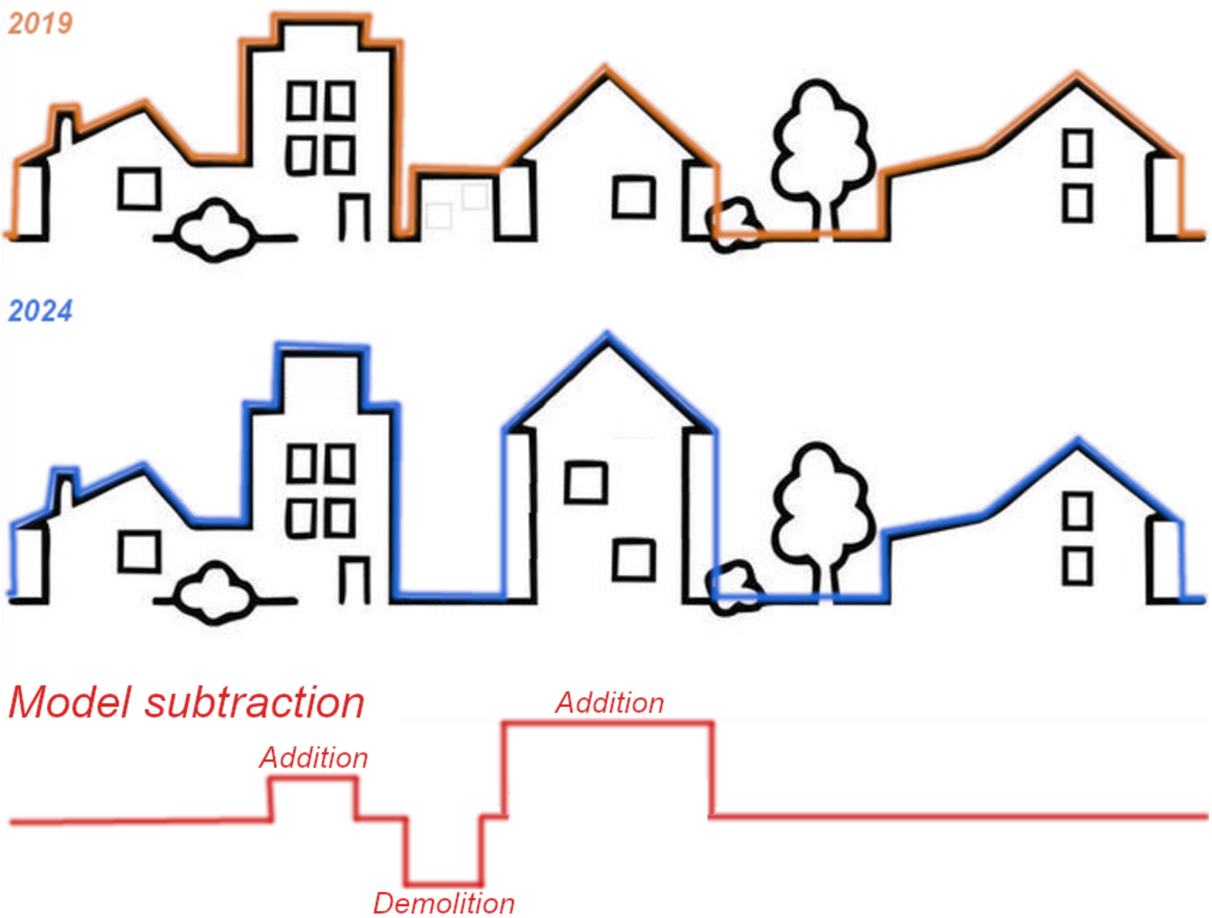

Figure 4. Schematic diagram of possible outputs derived from model subtraction

2.2.4 Zonal Statistics

To summarize changes for existing buildings, zonal statistics (mode, mean, median) of the vertical difference will be calculated for each building footprint in the 2019-updated vector layer. This results in a lighter, more manageable dataset for visualization. However, this product is restricted to changes affecting buildings that existed in 2019. New constructions built after 2019 are only captured in the full-resolution raster product.

3. RESULTS

3.1 Filtering of points related to buildings and exposed ground

As an example, Figures 5 and 6 show the result of filtering the point clouds to include only the classes for exposed ground, low vegetation, and buildings. The images correspond to the same area shown in Figures 2 and 3.

Figure 5. Filtered LiDAR point cloud showing classes 1 (ground), 2 (low vegetation), and 6 (building), over an orthomosaic. Both datasets are from the 2019 flight.

Figure 6. Filtered LiDAR point cloud showing classes 1 (ground), 2 (low vegetation), and 6 (building), over an orthomosaic. Both datasets are from the 2024 flight.

3.2 Conversion of point clouds into raster (grid) format elevation models.

Also as an example, Figures 7 and 8 demonstrate the raster digital surface model, created exclusively from the exposed ground, low vegetation, and building classes. These also relate to the area shown in Figures 2 and 3.

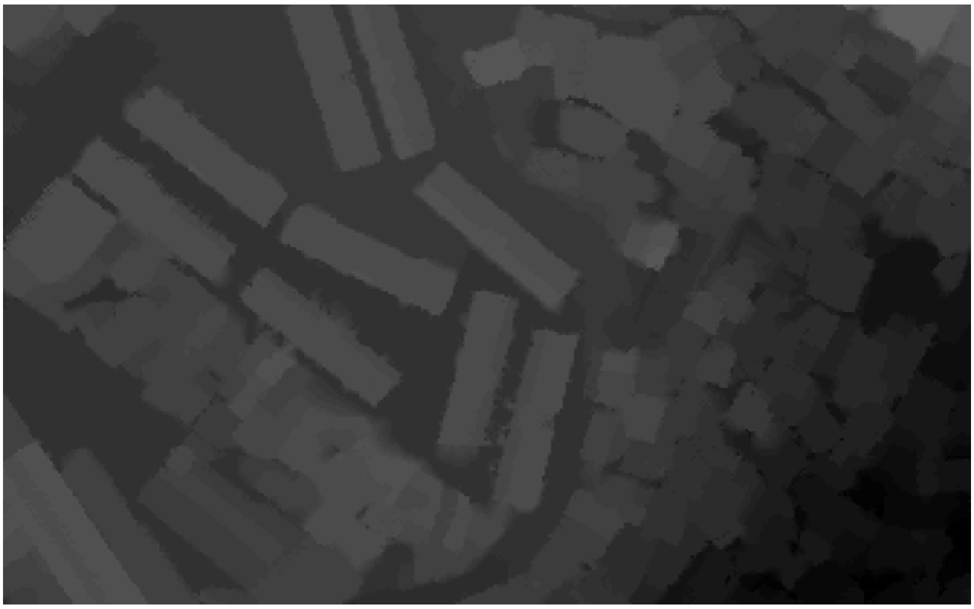

Figure 7. Raster building model, generated solely from the interpolation of the point cloud, referring to the 2019 flight.

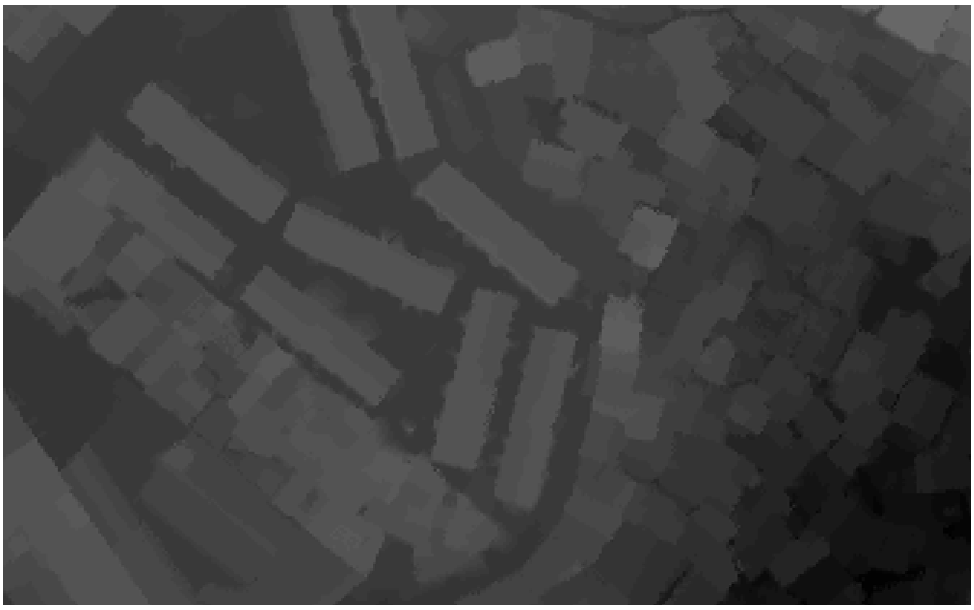

Figure 8. Raster building model, generated solely from the interpolation of the point cloud, referring to the 2024 flight.

3.3 Image classification according to altitude difference values

The initial differential raster dataset presented practical challenges for analysis and dissemination due to its substantial file size from storing raw elevation values and containing residual noise. To address these issues, the data underwent a reclassification process using 3-meter intervals as classification thresholds. This 3-meter criterion was carefully selected based on several considerations: it exceeds standard floor height additions in Brazilian construction (minimum 2.5m per floor excluding structural elements), accounts for potential systematic errors in both the 2013 photogrammetric and 2019 LiDAR datasets (known mean standard error of 33 cm), and helps mitigate false positives from roof slope variations. The reclassification scheme categorized changes as follows:

- -3: Altitude differences below -3m (Demolition) – represented by the color purple.
- 0: Absolute altitude differences less than 3m (Inconclusive whether addition or demolition occurred).
- 3: Altitude differences above 3m and below 6m (Addition of 1 floor) – represented by the color yellow.
- 6: Altitude differences above 6m and below 9m (Addition of 2 floors) – represented by the color orange.
- 9: Altitude differences above 9m and below 12m (Addition of 3 floors) – represented by the color coral.
- 12: Altitude differences above 12m and below 15m (Addition of 4 floors) – represented by the color red.
- 15: Altitude differences above 15m (Addition of 5 or more floors) – represented by the color crimson.

3.4 Zonal Statistics (summaries by building footprint polygons), referenced to the 2019 vector base

The zonal statistics calculate the mean, mode, and median of the pixel values within each polygon. This determines, for each roof, the average, the most frequent value (mode), and the central tendency value (median) among the altitude differences captured in the raster algebra. Figures 9 and 10 show the two products (raster and vector). The arrow highlights a limitation of using zonal statistics per polygon: it cannot capture new constructions built from the ground up (i.e., where no polygons exist in the 2019 vector base). Therefore, while the raster product is more difficult to visualize (due to capturing building edge noise), it allows for a more accurate visual analysis. The vector product, which is easier to visualize, allows for understanding changes in urban morphology, but only for buildings that already existed in the prior 2019 database.

Figure 9. Raster map algebra, highlighting demolitions and new constructions.

Figure 10. Zonal statistics (mean) per roof. Note that the building indicated by an arrow in this figure and in Figure 8 was not captured in the vector product because it did not exist in 2019.

4. DISCUSSION

This building change model is comprehensive enough to be used for a variety of scenarios. Figures 11 and 12 show how the raster data can be used to monitor construction in both informal settlements and in formal areas of the city.

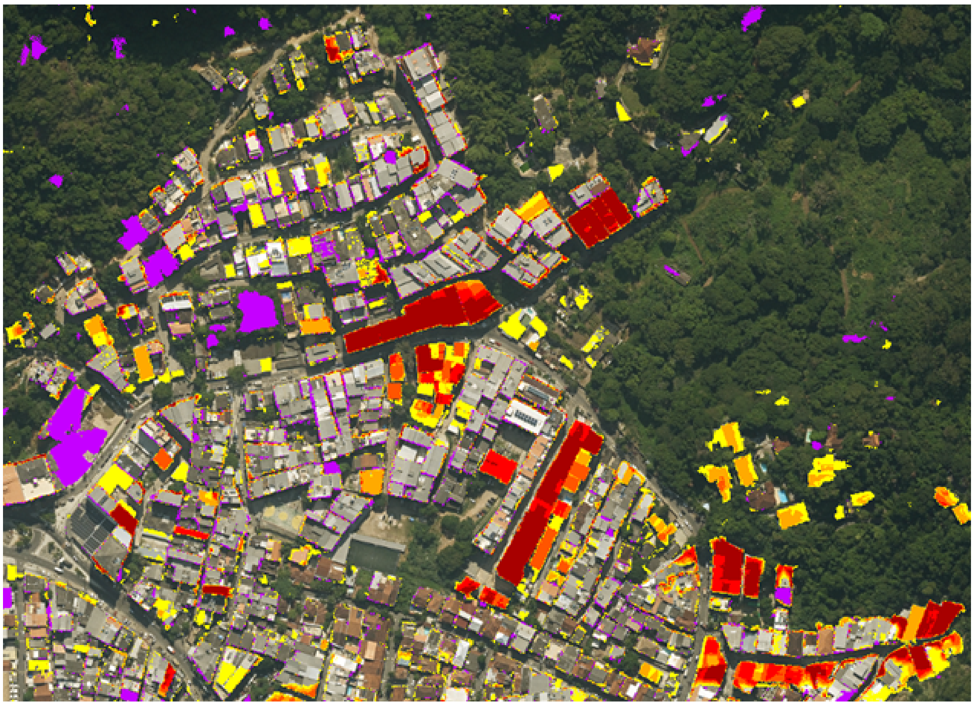

Figure 11. Vertical growth in the Muzema region (raster dataset)

Figure 12. New buildings in Jardim Oceânico (raster dataset)

Nevertheless, these raster datasets contain several artifacts, which look like minor demolitions among the edges of buildings. These stem from minor planimetric differences between the two models and, while not necessarily difficult to understand for trained personnel, may be hard to guess for regular users not fully acquainted with geotechnologies.
On the other hand, when summarized per building, the same model is clearer and easier to read. Figure 13 shows the same area covered by Figure 11. Notice that this procedure does not capture

new constructions - only changes in buildings already extant in 2019 (see Figure 14 for a more comprehensive visual example).

Figure 13. Vertical growth in the Muzema region (vector dataset)

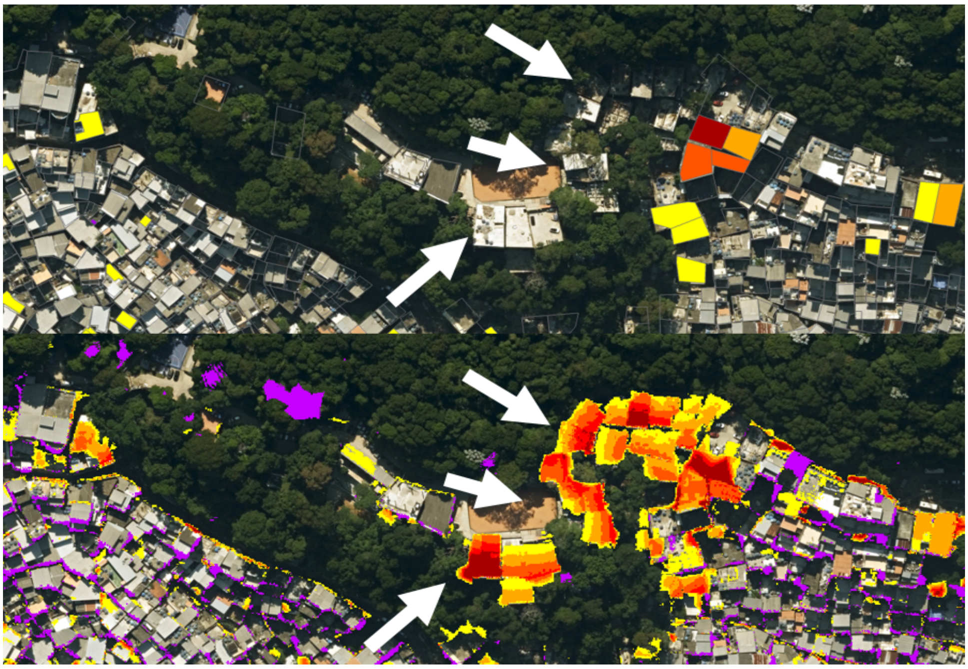

Figure 14. From the comparison between the two products, it is possible to identify areas of significant expansion from bare ground or through deforestation, as in this example from Rocinha Favela, alongside expansion by adding floors to extant buildings.

Another important application of this building model is to compatibilize permits and actual construction, as can be inferred from Figure 15, which shows a large condominium entirely built from scratch, whose altitude was properly captured by the procedure.

Figure 15. New construction in Santa Cruz. By crossing measured altitudes in the model, it is possible to determine if permits were properly followed.

Furthermore, the resulting data can be integrated into GIS for cluster analysis to identify urban areas most impacted by building market dynamics (Figure 16).

Figure 16. The analysis allows for the identification of hotspots in the real estate dynamics of favelas, as shown in this example from the Complexo do Alemão.

Finally, when summarized through zonal statistics, the dataset could also be used as a virtual 3D model, which easily helps identify notable changes in building height, and significantly enhancing the dataset's utility for both analytical purposes and visualization (Figures 17 and 18).

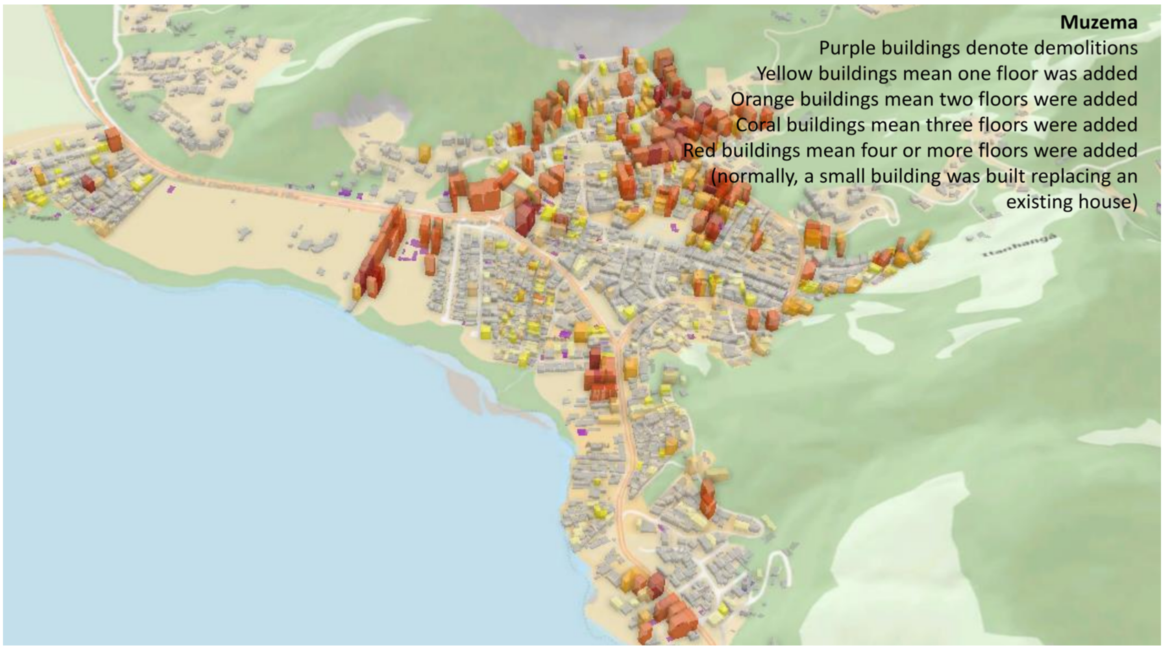

Figure 17. Vertical growth analysis applied to informal settlements in Muzema

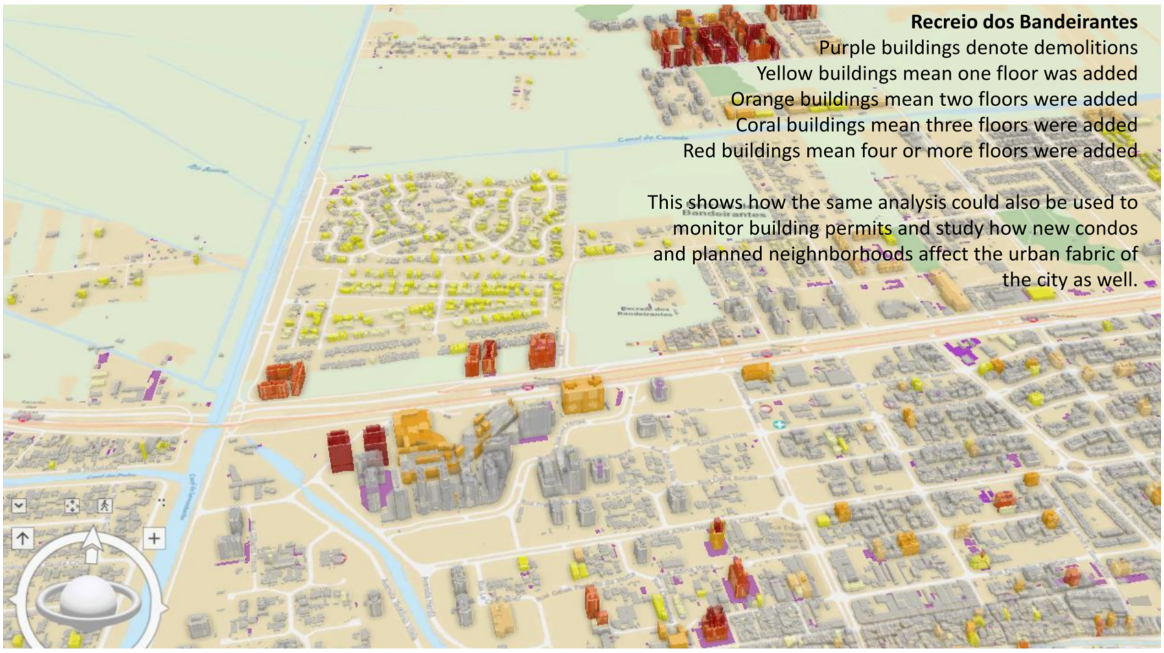

Figure 18. Vertical growth analysis applied to the neighborhood of Recreio dos Bandeirantes

Rio de Janeiro's current cadastre consists of 2D parcels and building footprints, among other data classes. The integration of 3D building models enables the semi-automatic updating of building heights, which enhances property taxation and captures the surplus value generated by added floors. By automating updates to the city's physical cadastre, the economic cadastre can also be kept current through the application of a generic valuation table to the actual number of floors and total built area of each building.

Furthermore, this tool aids the municipality in regulating building permits. It can identify areas (even in formal districts) where unauthorized self-construction has exceeded approved parameters or where construction deviates from permit specifications.

The tool also simplifies the tracking of demolitions and building additions by summarizing data on extant structures. This capability helps illuminate real estate market dynamics and pinpoints zones experiencing more intensive construction. Such insights are particularly valuable in favelas, which have a fully informal market that requires better understanding and integration into the city's official cadastre.

A current limitation of the tool is that newly constructed buildings are only identifiable in the raster building model. Future studies should therefore address the simplified segmentation of these new structures into basic polygons. These polygons could then be incorporated into the municipal geospatial dataset following the "fit-for-purpose" Land Administration principle. While not adhering to strict precision standards, these new building footprints would serve as a crucial first step toward regularization and establishing formal land tenure.

5. CONCLUSION

The applications of LiDAR in 3D cadastre are far broader than merely altimetry. It enables cities to cross-check construction permits against actual development, ensuring compliance with zoning laws and building codes. It also identifies informal expansions in formal neighborhoods, allowing for fairer property taxation, while pinpointing underutilized land that could be repurposed for social housing or public infrastructure (Erba & Piumetto, 2021). Beyond enforcement, this data supports predictive modeling for transportation planning, disaster risk management, and zoning reforms.

Yet, none of these functions are sustainable without a continuously updated cadastral base map —one that is dynamically linked to a geodatabase capable of integrating administrative, fiscal, and territorial information. In Rio's case, the combination of LiDAR and MLC represents a step toward smarter urban governance (Palme & Ramírez, 2013), but its long-term success depends on institutional commitment to data transparency, interoperability, and systemic coordination across all levels of government, and, most notably, the execution of regular surveys, that allow for cartographic updating of building footprints (Priestnall et al., 2000; Tian et al., 2014) and multi-year comparison to better understand informal growth (Sass & Amorim, 2014).

As a concluding remark, the work underway today—from LiDAR-aided surveys to 3D cadastral updating—holds immense potential to provide for effective land valuation. By prioritizing interoperability, equitable data access, and partnerships between academia and municipalities, it is possible to advance planning tools that empower cities (particularly in Latin America) to harness land value capture more fairly and efficiently. The goal is not merely technological innovation, but the translation of these tools into equitable fiscal policies: ensuring that urban growth generates public revenue which, in turn, funds inclusive urban development. The path forward demands not only technical solutions, but institutional commitment to see geospatial surveys as effective tools for urban governance.

REFERENCES

ALMEIDA, G. A. G., & LOCH, C. (2012). O cadastro técnico multifinalitário como ferramenta de gestão fundiária e ambiental de uma unidade de conservação e seu entorno. Profiscientia, 7.

AMORIM, A., PELEGRINA, M. A., & JULIÃO, R. P. (2018). Cadastro e gestão territorial: Uma visão luso-brasileira para a implementação de sistemas de informação cadastral nos municípios. Editora Unesp Digital.

ASPRS. LAS Specifications. The American Society of Photogrammetry and Remote Sensing.

BRITO, J. L. N. S. (1997). Precision of digital orthoimages: Assessment and application to the occlusion detection problem [Doctoral dissertation, The Ohio State University].

BURROUGH, P. A., MCDONNELL, R. A., & LLOYD, C. D. (2015). Principles of geographical information systems. Oxford University Press.

COELHO, L. C. T., & BRITO, J. L. N. S. (2007). Fotogrametria digital. Ed. UERJ.

CONCAR (Comissão Nacional de Cartografia). (2016). Especificação técnica para a aquisição de dados geoespaciais vetoriais.

COWEN, D. J., & CRAIG, W. J. (2003). A retrospective look at the need for a multipurpose cadastre. Surveying and Land Information Science, 63(4), 205-214.

ERBA, D. A., & OLIVEIRA, F. L., & LIMA, P. N., JR. (2005). Cadastro multifinalitário como instrumento de política fiscal e urbana. IPPUR.

ERBA, D. A., & PIUMETTO, M. A. (2021). Para compreender o solo urbano: cadastros multifinalitários para o planejamento e o desenvolvimento das cidades na América Latina. Lincoln Institute of Land Policy.

GOMARASCA, M. A. (2009). Basics of geomatics. Springer.

KRAUS, K. (1992). Photogrammetry: Fundamentals and standard processes (Vols. 1-2). Ferd Dümmler Verlag.

KREILING, A. (2009). Photogrammetric guide. Wichman.

LERMA GARCÍA, J. L. (2002). Fotogrametría moderna: Analítica y digital (1st ed.). Editorial Universitat Politècnica de València.

LILLESAND, T., KIEFER, R. W., & CHIPMAN, J. W. (2015). Remote sensing and image interpretation (7th ed.). Wiley.

LOCH, C., & ERBA, D. A. (2007). Cadastro técnico multifinalitário rural e urbano. Lincoln Institute of Land Policy.

LONGLEY, P. A., GOODCHILD, M. F., MAGUIRE, D. J., & RHIND, D. W. (2015). Geographic information systems and science (4th ed.). Wiley.

MAGAROTTO, M. G., DA COSTA, M. F., TENEDÓRIO, J. A., & SILVA, C. P. (2016). Vertical growth in a coastal city: An analysis of Boa Viagem (Recife, Brazil). Journal of Coastal Conservation, 20, 31-42.

MIKHAIL, E. M., BETHEL, J. S., & MCGLONE, C. (2001). Introduction to modern photogrammetry. John Wiley & Sons.

PALME, M., & RAMÍREZ, J. G. (2013). A critical assessment and projection of urban vertical growth in Antofagasta, Chile. Sustainability, 5(7), 65-78.

PRIESTNALL, G., JAAFAR, J., & DUNCAN, A. (2000). Extracting urban features from LiDAR digital surface models. Computers, Environment and Urban Systems, 24, 65-78.

SASS, G. G., & AMORIM, A. (2014). Multipurpose land cadastre and data temporality. Revista Brasileira de Cartografia, 66(5), 1029-1038.

SCHENK, T. (1999). Digital photogrammetry. TerraScience.

TIAN, J., CUI, S., & REINARTZ, P. (2014). Building change detection based on satellite stereo imagery and digital surface models. IEEE Transactions on Geoscience and Remote Sensing, 52(1), 406-417.

WOLF, P., DEWITT, B. A., & WILKINSON, B. E. (2014). Elements of photogrammetry with application in GIS (4th ed.). McGraw-Hill.

YUAN, B., ZHOU, L., DANG, X., SUN, D., HU, F., & MU, H. (2021). Separate and combined effects of 3D building features and urban green space on land surface temperature. Journal of Environmental Management, 295. https://doi.org/10.1016/j.jenvman.2021.113116

ZAMBON, I., COLANTONI, A., & SALVATI, L. (2019). Horizontal vs vertical growth: Understanding latent patterns of urban expansion in large metropolitan regions. Science of The Total Environment, 654, 778-785.

BIOGRAPHICAL NOTES

Luiz Carlos Teixeira Coelho holds a Bachelor's degree in Geomatics Engineering from the Military Institute of Engineering, a Master's degree in Informatics from the Federal University of Amazonas, and a Doctor of Sciences degree in Urban and Regional Planning from the Federal University of Rio de Janeiro. He is currently a professor at the Rio de Janeiro State University and a researcher at the Pereira Passos Municipal Institute of Urban Planning.

Leandro Gomes Souza is a Geographer, with a Bachelor's degree from the Federal University of Rio de Janeiro and a Master's degree in Urban and Regional Planning from the same university. He is the current Cartography Manager at the Pereira Passos Municipal Institute of Urban Planning.

Felipe Cerbella Mandarino is also a Geographer, having obtained his undergraduate degree from the Federal University of Rio de Janeiro. He is the Coordinator of City Information at the Pereira Passos Municipal Institute of Urban Planning.

CONTACTS

Luiz Carlos Teixeira Coelho
Instituto Municipal de Urbanismo Pereira Passos
Rua Gago Coutinho 52, Laranjeiras
Rio de Janeiro, RJ

BRAZIL
Phone: + 55 21 2976-6593.
E-mail: lcteixeiracoelho@prefeitura.rio
Website: https://ipp.prefeitura.rio

Leandro Gomes Souza
Instituto Municipal de Urbanismo Pereira Passos
Rua Gago Coutinho 52, Laranjeiras
Rio de Janeiro, RJ
BRAZIL
Phone: + 55 21 2976-6593.
E-mail: leandro.souza@prefeitura.rio
Website: https://ipp.prefeitura.rio

Felipe Cerbella Mandarino
Instituto Municipal de Urbanismo Pereira Passos
Rua Gago Coutinho 52, Laranjeiras
Rio de Janeiro, RJ
BRAZIL
Phone: + 55 21 2976-6593.
E-mail: felipe.mandarino@prefeitura.rio
Website: https://ipp.prefeitura.rio