

A workflow to create urban digital twins from open data

Open 3D city models for Mexico

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3D city models are valuable tools for urban planning, solar potential analysis, wind simulations and many other applications. Yet openly available models currently exist for only a limited number of cities across some 20 countries, almost all of which are in the Global North. Recent research in Mexico demonstrates that detailed 3D city models can be automatically generated for the country's cities using only open data from the national mapping agency. Significant limitations in the available datasets are overcome by an approach that derives building footprints and road polygons from existing sources.

In some countries, creating 3D city models follows a well-established workflow. A 2D topographic dataset providing building footprints and road polygons is combined with a high-resolution elevation dataset such as a point cloud or digital surface model (DSM). The elevation information lifts the 2D geometries into three dimensions. This approach works efficiently when both datasets are available at sufficient quality. However, this is not the case in much of the world.

Mexico presents a particularly illustrative example. The National Institute of Statistics and Geography (INEGI) provides extensive topographic and elevation datasets covering the entire country. The 1:50,000-scale

vector topographic dataset contains useful polygonal features including city blocks (known as *manzanas* in Spanish), land-use types such as schools and recreational areas, and water bodies. However, it lacks two of the most important feature types for 3D city models: individual building footprints, which are not recorded at all, and roads, which are represented only as centre lines rather than as area polygons (Figure 1).

Elevation data is available but with considerable variation in coverage and resolution. INEGI provides DSMs at 1.5m resolution in and around some of the larger cities, acquired through a mix of satellite photogrammetry, aerial imagery

and Lidar surveys. Older 5m models cover approximately a third of the country, and a nationwide digital terrain model (DTM) at 15m resolution completes the picture. This means that, while buildings can be clearly seen in the high-resolution DSMs where they are available (Figure 2), the incomplete 2D topographic features and the patchy coverage of the best elevation data render the standard 3D city model pipeline inapplicable.

As a result, no 3D city models are currently openly available for any city in Mexico. Previous academic efforts have been limited to small areas using largely manual modelling methods or proprietary software. While global building-footprint datasets



▲ Figure 1: Some of the topographic features available in the 1:50,000 vector topographic dataset from INEGI, with city blocks (yellow), roads (red lines), public areas (green), water bodies and canals (blue).



▲ Figure 2: Individual buildings can be clearly seen in the 1.5m DSM from INEGI.



▲ Figure 3: A view of the 3D city model created using the methodology. The Paseo de la Reforma can be seen on the right.

from Microsoft and Google do cover parts or all of Mexico, they have significant quality problems in dense urban environments.

Computational steps to fill the data gaps

The novel methodology addresses these challenges through a series of computational steps. Instead of using pre-existing building footprints, it derives them directly from the elevation data. Rather than relying on pre-existing road polygons, it generates them from the empty spaces between city blocks in the topographic dataset.

Building-footprint extraction begins by subtracting the DTM (not including buildings and other objects above ground level) from the DSM (including buildings and other objects) to obtain an elevation map showing only the heights of objects above ground level. Areas where buildings are not expected, such as green spaces, water bodies and the newly identified road areas, are masked out to avoid generating false footprints from tree canopies. From the

resulting raster, building footprints are extracted using a region-growing algorithm that starts from seed points where the height exceeds 10m, a threshold chosen to distinguish building roofs from vegetation.

From these seed points, regions are expanded using two different height-difference tolerances to identify different types of buildings. For tall buildings above 100m in height, a tolerance of 15m between neighbouring pixels captures steeply inclined facades and spires without merging adjacent structures, which are always well separated at such heights. For shorter buildings, where adjacent structures often have no discernible gap between them, a stricter tolerance of 0.75m helps to keep them separate. Small artefacts are removed by discarding polygons with an area below approximately 100m², and the outlines are simplified to eliminate the staircase effect typical of raster-to-vector conversions.

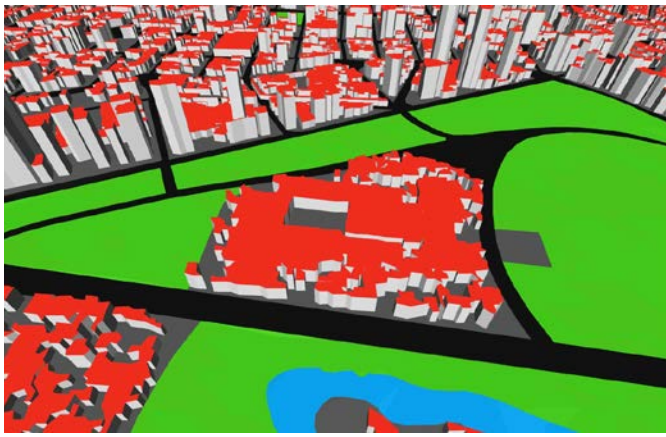
Road polygons are generated through a complementary logic. By computing the Boolean union of certain areal features present in the INEGI data, including city blocks, land use types and water features, a complete coverage of the built-up land surface is obtained. The remaining empty spaces, located between city blocks, largely correspond to roads, railways and smaller water streams. These are then classified by proximity to the linear road and railway centre lines in the original dataset, enabling the assignment of correct semantic labels to each newly created area.

Lifting to 3D

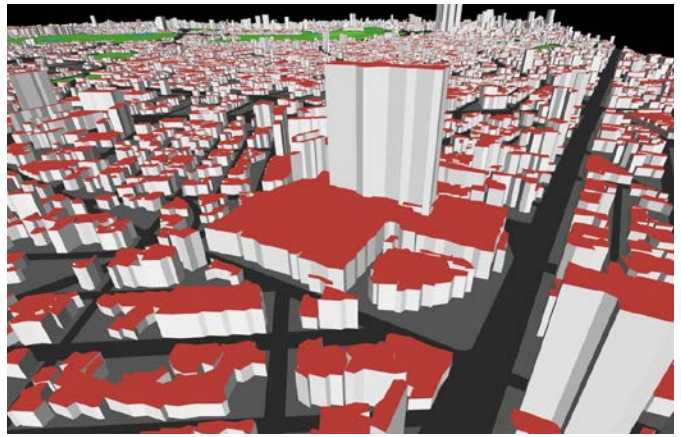
Once the building footprints, road polygons and additional feature types (including plant cover, water bodies and terrain) have been prepared, they are processed into full three-dimensional geometries using three different lifting rules. Buildings are lifted uniformly to a flat height computed as the 90th percentile of all DSM cells within each footprint. This yields a value close to the maximum



▲ Figure 4: Google's Open Buildings over-segments the data, creating new polygons for smaller rooftop features and for clearly non-existent buildings.



▲ Figure 5: Tall vegetation is identified as buildings around the National Museum of Anthropology.



▲ Figure 6: The terraced architecture of the World Trade Center is recognized as multiple buildings.

building height while avoiding outliers in the elevation data. Roads, water bodies and terrain are lifted by snapping polygon vertices to the heights at those locations in a simplified DTM. Plant-cover areas use a more detailed approach: polygon vertices are lifted to DTM heights, and additional interior points from the DTM are added to the polygonal surface, with the polygon re-triangulated to capture terrain variations beneath vegetation.

Vertical surfaces are generated to close the gaps between differently lifted polygons, creating building walls and any other vertical features. The completed model is exported in two formats: CityJSON, a compact JSON-based encoding of the CityGML standard that preserves full semantic information, and OBJ for easy visualization in standard 3D graphics software. The workflow was implemented in Python and C++ with some preprocessing steps directly performed in QGIS, and all code is publicly available on GitHub.

Results in Mexico City

The methodology was tested in a tile covering central-western Mexico City (Figure 3). The area was chosen for its rich mix of building types spanning detached homes, apartment blocks and high-rise office towers, as well as its varied land uses and terrain. The area includes several of Mexico City's best-known landmark buildings, providing a straightforward way to visually assess the generated models.

Most landmarks are clearly visible and recognizable in the reconstructed 3D model, with heights that match publicly available

information. The Torre Mayor, Torre Reforma and the distinctive buildings along the Paseo de la Reforma are all identifiable. The road polygons are accurately placed and correctly reflect the hierarchy of road widths visible in the city's street network, with major avenues clearly wider than side streets.

Perhaps most notably, the building footprints generated by this method often outperform those from global datasets (Figure 4). Microsoft's Global ML Building Footprints consistently under-segments dense built-up areas, frequently merging entire city blocks into single polygons. Google's Open Buildings dataset captures more individual buildings but over-segments the data, creating spurious footprints from rooftop features and even clearly non-existent structures. Neither handles non-rectilinear buildings. By contrast, the INEGI-derived method captures complex building shapes well and avoids placing buildings on roads or in other unlikely locations.

Current limitations

Despite these promising results, the methodology has some known shortcomings. Approximately a third of buildings in the study area remain undetected, predominantly smaller structures that cannot be clearly distinguished in the 1.5m-resolution DSM. Uniform vegetation taller than 10m in areas not classified as green space is sometimes incorrectly identified as buildings. This issue is particularly visible around the National Museum of Anthropology where rows of tall trees generate spurious building footprints (Figure 5).

Terrace-shaped buildings with sections at significantly different heights, such as the stepped architecture of the Mexico City World Trade Center, are occasionally split into multiple detected buildings (Figure 6). Conversely, adjacent buildings of the same height with no visible separation are merged into a single footprint. Three-dimensional road structures such as overpasses and

Further reading

- Biljecki, F., Stoter, J., Ledoux, H., Zlatanova, S., Çöltekin, A. (2015) Applications of 3D City Models: State of the Art Review. *ISPRS International Journal of Geo-Information*, 4(4), pp. 2842–2889.
- Ledoux, H., Arroyo Ohori, K., Kumar, K., Dukai, B., Labetski, A., Vitalis, S. (2019) CityJSON: A compact and easy-to-use encoding of the CityGML data model. *Open Geospatial Data, Software and Standards*, 4(4).
- Ledoux, H., Biljecki, F., Dukai, B., Kumar, K., Peters, R., Stoter, J., Commandeur, T. (2021) 3dfier: automatic reconstruction of 3D city models. *Journal of Open Source Software*, 6(57), 2866.
- INEGI elevation models: <https://www.arccgis.com/apps/mapviewer/index.html?webmap=b593168ba9784bbc9dd4b909407e559a>
- Methodology source code: <https://github.com/kenohori/3dcm-mexico>

highway interchanges are not modelled, since all roads are set at the simplified DTM height.

Directions for further development

Several promising avenues exist for extending this initial work. The building detection algorithm could incorporate machine learning techniques for improved classifications. A more flexible rectilinear optimization of building footprints could enhance geometric quality without the aggressive regularization that limits existing global datasets. Testing the methodology in other Mexican cities where high-resolution elevation data is available would help assess how well the parameters generalize across different climates and urban morphologies.

Fine-tuning parameters such as height thresholds, minimum areas and height-difference tolerances could substantially improve results. Incorporating 3D road modelling and applying the lifting algorithms in varied configurations would add significant detail for professional urban planning and analysis applications.

Conclusion

This research demonstrates that detailed 3D city models can be created for Mexican cities using only open data, despite the limitations of national datasets. By deriving building footprints from elevation models, and road polygons from the gaps between city blocks, the methodology overcomes the absence of these critical features in Mexico's topographic data. The results show that the approach already produces more accurate building footprints than those in widely used global datasets for dense

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urban areas, particularly for non-rectilinear landmark buildings. While approximately 30% of smaller buildings remain undetected and vegetation occasionally causes false positives, the work establishes a viable foundation for open 3D city models across all areas of Mexico where high-resolution elevation data exists. The methodology and source code are openly available for further development by the geospatial community. ■

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