• **Article** •

Procedural modeling applied to the 3D city model of bogota: a case study

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Abstract Background Computer Generated Animations (CGA) applied to 3D City Models (3DCM) can be used as powerful tools to support urban decision making. This leads to a new paradigm based on procedural modeling that allows the integration of known urban structure. This paper introduces a new workflow for developing high-quality approximations of urban models in a short time and facilities imported from other cities into a given city model following specific generation rules. Thus, this workflow provides a very simple way to observe, study and simulate the implementation of models already developed in other cities in a city where they do not exist. Examples of these models can be all types of mobility systems and urban infrastructures. All this allows us to have a perception of the environmental impact that these types of decisions can produce in the real world, as well as to carry out simple simulations to determine the changes that can occur in the flows of people, traffic, or any other type.

Keywords Computer Generated Animations, Geographical Information System, Urban planning, 3D City Modeling.

1 Introduction

This paper presents a new workflow for developing high-quality approximations of urban models in a short time. Using CGA rules, a compact, efficient and reusable procedural representation of a polygonal 3D architectural model is generated. This leads to a new paradigm that allows the integration of new urban structures into the approximated city model, providing a powerful tool for urban planning and simulation projects. Moreover, it also presents the case study of an urban area of 5Km long and 4Km wide in Bogota. The goal of the study is to generate an approximated 3DCM of the target area (a 3DCM is a computer model of a city) and add a new highway in substitution of one of the main roads. On this spot, 2D GIS data is used to generate a set of 3D urban installations. To this end, around 20,000 3D models referring to urban facilities (roads, houses, trees, green areas) were extruded using procedural modeling in less than 3 minutes. The final result shows a high definition 3DCM that has a new highway network and urban structure set deployed on an originally empty terrain that can be used as a basis for simulation projects and urban planning. This avoids the laborious manual modeling task and provides a 3DCM that can be analyzed, changed and adjusted, the generated 3DCM serves as the basis for urban planning and simulation projects.

3DCMs are a key point in decision making for urban problems [1]. Its implementation in fields related to urban planning (decision-making processes, analysis of city characteristics, architectural and urban design, visualization, among others) has had a growing boom since the development of GIS in the 1960s.

GIS is an organized integration of hardware, software, and geographic data, designed to capture, store, manipulate, analyze, and display in all its forms geographic information that refers to real-world urban facilities, roads, land use, altitudes, among others.

The aerial images serve as the basis for selecting the GIS data referring to roads and parcels that will be integrated into the Digital Terrain Model (DTM) of the city. This integration generates a two-dimensional model of roads and lots on a three-dimensional model of the terrain. Urban spaces in the city lacking geographic information are subjected to a generative road modeling process that closely follows previously created positioning, direction and elevation data, connects road ends to each other and generates new streets on the DTM.

The 3D visualization improves the mental image during the planning of controls of the urban planners that traditionally work with 2D data by representing the three-dimensional data by means of text [2].

Currently, the development of 3D models and their data structure is in a conceptual stage. Thus, its applicability to solve problems in urban areas awaits further exploration [3] [4].

In this sense, new procedural modeling techniques allow large-scale urban facilities to be modeled from 2D data representations without the need for individual modeling, significantly reducing the development time of a 3DCM [2] [5].

Regarding urban spaces, these are made up of a collection of buildings, parcels, blocks and neighborhoods interconnected by streets. The credibility of a 3DCM depends on the accuracy of the geospatial data and the Level of Detail (LoD) of its urban facilities [3]. The construction of a 3DCM starts from various sources and technologies (aerial, vertical and oblique photos, high resolution satellite images, etc.). Procedural modeling produces data that fits existing data sets according to specific rules.

Procedural urban modeling techniques have the same expressive power and precision as any other traditional technique, with the added convenience for manipulation [6]. This follows the basic principles of a shape grammar, the main concept of which is based on a set of rules: starting from an initial axiom shape (e.g., the outline of a building), the rules are applied iteratively, replacing shapes with other shapes.

The automated nature of these modeling techniques can take advantage of related research in the modeling of crowds of people and vehicles that can help to adjust and improve the process. In some approaches, this is achieved through the inference of rules and parameters that allow the generation of bigger and more complex environments. Two groups of agents are addressed in most of those approaches: vehicles and crowds, and some simulation models contemplate the interaction between them.

The interaction of vehicles and pedestrians with the different types of roads simulated in the 3DCMs can be quite relevant to the overall robustness of the model. For example, the work in [7] addresses the flow of these agents through model-based simulations and data driven animations focused on autonomous vehicles. In this model, the traffic flow is similar to the crowd flow, and tested with CityEngine and improved in further research. In addition, the layout of an urban environment can be designed according to properties of the crowd, optimizing parameters such as mobility, accessibility and coziness, using a data-driven approach with non-linear regressors to manage relationships between agents of the crowd and the environment [8].

The behavior of those virtual agents (pedestrians and vehicles) can be simulated with deep neural networks and reward functions, which allows them to adapt to ever changing environments where heavy decision making is involved, as stated on [9], and the approach in [10] introduces a parameterizable continuum model to simulate the behavior of individuals in a crowd on an evacuation scenario.

The approach in [11] considers geographical discontinuities on the territory and analyzes the behavior of the transportation system flow. This could lead to a better validation of the parameters used in the creation of the 3DCMs. A 3DCM built that way could provide a more efficient use of sustainable transportation systems [12], a better way of planning evacuation routes on emergencies [13], and a more efficient planning of routes for freight vehicles [14].

The main contribution of this paper is the development of a new workflow to generate 3D models from a two-dimensional representation of urban data. As a result, this tool can serve as support in decision-making for urban planning and provide support in the control and evaluation of this type of processes. Moreover, this workflow is a first step for the integration of parameterizable crowd and traffic simulation models, whose interaction with the 3DCM can be controlled in some way. This would allow the proposed workflow to produce more accurate environments by simulating the flow of people and vehicles. Thus, this work presents a new paradigm based on procedural modeling that integrates known urban structures and facilities imported from other cities into a given city model following specific generation rules. As a result, it is possible to observe, study and simulate the implementation of models already developed in other cities in a city where they do not exist.

The rest of this document is organized as follows. Section 2 introduces a 3DCM generation workflow and describes its main elements. To generate the 3DCM, procedural modeling is integrated with data from GIS. Section 3 shows the results for a case study of the application of this workflow in the city of Bogota, where the possibility of connecting parts of the city through highways is analyzed. Finally, Section 4 concludes.

2 Workflow for 3DCM Generation

The workflow aim is to provide a mechanism for large-scale generation of 3D urban models using CGA. Thus, the workflow can generate in a short time an approximated 3DCM containing basic urban installations, flexible for being explored, analyzed, and eventually modified. Consequently, this flexibility allows automated modifications on the urban model based on custom rules, providing a tool for urban planning and simulation of new scenarios. The workflow consists of four steps that generates a 3DCM from a GIS database as shown in Figure 1.

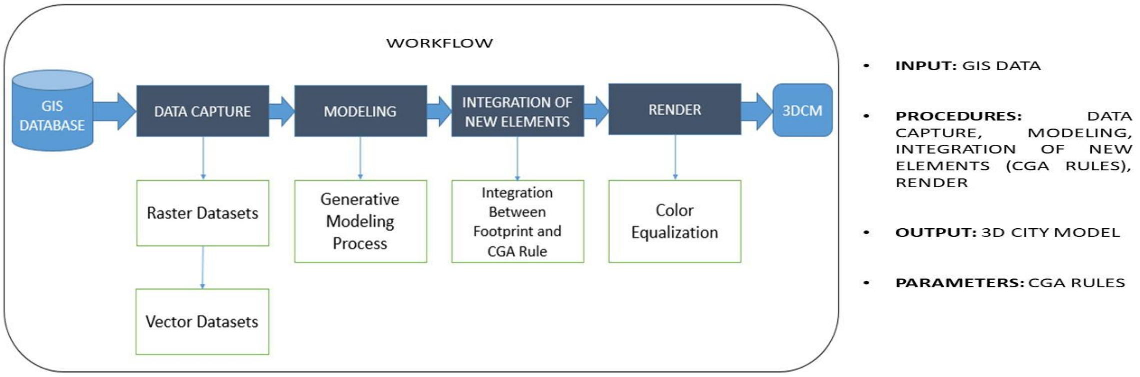

Figure 1 Proposed workflow for 3DCM generation.

Figure 1 describes the proposed workflow that utilizes GIS data from OSM as an input and produces a high quality 3DCM as its final output. All procedures and execution parameters for each step are described in the next paragraphs.

The first step of the workflow is *Data Capture.* It focuses on providing general-purpose basemaps and reference layers, such as imagery, streets, topography, and boundaries that serve as the basis for the modeling process. Due to compatibility with geospatial data sets, urban models are produced in regular grids called parcel [18]. Each parcel contains GIS data regarding the use of the area and the overlay controls for the adjacent plots as seen in Figure 2. In the context of urban modeling, 3D building objects can be generated from vector data such as land use and cadastral lots [18]. Consequently, during this first step GIS cadastral data is captured. This data is later stored in a raster format and discretized as a continuous space in cells of identical size. GIS cartographic data are stored in a vector format that links the vertices of each urban installation to custom terrain positions.

Captured cadastral data represents geographically-located features as points, lines or polygons. Thus, to measure shapes, polygons represent objects that are large enough to have boundaries, such as countries, lakes, or tracts of land. Lines represent objects that are relatively too narrow to be polygons, such as rivers, roads, or pipelines. Points are used for objects that are relatively too small to be polygons, such as cities, schools, houses, or fire hydrants [19]. Thus, the geometry type for street axes is lines. After organizing vector and raster data, the line layer attributes that define street widths from OpenStreet Maps street types are created. According to the geographic attributes of each urban installation, each point is assigned a 2D footprint that consists of building type, height, number of floors, etc., as described in Figure 2.

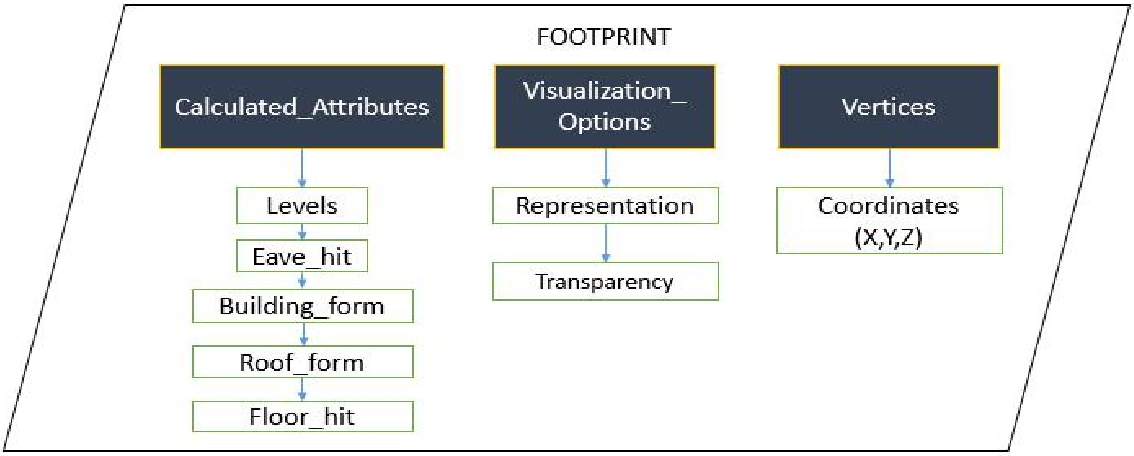

Figure 2 Footprint Layer Structure.

The second step is *Modeling*. GIS 3D city modeling is the most efficient and effective modeling method. This generates a reusable model that can be applied to various applications. Moreover, it is created in a minimum time and with minimal labor [15]. The proposed 3D modeling process uses ESRI maps from CityEngine Software, which capture the raster data from the DTM and Digital Surface Model (DSM) and integrate it with the GIS data output from step 1.

The geometric shapes are aligned to the DTM. However, due to the lack of GIS data associated with specific areas, a generative modeling process is executed to enlarge the road network and to add new footprints on the parts of the DTM that do not contain urban information [16]. This process determines if the evaluated area has the required number of footprints. If necessary, the generative modeling begins. It starts at the ends of the roads in the scene and, through an iterative process, extends the scope of the road network over the DTM, generating new 2D polygons across the streets, and providing a larger number of urban facilities for their extrusion and modeling process.

Moreover, the modeling step is performed using grammar-based procedural extrusion to generate 3D urban installations from 2D footprint. This technique defines a shape grammar, which is based on a rule base: starting from an initial axiom shape (for example, the outline of a building, or a footprint), the rules are applied iteratively, replacing the shapes with other shapes, and generating a new geometric structure. The CGA rule file consists of several rules that define how the structure is going to be created.

The third step is *Integration of New Elements*. The proposed workflow contains an extrusion process that, through the creation or acquisition of new CGA rules and their integration into the footprints, generates or adds new urban structures in addition to the reconstruction of existing urban installations.

The CGA rule may use information about attributes stored in the GIS data such as the number of floors, floor height, roof type, wall material type, etc. to generate detailed high-level 3D models. To create a detailed high-level model, the extruded shapes, from initial axiom shapes, are divided into elements, e.g., windows and doors, and textures or colors are added to these elements.to accurately represent the properties of each feature.

The construction of a 3D model of a set of buildings or apartments requires a large amount of resources, in CGA, extrusion is the process of creating a 3D model with a high and diverse level of detail based on a modular development approach., the extrusion process consists of using 2D Footprints that can be get from cadastral data to build geometric models, each footprint of all meshes in the scene undergoes an iterative process that adds new features to the polygon as specified by the extrusion type of the procedural rule. In fact, our methodology applies procedural rules that separate through CGA code different aspects of our design into smaller blocks of code, which are then connected to generate the facilities and the environment. These blocks of code that form independent CGA rules are combined in several ways to achieve greater morphological diversity with less coding through different combinations.

The blocks of code are organized and categorized as: *Envelope*, which represents the external shape of the facility using the parameters of height, street offset, shape, lot coverage, and building orientation; *Volume*, which refines the external shape of the facility and determines the position of walls, doors, windows, slabs, green spaces, etc.; *Facade*, that adds details to the construction elements that were defined in the volume and green spaces that distribute plants in the designated areas.

The final step is *Render*. After extruding the 2D footprint using CGA rule, the building style is determined. This changes the visualization style from solid color to realistic with facade textures. As a consequence, the created urban installations and the terrain are integrated as a single object and a color equalization between the 3DCM textures is performed by rendering engines

The resulting 3DCM is a digital representation of the Earth's surface and its related objects, such as buildings, trees, vegetation and artificial elements that belong to the urban area [15]. The large-scale generation of 3D models of urban facilities involves multilevel modeling and a multi-representation of the city model [1]. Only automatic derivation based on rules allows large-scale procedural modeling [17].

Urban spaces in the city lacking geographic information are subjected to a generative road modeling process, this process consists of producing a road network, subdividing the blocks extracted from the road network into lots, and generating a building inside each lot that closely follows previously created positioning, direction and elevation data, connects road ends to each other, and generates new streets on top of the DTM. The attributes of this integration are interpreted by the CGA rules file and a visualization process is performed.

In order to process the corresponding graphical transformation towards a high LoD road model, we introduce a CGA rule, which evaluates the parameters of the street network from step 1 and applies pre-established geometry and texture parameters. The CGA rules file is divided into individual functions to be able to interpret the attributes of each polygon and extrude based on the height of the parcel.

3 3DCM Generation of a small neighborhood in Bogota: A Case Study

In this section we use the workflow of Section 2 to obtain a 3DCM generated from CGA rules of a small spot in Bogota (Figure 4) that contains several urban elements such as house, buildings, parks or roads, among others. The Colombian city of Bogota has been chosen for the example case study. This city is the largest in Colombia, with a census of 7,7743,955 inhabitants in 2021 and an area of 1,775 km^2. Despite its large size in population and extension, there are no high-capacity roads to communicate the different locations of this metropolis. This case study will focus on a small area of Bogota and through the workflow described in Section 2, the impact of converting part of the city's current roads into highways will be analyzed.

The mapping from GIS data to other formats is not an exact science [17], during the data capture phase it is possible to resort to several sources and technologies (aerial, vertical and oblique photos, video, high resolution satellite images, laser scanners, airborne sensors with automatic detection of objects and heights, etc.). The proposed workflow uses the GIS Open Street Maps as a tool for capturing urban data on the city of Bogota, specifically between Chapinero and Los Cerros, as evidenced in Figure 4.

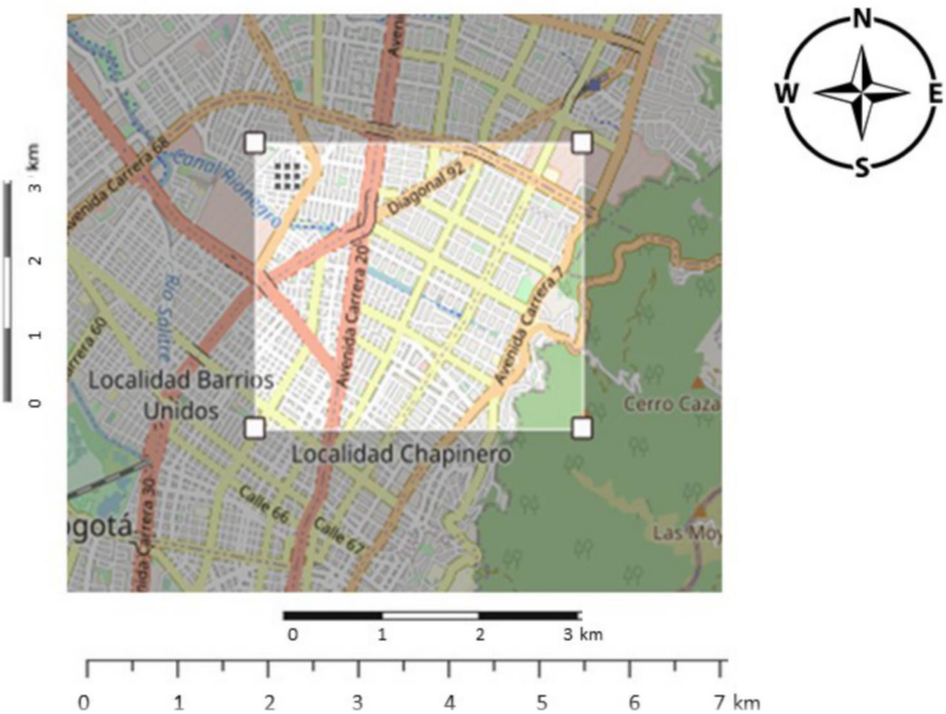

Figure 3 Capture of urban data of the city of Bogota using GIS Open Street Maps.

The raster data set presented in Figure 1 is processed and generated as a digital elevation model in DTM and DSM format. The DTM is the basis for all 3D building modeling operations, while the DSM is used as the basis for the road network [21]. The DTM and DSM used is a conventional 2D GIS dataset stored in an ESRI file geodatabase derived from a CAD drawing of the area and the attributes of geographic features [15].

ESRI Maps is focused on providing general-purpose basemaps and reference layers, such as imagery, streets, topography, boundaries, and demographics that can be used in a wide variety of applications. Thus, the modeling process was carried out using ESRI software, CityEngine 2020.0, which allows importing and displaying GIS spatial data with ease. This software has a script editor and can generate objects in massive quantities using Shape Grammar Rules [22]. They were programmed in the CGA language, and were implemented on the subdivided cadastral lots to further refine the geometry and to generate new building objects. Programmed rules applied on the cadastral lots included land use building reference, stochastic lot omission, land suitability maps, and building object visualization

To create a plausible street model, the DTM and DSM are integrated with the 2D model of the streets of Bogota in a CityEngine edit scene. Figure 5.A shows the terrain before integration of the GIS dataset with the DTM, and DSM captured from the delimited area in Figure 4. The highways modeling uses as input a set of 2D vector parcels that are loaded into CityEngine and aligned with the terrain.

The 2D street model shown in Figure 5.B is already aligned with the terrain. Initially, the extrusion of urban installations produces a basic result. Therefore, it is necessary to apply CGA rules on the lots to produce a higher LoD and generate a complete urban model with a plausible street network and high-quality buildings. The CGA rules file is divided into individual functions to interpret the attributes of each polygon and extrude according to its height as seen in Figure 5.C.

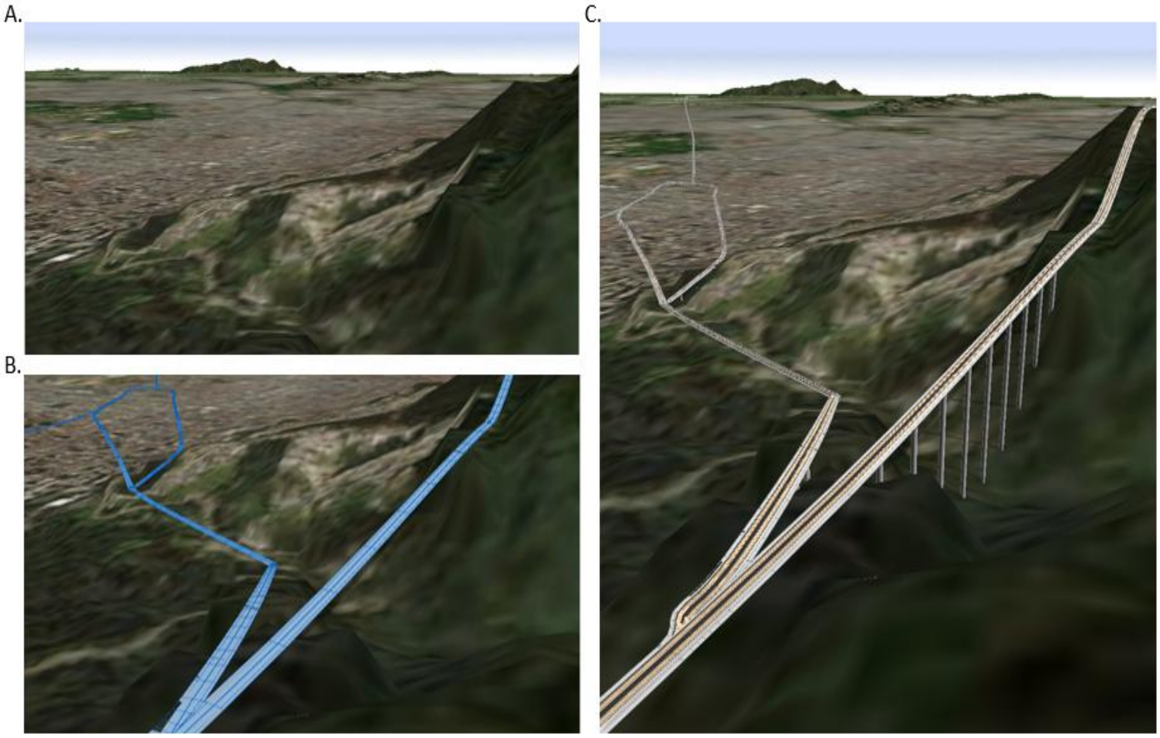

Figure 4. A) DTM and DSM of Bogota, B) Integration between Road , DTM and DSM of Bogota, C) Highway generated by CGA.

A simple extrusion on the footprints that have cadastral information of the buildings generates basic geometric structures that are seen in figure 6.A. In order to change the visualization style from solid color to realistic with facade textures according to the city, the "medium_city_style" building style is chosen as seen in figure 6B.

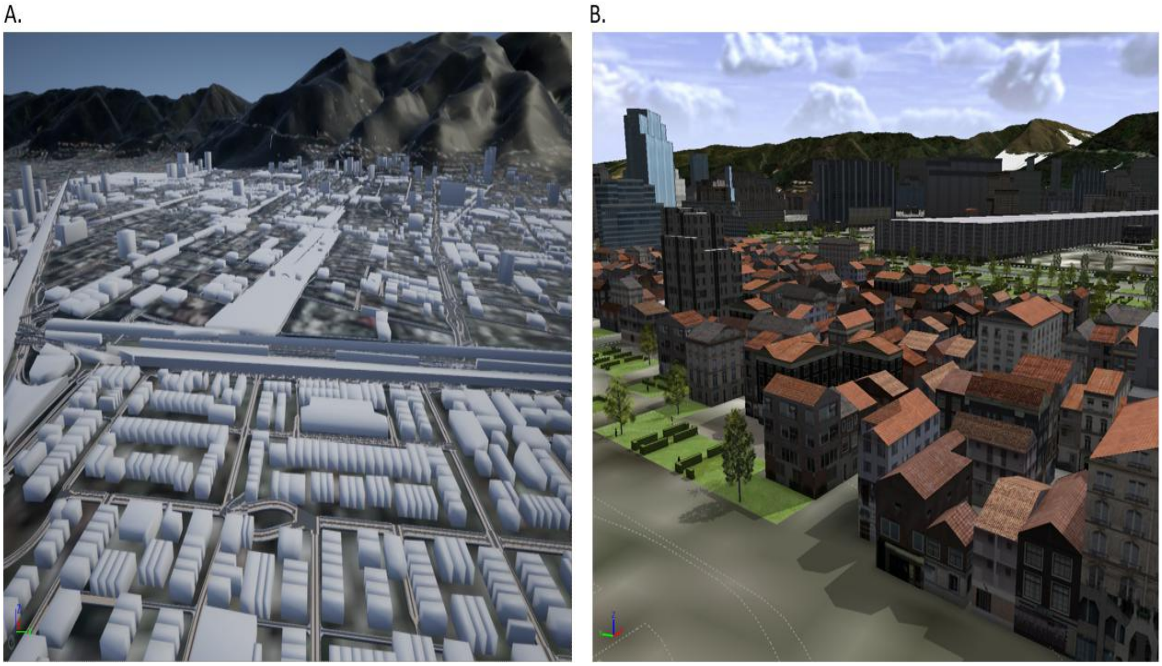

Figure 5 A) Basic shapes extruded from Footprints, B) Low resolution 3DCM of Bogota.

By introducing procedural modeling rules into building footprints, models are converted into shapes. The images are then taken from the internal repository for facade modeling. Generic facade textures can be obtained from a shared folder for all buildings. On the other hand, special facade designs can be stored in unique building-specific folders. With this method, a building can be faithfully recreated in minutes, as long as the base rule contains the facade that reflects the building's structure. In this way, it is possible to make a comparison between the different visual perspectives of a specific area during the different steps shown in this work, as seen in Figure 7.

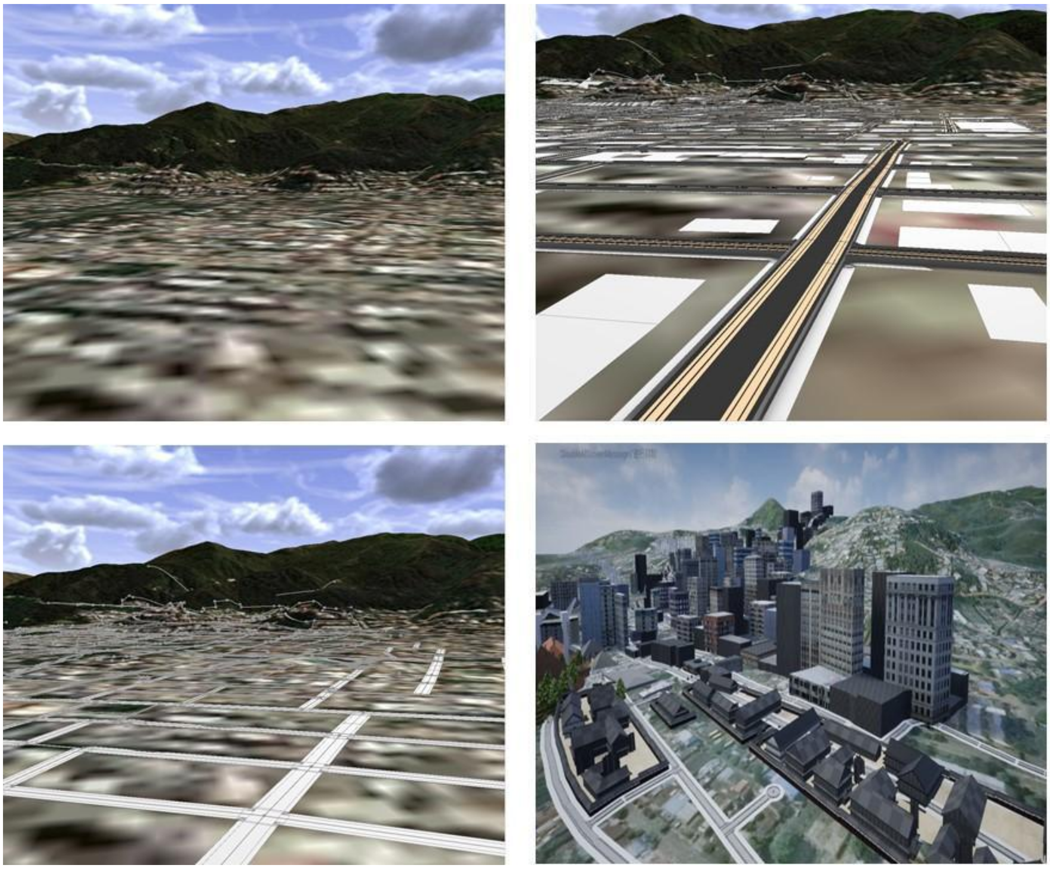

Figure 6. Comparison of the Bogota 3DCM from the first to the last step proposed by the workflow.

Providing detailed building models is very important for applications involving spatial analysis and realistic visualization. Current graphics processing hardware includes several useful functions that allow selective removal of occlusions. This also includes the selective removal of occlusions at the pixel level which can avoid costly shading operations [17]. Texture rendering techniques are applied to the resulting model to enhance the facade style and shadow effects on adjacent buildings and the ground as can be observed in Figure 8.

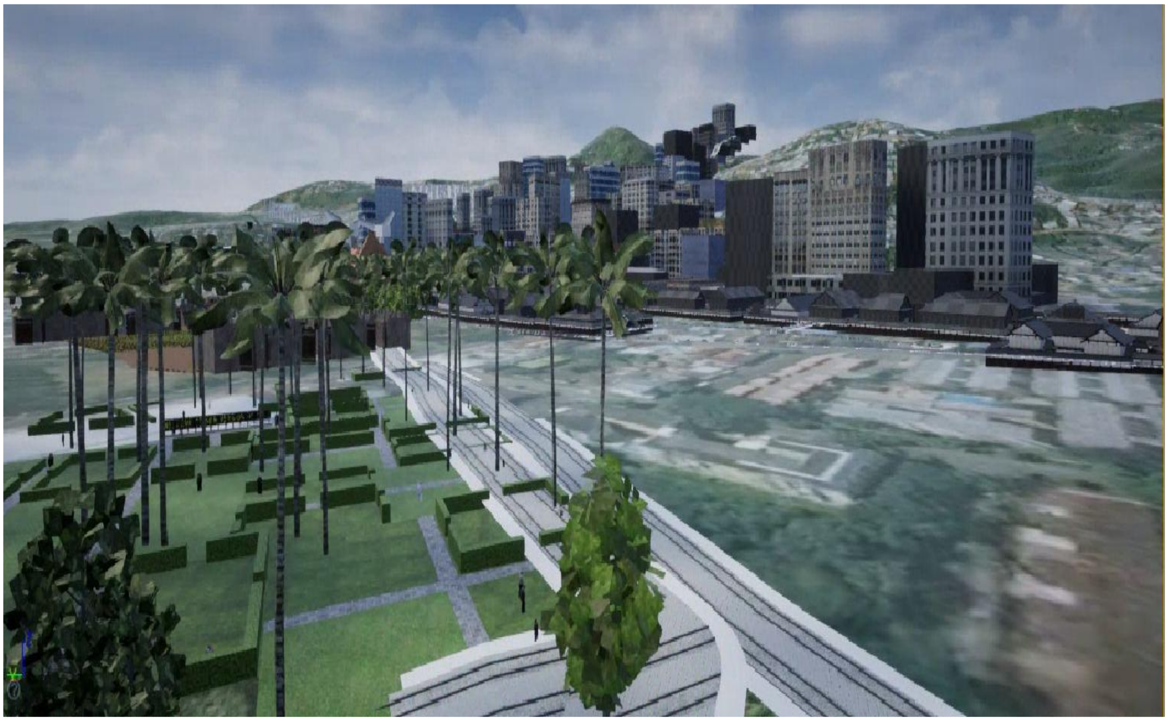

Figure 7. Final Bogota neighborhood 3DCM generated using CGA rules after the application of render engines.

The generated 3DCM allows one to visualize the effects of the implementation of a highway system in the city of Bogota. This model is more complete than the original one and serves as a basis for simulating urban planning projects and evaluating their consequences. Some practical applications can be the modeling of floods, traffic, energy consumption, water supply and disposal, air pollution, noise and environmental quality [20]. Thus, this particular result could be used to assess the visual impact of a highway infrastructure, or the impact on traffic patterns and urban mobility.

The street network deployed on the final 3DCM has a highway network instead of a simple road. The area covered by the road network and the number of footprints has increased due to generative modeling on empty zones. These areas are notably higher in density and have a color equalization process that improves the shadow and occlusion effects of the 3DCM.

4 Conclusions

This paper presents a workflow that integrates GIS data and new procedural modeling techniques to generate a 3DCM. The workflow is also designed to allow the modification of different elements in such a way that new applications can be created. The goal is that it can be used as a tool for urban planning activities and be implemented in any urban environment. This work will also lay the foundations for the development of tools that automatically produce CGA rules from the extraction of GIS data. There are currently no methods available for automatic GIS data capture that can serve as a geodatabase for 3D modeling.

In order to validate the workflow, we have presented a case study showing that it is capable of reconstructing a highway network, as well as different classes of buildings in a short time, resulting in a 3DCM base that can be used for planning projects and urban simulation.

The models for visualization and navigation of the environment have been perfected with the development of new 3D modeling techniques. On the other hand, the exploration and spatial analysis of data has had a notable development within GIS technology.

3DCMs are essential in planning tasks that use geographic information [22]. However, the integration of GIS and 3D urban models is in many of its phases in a conceptual state and although their application has already been verified, further evolution of them is still required.

Procedural modeling can use a 2D GIS layer to extrude large-scale urban facilities without the need for site-by-site modeling. This reduces the time required to develop 3D models of urban environments. Our approach uses procedural modeling techniques to automate the generation of complex urban structures, including buildings and houses from a set of GIS data and procedural rules.

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