Procedural modeling applied to the 3D city model of Bogota: A case study

Gustavo ALOMÍA, Diego LOAIZA, Claudia ZÚÑIGA, Xun LUO, Rafael ASOREY-CACHEDA

1. Department of Engineering, Universidad Santiago de Cali, CO 760001, Colombia
2. Department of Engineering, Tianjin University of Technology, Tianjin 300384, China
3. Department of Information & Communications Technologies, Universidad Politécnica de Cartagena, ES 30202, Spain

* Corresponding author, gustavo.alomia00@usc.edu.co
Received: 28 March 2021 Accepted: 20 June 2021


Citation: Gustavo ALOMÍA, Diego LOAIZA, Claudia ZÚÑIGA, Xun LUO, Rafael ASOREY-CACHEDA. Procedural modeling applied to the 3D city model of Bogota: A case study. Virtual Reality & Intelligent Hardware, 2021, 3(5): 423—433 DOI: 10.1016/j.vrih.2021.06.002

Abstract

Background

Computer Generated Animations (CGA), when applied to three-dimensional (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 structures. This leads to a new paradigm that allows the integration of known urban structures and urban infrastructure. This allows us to perceive the environmental impact of certain decisions 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, and other city activities.

Methods

This paper introduces a new workflow for the development of high-quality approximations of urban models in a short time and enables facilities to be imported from other cities into a given city model, following specific generation rules.

Results

Thus, this workflow provides a very simple approach to observe, study, and simulate the implementation of models already developed in other cities, in a city where they are not yet adopted. Examples of these models include all types of mobility systems and urban infrastructure.

Conclusions

This allows us to perceive the environmental impact of certain decisions 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, and other city activities.

Keywords

Computer Generated Animations; Geographical information system; Urban planning; 3D City Modeling

1 Introduction

This paper presents a new workflow for the development of high-quality approximations of urban models in a short time. Using Computer Generated Animations (CGA) rules, a compact, efficient, and reusable procedural representation of a polygonal three-dimensional (3D) architectural model was 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 a
case study of an urban area that is 5km long and 4km wide in Bogota. The goal of study is to generate an approximated three-dimensional city models of the target area (a 3DCM is a computer model of a city) and add a new highway, substituting one of the main roads. In this study, 2D GIS data were used to generate a set of 3D urban installations. To this end, approximately 20000 3D models, referring to urban facilities such as roads, houses, trees, and green areas, were extruded using procedural modeling in less than 3min. The final result shows a high-definition 3DCM, which has a new highway network and urban structure set deployed on an originally empty terrain, which can be used as a basis for simulation projects and urban planning. This avoids the laborious manual task of modeling 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 of great importance in the decision-making process for urban problems. The implementation of 3DCM, in areas related to urban planning (decision-making processes, analysis of city characteristics, architectural and urban design, visualization, etc.), has increased rapidly 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 geographic information that refers to real-world urban facilities, roads, land use, altitudes, and more.

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 using a three-dimensional model of the terrain. Urban spaces in cities lacking geographic information are subjected to a generative road modeling process. The process closely follows the previously created positioning, direction, and elevation data, and roads are connected end to end. New streets are generated on the DTM.

The 3D visualization improves the mental image, thus aiding the work of urban planners that traditionally work with 2D data, by representing three-dimensional data by means of text. Currently, the development of 3D models and their data structure is at the conceptual stage. Thus, its applicability in solving problems in urban areas requires further exploration.

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.

Urban spaces 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 the urban facilities. 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 fit existing datasets, according to specific rules.

Procedural urban modeling techniques have the same expressive power and precision as other traditional techniques, with the added convenience of manipulation. This follows the basic principle of 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, helping to adjust and improve the process. In some approaches, this is achieved through the inference of rules and parameters that allow the generation of larger and more complex environments. Two groups of agents are addressed in most of these approaches, namely vehicles and crowds, and some simulation models contemplate the interaction between them.
The interaction of vehicles and pedestrians with different types of roads simulated in 3DCMs can be quite relevant to the overall robustness of the model. For example, the work in [8] addressed 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 crowd flow and is tested with CityEngine. In addition, the layout of an urban environment can be designed according to the 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\(^9\).

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 by [10]. The approach detailed in [11] introduces a parameterizable continuum model to simulate the behavior of individuals in a crowd during an evacuation scenario.

The approach in [12] considers geographical discontinuities in 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 3DCMs. A 3DCM built using the same approach provided by [12] could enable more efficient use of sustainable transportation systems\(^{13}\), a better method of planning evacuation routes for emergencies\(^{14}\), and a more efficient planning of routes for freight vehicles\(^{15}\).

The main contribution of this study is the development of a new workflow for generating 3D models from a two-dimensional representation of urban data. As a result, this tool can aid decision-making for urban planning and provide support to the control and evaluation of this type of process. Moreover, this workflow is the first step for the integration of parameterizable crowd and traffic simulation models, whose interaction with the 3DCM can be controlled in some manner. 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 yet exist.

The remainder of this paper is organized as follows. Section 2 introduces the 3DCM generation workflow and describes its main elements. To generate the 3DCM, procedural modeling was integrated with data from the GIS. Section 3 presents the results of 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 the article.

## 2 Workflow for 3DCM generation

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

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

The first step in the workflow is *data capture*. During this stage, the focus is on providing general-
purpose base maps and reference layers, such as imagery, streets, topography, and boundaries, which serve as the basis for the modeling process. Owing to their compatibility with geospatial datasets, urban models are produced in regular grids called parcels\(^1\). Each parcel contains GIS data regarding the use of the area and the overlay controls for the adjacent plots, as shown 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\(^2\). Consequently, during this first step, GIS cadastral data were captured. These data are 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 the custom terrain positions.

Captured cadastral data represent geographically located features such 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 too narrow to be polygons, such as rivers, roads, or pipelines. Points are used for objects that are too small to be polygons, such as cities, schools, houses, or fire hydrants\(^3\). Thus, the geometry of the 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, and number of floors, as shown in Figure 2.

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 relatively quickly, with minimal labor\(^4\). The proposed 3D modeling process uses ESRI maps from CityEngine Software, which captures the raster data from the DTM and digital surface model (DSM) and

---

**Figure 1** Proposed workflow for 3DCM generation.

**Figure 2** Footprint layer structure.
integrates it with the GIS data output from step 1.

The geometric shapes were aligned with the DTM. However, owing to the lack of GIS data associated with specific areas, a generative modeling process is executed to enlarge the road network and add new footprints to the areas of the DTM that do not contain urban information\(^\text{[18]}\). This process determines whether the evaluated area has the required number of footprints. If necessary, generative modeling is initiated. 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 a 2D footprint. This technique defines 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 a structure will be created.

The third step is *the integration of the 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, and wall material type 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 such as 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 obtained 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 the 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 follows: *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.; and *Facade*, which 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 was the *Render* step. After extruding the 2D footprint using the CGA rule, the building style was determined. This changes the visualization style from solid to realistic with facade textures. Consequently, the created urban installations and the terrain are integrated as a single object, and 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\(^\text{[18]}\). The large-scale generation of 3D models of urban facilities involves multilevel modeling and multi-representation of the city model\(^\text{[19]}\). Automatic derivation based on rules allows for large-scale procedural modeling\(^\text{[19]}\).

Urban spaces in a city lacking geographic information are subjected to a generative road modeling
process, which 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, connecting road ends to each other, and generating 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.

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 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 that contains several urban elements such as houses, buildings, parks, and roads, among others. The Colombian city of Bogota was chosen as an example case study. This city is the largest in Colombia, with a census of 7,774,3955 inhabitants in 2021 and an area of 1,775 km². Despite its large size, in terms of population and extension, there are no high-capacity roads to connect the different locations within 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.

Mapping from GIS data to other formats is not an exact science [20], and 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 shown in Figure 3.

The raster data set, presented in Figure 1, was processed and generated as a digital elevation model in the DTM and DSM formats. 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 are focused on providing general-purpose basemaps and reference layers, such as imagery, streets, topography, boundaries, and demographics, which can be used in a wide variety of applications. Thus, the modeling process was carried out using ESRI software, CityEngine 2020.0, which enables GIS spatial data to be imported and displayed 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 subdivided cadastral lots to further refine the geometry and generate new
building objects. Programmed rules applied to 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 were integrated with the 2D model of the streets of Bogota in a CityEngine edit scene. Figure 4a shows the terrain before integration of the GIS dataset with the DTM and DSM, captured from the delimited area in Figure 3. The highway modeling process uses a set of 2D vector parcels as input that are then loaded into CityEngine and aligned with the terrain. The 2D street model, shown in Figure 4b, was aligned with the terrain. Initially, the extrusion of urban installations produced 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 shown in Figure 4c.

A simple extrusion on the footprints with cadastral information of the buildings generates basic geometric structures, as shown in Figure 5a. In order to change the visualization style from solid color to look more realistic, i.e., with facade textures according to the city, the "medium_city_style" building style is chosen, as shown in Figure 5b.

By introducing procedural modeling rules into building footprints, the models were converted into shapes. The images were then taken from the internal repository for facade modeling. Generic facade textures can be obtained from a shared folder for all buildings. In contrast, 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 façade that reflects the building's structure. In this manner, it is possible to make a comparison between the different visual perspectives of a specific area during the different stages discussed in this work, as shown in Figure 6.

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 the selective removal of occlusions. This also includes the selective removal of occlusions at the pixel level, which can avoid costly shading operations [18]. Texture rendering techniques are applied to the
resulting model to enhance the facade style and shadow effects on adjacent buildings and the ground, as shown in Figure 7.

The generated 3DCM enables the impact of the addition of a highway system in the city of Bogota to be visualized. This model is more complete than the original model and serves as a basis for simulating urban planning projects and evaluating their consequences. Some practical applications include the modeling of floods, traffic, energy consumption, water supply and disposal, air pollution, noise, and environmental quality. Thus, this particular result could be used to assess the visual impact of a highway infrastructure or its 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 because of the generative modeling of empty zones. These areas are notably higher in density and have a color equalization process that improves the shadow and occlusion effects of 3DCM.
4 Conclusion

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 to use it as a tool for urban planning activities and for be applicable for use in any urban environment. This work will also lay the foundation for the development of tools that automatically produce CGA rules from the extraction of GIS data. Currently, there are no methods available for automatic GIS data capture that can serve as a geodatabase for 3D modeling.

To validate the workflow, we 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. However, the exploration and spatial analysis of data has led to notable developments in GIS technology.

3DCMs are essential for planning tasks that use geographic information[22]. However, the integration of GIS and 3D urban models is currently 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.

Declaration of competing interest
We declare that we have no conflict of interest.

References

DOI:10.1051/3u3d/201202006


18 Turksever S. 3D modeling with city engine. 2015
DOI:10.13140/RG.2.2.30548.30085.

DOI:10.1016/j.foar.2020.09.001

DOI:10.1111/j.1467-8659.2009.01535.x
