Urban simulation in open CityGML models: application to the maximum height of buildings in Lisbon

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September 2020

Abstract

Cities are increasingly being represented by 3D semantic city models in different application areas. Sharing common elements between applications encourages the creation of a global model. CityGML promotes interoperability between systems and is both a free and open model.

This work intends to contribute to a better understanding of the creation and application of 3D semantic city models in order to answer practical challenges. In this sense, a 3D semantic city model of part of Lisbon was created for the simulation of the evolution of the height of buildings in the long term, considering the urban regulations in force. A tool was developed to map the regulations on the maximum height allowed in a building and to carry out simulations allowing the user to choose a subset of the rules to be simulated.

The dissertation systematizes a way for data processing and provides a methodology for the creation of 3D semantic city models, as well as its use in the study of urban planning. The results obtained, for the chosen problem, allow to identify which buildings have the greatest growth potential and to perceive the influence that the mapped rules cause in the expansion or reconstruction of the buildings. This simulation can be useful both from the perspective of public administration planning technicians and private promoters.

Keywords: 3D Semantic city model; CityGML; Simulation; Maximum height

1. Introduction

Traditionally, city planners resort to two-dimensional representations (2D) and physical models (3D) to reproduce reality, but technological developments, both in terms of visualization and in terms of the manipulation of georeferenced information, have leveraged the development of new complementary approaches using interactive virtual three-dimensional representations. In this regard, cities are increasingly being represented by 3D semantic city models (Kolbe et al., 2005 [13]). This new representation adds a semantic component to the elements of three-dimensional representations and, thus, allows improvements in decision making in applications such as, for example, the propagation of noise in the surrounding area of a road axis, taking into account the acoustic properties of the cladding of the facades of buildings, or the estimate of sun exposure on the roof of a building, considering the shadow created by the surrounding buildings, with the objective of evaluating whether it is economically viable to install a solar panel, or even, the visibility analysis that allows to identify the strategic locations, for example to place advertising signs or plan the installation of security cameras in order to maximize the registered area, among others (Biljecki, 2017 [2]).

As more models are developed for different application areas, it is more justified to share the elements that are common between application areas, thus, the need arises for a global model capable of mapping these semantic 3D city models. CityGML could be the answer to this need as it is a free and open model, allowing its users not to be dependent on a particular supplier and, simultaneously, this format works as a lingua franca between users promoting the interoperability of systems (Tolmer et al., 2013 [19]).

The territorial characterization studies, carried out during the Lisbon MMP [1] review process, ([14], p.27), "confirmed the importance and interest in urban rehabilitation, as an instrument to attract new inhabitants to the city, as far as in which more than 50% of the new residents of Lisbon came to live in buildings over 30 years old". This shows a pref-

[1] Municipal Master Plan

erence for buildings in the center of Lisbon as an alternative to the continuous growth of metropolitan peripheries.

According to Biljecki [2] in densely populated urban areas, promoters explore the limits of the current regulations regarding the size of the building, so it is reasonable to assume that the height of new buildings or, in the case of ampliations, these correspond to the maximum limit allowed. This was the motivation for the chosen application case.

1.1. Objectives

The general objective of this work is to contribute to a better understanding of the creation and application of 3D semantic city models in order to answer practical challenges in a context of urbanism. To achieve this, the use of free and open source software is privileged, both in the creation of a database and in all other tools that support the operation.

Thus, the design of the database model is aligned with the practical challenge, in this sense the analysis will be directed in order to create a model based on CityGML that can guarantee an applicability to various problems in the area of urbanism, and at the same time to be replicable in any city.

To this end, as a specific application of the general objective it is proposed to use a 3D semantic city model of part of the city of Lisbon to simulate the evolution of the height of buildings in the long term taking into account the legislation and urban regulations in force.

This report may benefit the producers of urban regulation and those responsible for urban planning, in the sense of providing a methodology for creating a model that simulates the results of the current regulation, as well as the tools for potential changes. In addition, the real estate promotion and management sector may use the same simulation in order to assess which buildings have the greatest growth potential.

2. Background

2.1. 3D Semantic city model

A city model is an abstraction of a part of the real world that encompasses urban entities and the global urban environment in which it is located. Each entity in the model corresponds to an urban characteristic of the real world (Billen et al., 2014 [4]). These virtual city models generally consist of digital terrain models, buildings, vegetation, streets and other infrastructure, which can be represented through geographic information systems, GIS (Dollner et al., 2006 [6]). The visualization of a 3D city model helps to create a better mental image of the proposed buildings and their relationship with other nearby objects, for example the shadows caused in other buildings (Herbert & Chen, 2015 [10]), alternatively, 2D models make it difficult interpretation to people without technical training. Therefore 3D models are a better communication tool. The requirements of 3D city models vary between different applications: in areas such as tourism, entertainment, a high degree of photorealism is required; in applications with an analytical aspect, the representation of these models serves as a means to transmit thematic information with a geographical context (Dollner et al., 2006 [6]).

To the 3D city models it is possible to add certain characteristics or properties of objects, thus creating a 3D semantic city model, this is a three-dimensional representation of the city that also includes thematic characteristics, such as type of soil, material or year of construction. In this way, it is possible to associate, at the level of objects, properties that are relevant to the model. These models allow a better understanding of the data, being particularly useful in contexts of simulation and decision making.

The semantic modeling of cities requires a phase of insertion and maintenance of information in the model, the process being generally manual, and in some cases it can be automated. This phase requires a high consumption of resources, so it is advantageous that the same data is used in several applications with different study areas. Thus, from the point of view of the overall cost of the project, it is beneficial to use a central repository instead of building and validating several independent models, however, this option would require finding a comprehensive model that could serve several different applications, which it can always be achieved (Kolbe, 2009 [11]).

3D semantic city models should be represented in a free and open format. By free we mean that a user can use without monetary costs and open that has access to the complete syntactic structure and its meaning. The added value of free and open models is that it does not cause dependence on a particular supplier and at the same time works as a lingua franca among users, promoting the interoperability of systems.

The CityGML and IFC (Industry Foundation Classes) model formats are both considered reference for mapping semantic 3D models (El-Mekawy et al., 2012 [7]).Both CityGML and IFC are free and open but are limited in that there is no solution for all applications, IFC takes a building-oriented approach, while CityGML seeks to be a solution on a smaller scale, typically at city level (Tolmer et al., 2013 [20]). Thus, the use of the CityGML format was privileged.

CityGML is used to store and exchange 3D semantic city models and works both as an information model and a data format, it is an application scheme of GML, Geography Markup Language, (OGC, 2012 [8]). CityGML aims to a common definition of the basic concepts in a model so that it can be a central aggregator of information (in a relational way) so that applications from different areas can couple their specific attributes to the main structure of CityGML.

The objects in the CityGML model can be represented in five levels of detail (LODs) (see Fig. 1), from level 0 to 4, with LOD0 being the lowest level. The higher levels are more accurate and have a greater structural complexity than the lower levels. According to Groger & Plumer ([9]) the existence of LOD facilitates integration and interoperability tasks between import and export tools.

Figure 1: Levels of detail, source Biljecki [2]

There are some tools that allow you to create the CityGML structure in the form of a database. However, there is still no tool regularly followed. This is not a problem specific to Portugal, in Finland different municipalities face the same problem (Jokela, 2016 [12]). The availability of several formats leads to interoperability problems for the entities responsible for the development of models (Santos, 2016 [18]). The introduction of new tools is expected to make the process simpler.

One of the problems associated with the theme of city modeling is the difficulty of interoperability between systems. In addition to CityGML, the use of database systems, which support interoperability between applications and people, has already been proposed by other authors (Preka & Doulamis, 2016 [15]). Following this guidance, this work proposes the procedures from the creation of a model in SketchUp, to its representation in a CityGML / 3DCityDB database, implemented in the PostgreSQL / PostGIS database system.

3DCityDB is an open source tool that allows you to build a database schema that follows the rules of CityGML. The project started in 2003 led by Thomas Kolbe and since then the developments continue to be in charge of a partnership between several organizations. This tool also incorporates functionality for importing, maintaining, analyzing, visualizing and exporting 3D semantic city models. The 3DCityDB (Fig.2) allows creating the data structure (schema) of the CityGML model in two systems of spatial and relational databases: Oracle with the spatial license and PostgreSQL. In the first there are versions with free use licenses, namely Oracle 10G R2, in the second case, it is an open source tool.

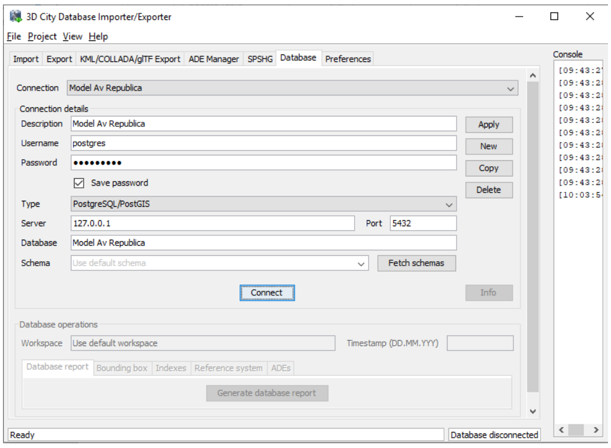

Figure 2: 3DCityDB, database configuration window

Tab.1 presents the characteristics of some tables referred in the 3DCityDB relational schema. Briefly, the spatial data that are imported are stored in the surface geometry table and the remaining tables allow to associate the semantic information of the model.

3D semantic city models have been used in the past mainly for the visualization of urban buildings. Currently, these models are created with objectives beyond visualization, that is, they are also used to perform analyzes and simulations (Ohori et al., 2018 [1]). The projects carried out have not been limited to just one study area, in fact, one can verify works carried out in several cities in areas as diverse as: urban planning, telecommunications, logistics, estimate of sun exposure, noise level calculation, and assisted navigation, etc. All of these models modified additional information about city objects in a standardized way. On the work of Biljecki et al. (2015 [3]) several applications are presented and identified the advantages of using a 3D semantic city model.

2.2. Urban legislation and regulation

With regard to the use of software, the portuguese government has been intending to opt for a strategy that uses free and open source software([17] [16]).

As the urbanization process evolves, the need to legislate and regulate this operation arose. The approval of the "*Regulamento Geral das Edificações Urbanas*" (RGEU) sets the rules, at a national level, applicable to the execution of new buildings or any civil construction works, reconstruction, expansion,

Table 1: 3DCityDB description tables

Table	Description
CityObject	It is part of the base class of CityGML, identifies the LOD to which the object is integrated and is where information about the creation and modification of the object can be stored.
External Reference	It is used to store the external reference of the object at the time of its import. From this field, CityObject can be identified in the original GML file.
Building	Keeps information related to the building concept, allows specific building information such as the year of construction or number of floors (below and above ground) to be saved. It allows to relate grouping surfaces through a common identifier "building root id", for example, in the case of two structures, annex and the main building, they can have the same common identifier.
Surface Geometry	Each building consists of several surfaces (base, roof and facades), this table stores the surfaces imported into the database.
CityObject Genericat-trib	It is used to represent the concept of a generic attribute. Through this table, semantic information can be introduced to better classify the model.
Address to Building	Connection table between Building and Address.
Address	Saves the building address.

alteration, repair or demolition of existing buildings and works. At the municipal level, the "Municipal Master Plan", "Urbanization Plan" and "Detail Plan" (MMP, UP and DP) are the documents that provide indexes and parameters that serve as a basis for building planning.

3. Development and Implementation

3.1. Methodology

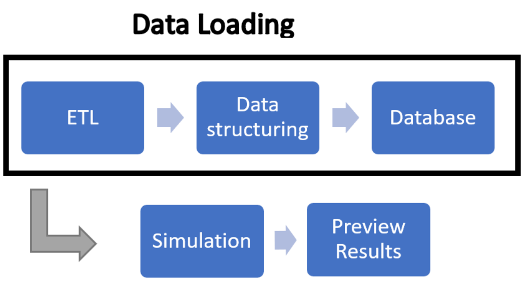

Figure 3: Desagregation of the general method in 5 stages

Fig. 3 identifies a generalized method of the phases that can be followed to construct a database model. The first phase of the process comprises the extraction, transformation and loading of data (ETL), possibly from different sources to a common repository. The next step is to insert data in a formal structure that allows data to be stored and exchanged with other entities. The "database" phase consists of importing the records into a database with the structure and relationships determined in the previous phases. The "Simulation" stage is the most generic of the process, with the purpose of developing a customized tool in order to respond to the particular scope of the proposed analysis. Finally, the visualization of the simulation results.

3.2. Problem formalization

According to Biljecki (2017 [2]), for densely populated areas, urbanized space is scarce, as such, there is a tendency to push the limits of the regulations in force regarding the size of buildings. Thus, the height of new buildings tends to correspond to the maximum allowed limit. Taking into account the legislation in force, we can assess the following objective variable:

$$H_i^t = max\big(H_i^0; min(R_{ij}^t)\big) \tag{1}$$

The main result of the simulation is the variable H_i^t, height of a building i for an instant t. To measure this variable, it will be necessary to compare the initial height of building i, H_i^0, with the maximum height allowed for building i, taking into account j restrictions over time t, R_{ij}^t. Taking into account the articles on Lisbon MMP and the RGEU, Tab. 2 lists the restrictions that contribute to the definition of the height of the building.

3.3. Data schema

To carry out the simulation of the height of buildings, a fully customizable SQL tool was developed using the spatial capabilities of the PostGresSQL / PostGis database. The tool was developed within a new schema with the name "custom" so that it is

Table 2: Restrictions on the building height and yard dimensions

R_{ij}^t	Restriction	Article	Description
R_{i1}^t	R_Avg_Height	MMP - 42º, 4.a)	Average building height of the surrounding buildings.
R_{i2}^t	R_Neighbour_Height	MMP - 42º, 4.b)	The building can have the same height than an adjacent building.
R_{i3}^t	R_Distance_45	RGEU - 59º	Regulates the distance between the main façades of front buildings according to the respective heights.
R_{i4}^t	R_Distance_Back	RGEU - 62º	Regulates the building height by comparison with the backyard depth.
R_{i5}^t	R_SVP	MMP - 44º	Promote soil permeability.
R_{i6}^t	R_Classified_Building	MMP - 45º	Prevent expansion operations on a set of buildings.

clear the separation of the entities from the 3DCityDB tool. Fig.5 illustrates the "custom" relational scheme (signaled in green) and the way it integrates with the 3DCityDB model (signaled in blue). Table 3 describes the characteristics of the "custom" schema tables.

3.4. Data preparation

The buildings outline can be obtained by exporting a SketchUp file on Caddmapper (2013 [5]). Each yard has to be manually created and assigned to the building. To make the model 3D the height of the building could be obtained by GoogleEarth. When the information is missing, it has to be estimated. This estimation can be done by comparing with a neighboring building in which height is available. As a last resort, it can be estimated base on the number of floors.

The CityEditor (2016 [21]) extension allows to make a semantic characterization of the model, for that purpose, a survey was made of the buildings in the corner of the street and buildings not allowed to expand by local authorities. Since this is a manual process, it was decided to assign an address only to the streets, for buildings this field was not filled out.

3.5. Functions developed

In this dissertation, a custom tool was developed to calculate the building height (Eq. 1) based on the restrictions in Tab. 2. Due to the rules "R_Avg_Height" and "R_Neighbour_Height" the building maximum height is not a static value, that is, the expansion of a nearby building could influence the maximum height on the building under analysis. Therefore, the simulation process is iterative. The tool is flexible enough to make a simulation with all the restrictions applied or only a subset of them. The file "*custom functions.sql* " on `https://github.com/UrbanSimulCityGML/LisbonBuildingsMaxHeight` has the definition of all the 39 functions developed.

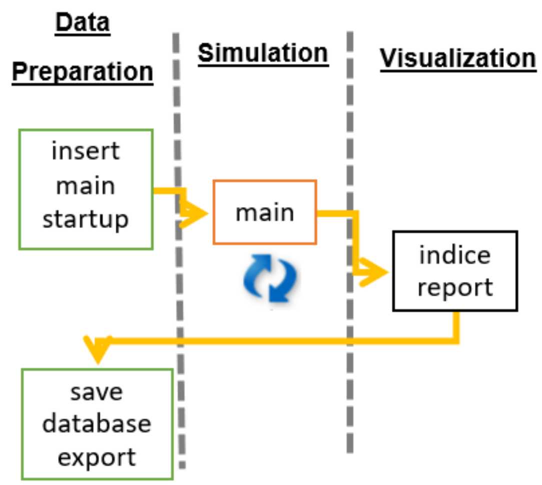

Figure 4: Functions directly performed by the user (1st level functions)

To make the tool simple, there is only four points of contact with the user (1st level functions, Fig. 4). First, check data quality and make all the calculation of the static information regarding the initial situation of the model ("*insert_main_startup*"). Next step is to perform the simulation ("*main*"). Right after, the view "*indice_report*" provides a way to visualize a dashboard with the simulation results. If needed, a different simulation can be ordered with new input parameters. Lastly, the function "*save_database_export*" materializes the results in the "*citydb*" schema, that is, it changes the dimension of the buildings from their initial height to the final height calculated during the simulation.

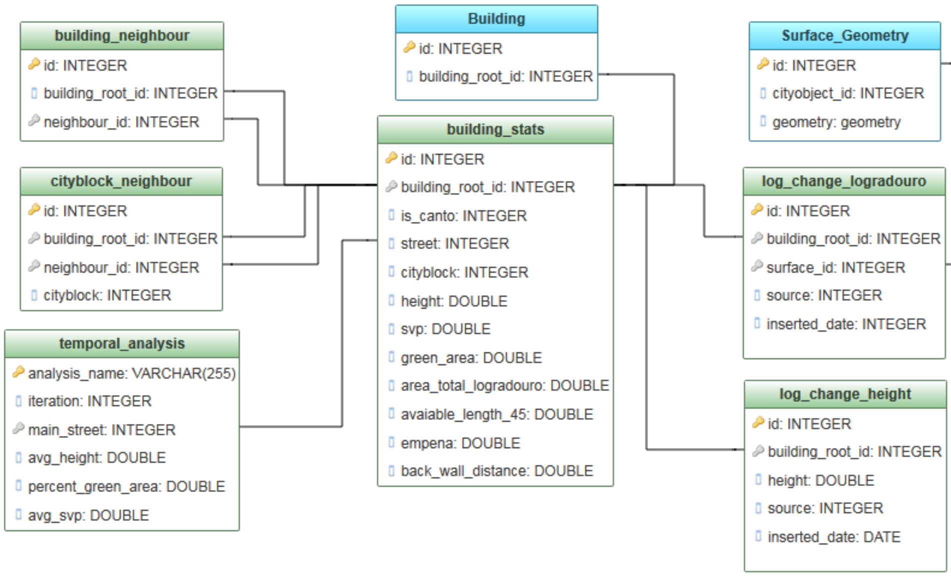

Figure 5: Developed "custom" scheme (green) integrates with 3DCityDB scheme (blue)

Table 3: "custom" description tables

Table	Description
Building Stats	This is the main application table, it is used to store static information about the building (street; block; height; SVP and Type A area, Article 44 of the Lisbon MMP; yard area ; avaiable distance according to the 45º rule, Article 59 of RGEU; gable; yard depth, Article 62 of RGEU).
Building Neighbour	Saves the pairs of buildings that are adjacent.
Cityblock Neighbour	Saves the pairs of buildings with adjacent lots.
Log Change Height	Records changes in the height of buildings during the simulation.
Log Change Yard	Records portions of yard that change from type C to type A soil, during the simulation.
Log Street Indicators	Records changes in height (average) and SVP (average) throughout the simulation. Information is made available from the perspective of the street.

4. Results

Tab. 4 list the simulations performed on a set of 241 buildings in the *Saldanha* area. As expected, adding restrictions limits the number of changes made.

Table 4: Simulations run

S_i	Description	No. changes
S_1	All restrictions	34
S_2	All except $R\_Classified\_Building$	55
S_3	Only R_Avg_Height	92
S_4	R_Avg_Height & $R\_Neighbour\_Height$	106

Unsurprisingly, the average height of the study area increases, from $23.8m$ to $24.9m$. This simulation resulted in 34 iterations spread over 33 buildings, that is, there is a building that was increased at two different stages (Tab. 5). It is at "Av. João XXI" that average building height boomed, also, on the same avenue is located the building with the most growth potential ($28m$). Overall, all streets have at least one building that increased and on average about 14% of the buildings have changed.

Fig. 6 allows to see the evolution of the buildings average height during the simulation. Each iteration corresponds to a building increase; it isn´t a temporal concept as the time between each change will certainly not be the same for all iterations.

Tab. 5 allows to compare some of the simulation results between simulations. Considering $S1$ as a

Table 5: Summary dashboard by simulation

Avenue	Height (m)					No. Buildings Changed				
	H_0	$S1$	$S2$	$S3$	$S4$	Initial	$S1$	$S2$	$S3$	$S4$
All	23.8	24.9	25.8	26.8	27.4	241	**33**	**53**	83	93
Av. 5 de Outubro	30.3	30.9	31.7	31.6	32.1	23	2	5	5	6
Av. Barbosa du Bocage	23.3	24.2	24.2	27.0	27.0	29	3	3	14	14
Av. João XXI	20.6	25.3	28.3	28.8	28.8	12	3	5	6	6
Av. da República	27.9	29.3	30.9	31.5	32.0	40	8	13	12	15
Av. Defensores de Chaves	21.6	21.8	22.0	23.1	23.3	26	1	2	4	5
Av. Duque de Avila	23.9	24.6	26.2	26.4	26.4	10	2	3	3	3
Av. Elias Garcia	24.5	25.3	25.7	27.1	27.3	31	6	9	15	15
Av. João Crisóstomo	19.5	20.2	20.2	**21.5**	**25.3**	22	2	2	**7**	**11**
Av. Miguel Bombarda	24.2	25.6	27.4	28.6	29.7	18	3	6	7	8
Av. Visconde de Valmor	19.3	20.3	21.0	21.9	21.9	30	3	5	10	10

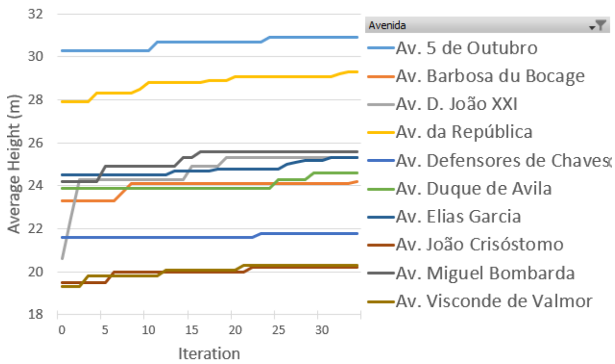

Figure 6: S1 simulation, perspective by iteration

base point, we find that in $S2$ on all streets the height of buildings either increased or remained unchanged. This is the expected behavior since at $S2$ we are removing a restriction, increasing the number of buildings available to make changes by 33 (number of buildings classified on the model, article 45 Lisbon MMP). Also this comparison concludes that the 20 buildings additionally altered $(53 - 33 = 20)$ are classified buildings, that is, according to the rules implemented in the model, 20 of the 33 buildings classified (67%) would be extended if this limitation didn´t prevented it.

When analyzing simulations $S3$ and $S4$, it is validated that on all streets the average height is higher than $S1$ since these simulations have fewer rules applied than $S1$. By comparing $S3$ with $S4$, one can quantify the impact that adding the $R\_Neighbour\_Height$ restriction has on the buildings under analysis. In total, another 10 buildings have a height extension, and *Av. João Crisóstomo* is the place with the most impact, an extension of 4 buildings causes the average height to increase $3.8m$ (from $21.5m$ to $25.3m$) .

During the simulation, the list of buildings with growth potential is compiled and the highest mark is chosen. This approach shortens the number of iterations because is the option thar most raises the threshold for the R_Avg_Height & $R\_Neighbour\_Height$ restrictions. An alternative would be in each iteration randomly select a building from the list. Taking that into account, a simulation with the same input parameters as S1 resulted in 3 more iterations and average building height remained slightly the same.

Fig. 7 is an aerial view of simulation S1. Blue (phase 1), green (phase 2), pink (phase 3) and red (phase 4) represents the fase in which the changed occurred.

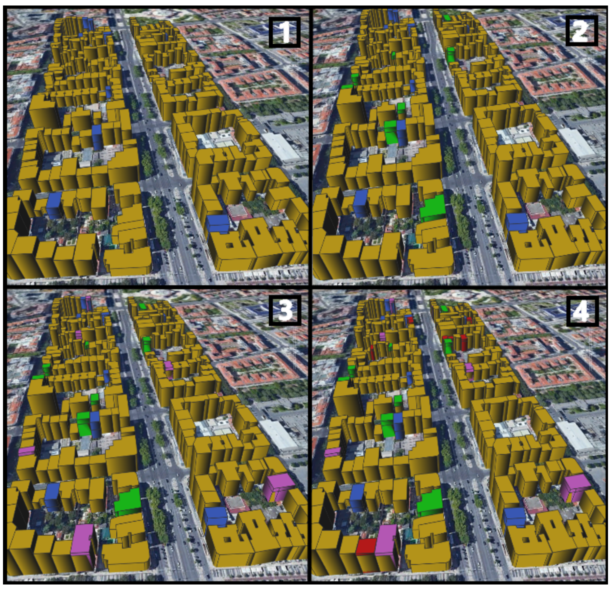

Figure 7: (S1) Aerial view over the case study, divided into 4 phases

5. Conclusions

This dissertation presents a study on the formulation of a 3D semantic city model, applied to the problem of simulating the maximum height of buildings using CityGML.

The methodology followed seeks to systematize the way in which problems arising from data processing can be addressed, regardless of the information technology used. It is also intended to guide on how to develop this type of model, so there was a particular attention to the possibility of being replicable in other contexts, providing a step-by-step description of the various model preparation and data entry procedures.

An important component of this dissertation was to develop a tool that is able to map the relevant points in terms of legislation and urban regulation at national and municipal level on the subject of the maximum height allowed in a building. For this mapping, the rules were implemented in articles 42, number 4 a) and b) ("R_Avg_Height" & "$R\_Neighbour\_Height$"), article 44 ("R_SVP") and 45 ("$R\_Classified\_Building$") of the Lisbon MMP; also articles 59 and 62 ("$R\_Distance\_45$" and "$R\_Distance\_Back$") from RGEU.

This tool aims to simplify the process of carrying out a simulation, in the sense that the referred rules were implemented as functionalities in the database, eliminating the requirement for the user to have programming knowledge. Thus, the tool should be an interface between the user and the simulation, in which all signaled restrictions or only a subset of them can be analyzed simultaneously. The built model is applicable to the city of Lisbon and is based on the assumption that there will continue to be a trend in the demand for housing in the city. As such, there is a tendency to exploit the permitted legal height limit as much as possible.

The simulation is an iterative process, in which, in each phase the growth potential of all buildings is analyzed and only one is selected to change. The growth potential is not constant, because the change in height of a certain building can influence the potential of another building. To select the building, the results of two different approaches were analyzed, the first consists of always selecting the building with the greatest potential, while the second approach randomly selects a building with growth potential. The first approach leads to a smaller number of iterations necessary for the simulation to end. In a long-term analysis, a priori there is no evidence that the first approach results in taller buildings.

5.1. Future work

One of the limitations of this dissertation comes from the need to obtain data so that simulations can be carried out in a larger study area, this is because, despite the developed model is able to respond to simulations with a larger amount of data, some of the data is collected and treated in a manual way which is not scalable. In terms of diversity, it would be interesting to obtain other urban indicators such as the year of construction of the building, the size of the lot, the type of building, classification regarding the predominant use, etc., which are not public or are difficult to access.

The incorporation of urban regulation from official sources was privileged. An alternative would be to propose and simulate new rules (either base on another country legislation or simply created by the user) in order to verify their impact on the data set. From the point of view of those responsible for urban planning, it would make it possible to understand and quantify the impact of altering or introducing a new measure. In this dissertation only the change in height of the building was simulated, it would also be interesting that a new building footprint is propose in light of the rules in force. In this work, the terrain morphology was not taken into account, however, it would be a point to include in order to study its influence on the presented rules.

Finally, the functions used were developed in SQL, this being a widely adopted and constantly evolving language, it would be important to optimize the components developed in order to improve its performance for larger data sets.

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