A DIGITAL BOTANICAL GARDEN: USING INTERACTIVE 3D MODELS FOR VISITOR EXPERIENCE ENHANCEMENT AND COLLECTION MANAGEMENT UN JARDÍN BOTÁNICO DIGITAL: UTILIZACIÓN DE MODE....

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A DIGITAL BOTANICAL GARDEN: USING INTERACTIVE 3D MODELS FOR VISITOR EXPERIENCE ENHANCEMENT AND COLLECTION MANAGEMENT

UN JARDÍN BOTÁNICO DIGITAL: UTILIZACIÓN DE MODELOS 3D INTERACTIVOS PARA MEJORAR LA EXPERIENCIA DEL VISITANTE Y LA GESTIÓN DE LAS COLECCIONES

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Highlights:

- A virtual 3D model of a botanical garden was built based on a GIS with plants botanical information and buildings, statues and other assets historical information.
- The height and crown diameter of individual trees were determined from watershed operations on aerial LiDAR data. Statues were modelled photogrammetrically. Buildings were modelled procedurally using CGA rules.
- Users found realism and information access to be the most positive points. The way of data organisation and the elaborated modelling rules make the product easily extendable for new data and objects.

Abstract:

Botanical gardens are important spots in urban spaces, both for researchers and for many different kinds of public. Conveying scientific information by means of an attractive digital product, on a pre- or post-visit experience, is a way of captivating the public, especially the younger generation, to the relevance of those gardens as repositories of knowledge and for conservation of plant species diversity. This approach also facilitates communication with the general public and access to historical data. On the other hand, bringing the garden to the desktop of researchers and managers can be an advantage, not only for an overview of the *status quo* but also in spatial planning matters. This paper describes the production of a 3D dynamic model of the Tropical Botanical Garden in Lisbon on top of a Geographic Information System (GIS). Its development included creating a spatial database to organise data originating from a variety of sources, the three-dimensional (3D) modelling of plants, buildings and statues, the creation of web pages with historic and contextual information, as well as the publication of a number of interactive 3D scenes. Several software packages were used, and the final outputs were published in ArcGIS Online to be explored by the public and researchers (link provided at the end of the text). The data are organised in a database, and most 3D modelling tasks are procedural through Computer Generated Architecture (CGA) rules. Thus, updating information or 3D models can be done without having to repeat all steps, an important feature for a dynamic botanical garden. Challenges and solutions are also addressed, providing a constructive contribution to the further implementation of similar experiences in other botanical gardens. According to a user survey carried out, the realism of the representation and the possibility of easily retrieving information from the objects are the most positive aspects of the project.

Keywords: virtual model; 3D Geographic Information System (GIS); LiDAR (Light Detection And Ranging); procedural modelling; CityEngine; trees 3D modelling

Resumen:

Los jardines botánicos son enclaves importantes en los espacios urbanos, tanto para los investigadores como para diferentes tipos de público. Transmitir la información científica mediante un producto digital atractivo, en una experiencia previa o posterior a la visita, es una forma de transmitir al público, especialmente a los más jóvenes, la relevancia de esos jardines como repositorios de conocimiento para la conservación de la diversidad de las especies vegetales. Este enfoque también facilita la comunicación con el público en general y el acceso a los datos históricos. Por otro lado, un acceso virtual del jardín tanto de los investigadores como de los gestores supondría una gran ventaja, no sólo para tener

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una visión global del estado actual, sino también para cuestiones referentes a la planificación territorial. El presente trabajo describe la producción de un modelo dinámico 3D del Jardín Botánico Tropical de Lisboa sobre un Sistema de Información Geográfica (SIG). Su desarrollo incorpora una base de datos espacial que organiza los datos procedentes de diversas fuentes, la modelización 3D de la vegetación, edificios y estatuas, páginas web con información histórica y contextual, así como la publicación de una serie de escenas interactivas en 3D. Para ello, se utilizaron varios programas informáticos y los resultados finales se publicaron en ArcGIS Online para que el público y los investigadores pudieran explorarlos (el enlace se proporciona al final del texto). Los datos se organizan en una base de datos y la mayoría de las tareas de modelado en 3D son procedimentales mediante reglas de '*Computer Generated Architecture*' (CGA). De este modo, la actualización de la información o de los modelos 3D puede realizarse sin tener que repetir todos los pasos, lo cual es importante para un jardín botánico dinámico. Con esta investigación se abordan retos y soluciones, contribuyendo de forma constructiva a la puesta en práctica de experiencias similares en otros jardines botánicos. Según una encuesta realizada a usuarios relacionados con los jardines botánicos, el realismo de la representación y la posibilidad de recuperar fácilmente la información de los objetos son los aspectos más positivos del proyecto.

Palabras clave: modelo virtual; Sistema de Información Geográfica (SIG) 3D; LiDAR; procedimiento de modelado; CityEngine; modelado 3D de árboles

1. Introduction

Botanical gardens are institutions that maintain properly documented collections of living plants, with research, conservation, exhibition, and education as key objectives (Wyse Jackson, 1999). Among the characteristics that should be present in a botanical garden, mention should be made of the existence of a scientific basis for the collections, proper labelling of plants, exchange of seeds or other materials with similar institutions, conducting research activities on the collections, and promoting conservation through outreach and environmental education activities (Smith & Harvey-Brown, 2017).

Botanical gardens play important roles in urban areas. In addition to the objectives previously listed, they provide a green and leisure environment for the citizens and are, nowadays, largely recognized by the urban ecosystem services they provide, such as microclimate and water regulation, pollution reduction and health effects, as well as providing shelter for spontaneous flora and fauna, increasing urban biodiversity (Maunder, Higgens, & Culham, 2001; Elmqvist et al., 2015).

According to Botanic Garden Conservation International (BGCI, 2022), botanical gardens attract about 500 million visitors each year. People around the world search for these green spaces while they travel or during their everyday lives (Gratzfeld, 2016). Visitors, as a financial source, are also essential for the sustainability of the gardens. However, more than just leisure or touristic attractions, botanical gardens should be seen as prominent scientific institutions. The collections they keep, built up over centuries, the taxonomic knowledge of their staff, and the horticultural skills of generations of gardeners are not only fundamental to managing plant diversity, but also useful to address current global challenges such as biodiversity conservation, climate change, food insecurity, water scarcity, renewable energy, or human health, to mention a few examples (Smith, 2019).

Botanical gardens should foster their crucial role as communication channels of scientific knowledge. The use of innovative communication means inviting to a visit or improving the visiting experience with educational, scientific, and cultural information is essential. Sharing knowledge about the plant collections, such as taxonomical information, native distribution, or uses, and applying different methods for displaying plant information (besides the traditional labels or information boards) is a way of enhancing a visitor experience while educating.

Geographic Information Systems (GIS) are a useful tool for managing information associated with locations and 3D technologies are an appealing way to represent the objects to which information is related. 2D GIS is used in all areas where geolocated information or spatial analysis is relevant, and has been frequently applied also to public gardens, mostly focused on plant collection management (e.g., Malinverni, Chiappini, & Pierdicca, 2019; Repetskaya, Petlukova, Tabunshchik, Vishnevski, & Savushkina, 2020). Krämer & Peris (2014) present a pilot study where GIS is integrated with Building Information Modelling (BIM) for facility management of the Botanical Garden in Berlin and Malinverni et al. (2019) describe the use of GIS for management support of a historical garden in Italy, including the photogrammetric 3D modelling of some statues. A software for collection management databases, BG-BASE, as well as the complement BG-Map for collections mapping of botanical gardens and arboreta (BG-BASE, 2022), is applied by several institutions to create online accessible interactive maps for the public. Other examples, such as the Botanical Garden of the University of California, Riverside (UCR, 2022) and the Smithsonian Gardens (Smithsonian, 2022), present an interactive GIS web map on a satellite image background, where specimens are identified by species name and can be selected; on the selection, a window opens offering high-quality photographs of the plants and, in some cases, a large set of information about the species. Other institutions hosting botanical gardens (e.g. Longwood Gardens (Longwood, 2022); New York Botanical Garden (NYBG, 2022); University of Pennsylvania (UPenn, 2022)) present CAD-based web maps on their websites with the location of individual specimens, and information about the species. Other GIS functions, like finding a plant by name or from a list and seeing the location of the specimens on a map, are common to those websites. A data model for supporting information management and analysis within public gardens has been developed by ESRI (Morgan & Greco 2019). It links two existent plant and animal record management systems and can be applied in botanical gardens, arboreta and zoos.

GIS has been evolving fast from 2D to 3D, and even 4D (considering time), due to developments in fields such as remote sensing and photogrammetry, geoinformation sciences, information and communication technology, and computer graphics science (Ross, 2010). Virtual 3D models can be used to represent and enable navigation in existing urban environments or to digitally construct non-existing places, either fiction, historical or planned.

Apart from cities, heritage buildings and places are the most modelled objects using 3D technologies (e.g., buildings or university *campi*: Antunes, 2013; Catita, Coutinho, & Miranda, 2018; Edvardsson, 2013; Lima, 2016; and cities: Almeida et al., 2016; 3D City DB, 2021; Fabricius, 2020; Patrick, 2021). Very interesting examples are also 3D models that reconstruct historical places enabling interpretation, management, and investigation of cities like Pompeii (Dell'Unto et al., 2016) or a pre-industrial area landscape in Michigan (Arnold, 2017). Although attractive and navigable, most of the 3D models cannot be considered 3D GIS since they do not have information attached to the objects.

3D GIS is particularly important where information density is high, and its association to a 2D representation becomes a challenge. 3D GIS of urban areas, where structures assume vertical layouts both over and underground, has caused a revolution in the fields of planning, communication and documentation of urban environments (Kelly, 2021).

Plants, on the other side, play mostly an ornamental role in virtual 3D models of urban or historical sites. They are seldom the focus of the 3D scenes and normally do not have individual information associated. To our knowledge, based on literature and web searches, there is no documented 3D GIS focused on the plant collection and assets of a botanical or another type of garden. The most similar 3D product to the one proposed here is described by Harrington et al. (2021) and represents the Virtual University of Central Florida Arboretum (VUCFA), allowing the visualization in Virtual Reality/Augmented Reality (using headsets) of ten natural communities distributed in a selected area of the Arboretum. The scenes were created based on data collected in place by biologists (plant types and density), and 3D plant prototypes were created. This product was built using Unreal Engine (Unreal, 2022) and all information associated with the plants is accessible through external web pages.

In botanical gardens, the available information goes far beyond what can be put on labels or in other written displays. Therefore, they have been investing in QR codes or applications for mobile devices. Such applications guide the visitor through maps, and GPS (Global Positioning System) tracking suggests routes and provides relevant information about the local or the visualized object. Examples of such applications can be found on the websites of the botanical gardens of Chicago, Memphis, New York, Kew, and Singapore (Jelles & Kessler, 2014). However, mobile applications have limitations on the quality and quantity of the information, due to reduced dimensions of the monitor and memory of most devices and queries to a database can be difficult to perform. In addition, Ballantyne, Packer & Hughes (2008) found that most visitors do not intend to visit a botanical garden having to look all the time at a mobile phone reading a load of information, but rather to enjoy nature and socialize. Desktop applications can help overcome this challenge as they are more adequate to include detailed information as well as to direct the user to other multimedia pages or existing repositories. Diversifying types of available information is also a means to reach multiple publics. Specifically, visualization of 3D models can be especially interesting as an educational tool when based on interactive and realistic models giving access to curated information of selected objects. These can also be helpful during times of conditioned access to the garden, as recently with the SARS-CoV-2 pandemic.

To the growing number of applications developed in recent years, both to increase the value of the leisure experiences enjoyed by visitors and to enrich the educational role of botanical gardens, the model we present here aims to go further by providing, also, a basis for management support. Effectively, by simultaneously integrating 3D modelling and georeferenced collection data, the project *Jardim Botânico Tropical* (Tropical Botanical Garden) – JBT 3D, aims to promote learning about the garden publicising its natural, cultural and historical heritage, to raise awareness of the important role of botanical gardens in the conservation of plants, and, also, to provide a tool that can be useful to plant collection management. To achieve these goals, three main requirements were defined: (1) the usage of visually appealing 3D models with a realistic appearance; (2) the association of the information in databases to the corresponding georeferenced objects of the garden; and (3) the possibility of navigating, selecting and querying the 3D model.

2. The case study: the Tropical Botanical Garden in Lisbon

This garden in Lisbon, Portugal, is one of the three botanical gardens in the city and has the particularity of hosting mostly tropical and subtropical plants. It covers an area of 7 ha, distributed along a slight slope with altitudes varying between 10 m and 35 m. The JBT has been founded in 1906 with a well-defined objective: to teach tropical agronomy techniques to the officials who would apply them in the former Portuguese colonies in Africa and Asia, to study the characteristics and potential of tropical plants brought to Portugal, and as a place for the acclimatization of new exotic plant species, with economic interest (Cunha et al., 2021).

The responsible entities for the garden have changed several times over the years and in 2015, it was integrated into the University of Lisbon (see Duarte, Moura, & Romeiras, 2021 for details). Since then, the JBT has been managed by the *Museu Nacional de História Natural e da Ciência* (National Museum of Science & Natural History) of the University of Lisbon.

The living plant collection of the JBT includes more than 600 different species, totalling more than 2000 specimens, some of them being older than 100 years, others very rare or exuberant (Duarte, 2021).

Besides the plant collection, buildings of historical relevance, such as the Palácio dos Condes da Calheta (17th century), marble statues of the 18th century, already in the place long before the foundation of the JBT, deserve attention as elements of cultural heritage, as well as other buildings, busts and mosaics with tropical motifs dating from the Portuguese World Exhibition of 1940 (Duarte, 2021).

3. Methods

The JBT objects to be represented in the 3D model include plants, buildings, statues, busts, and ponds. To improve the realistic aspect of the model, terrain, paths, water channels, flower beds, urban furniture, and various constructions were also included. Since the botanical collection has more than 2000 specimens, five groups of special interest were selected (trees, rosette trees, palms, relevant shrubs, bamboos, and cycads), resulting in 560 individuals being included in the 3D model.

The workflow for the project is presented in Figure 1. After the semantic modelling –i.e., after all the operations conducing to the right geographic position of each object, and after assigning the respective botanical attributes and other information (for example, the paths of the 3D static models)–, a geodatabase (JBT_2D) was created for the datasets to be imported to ArcGIS CityEngine (ESRI, 2020). The final 3D model was then generated in this software, which is normally used for 3D city modelling and, in the present case, was adapted to a garden.

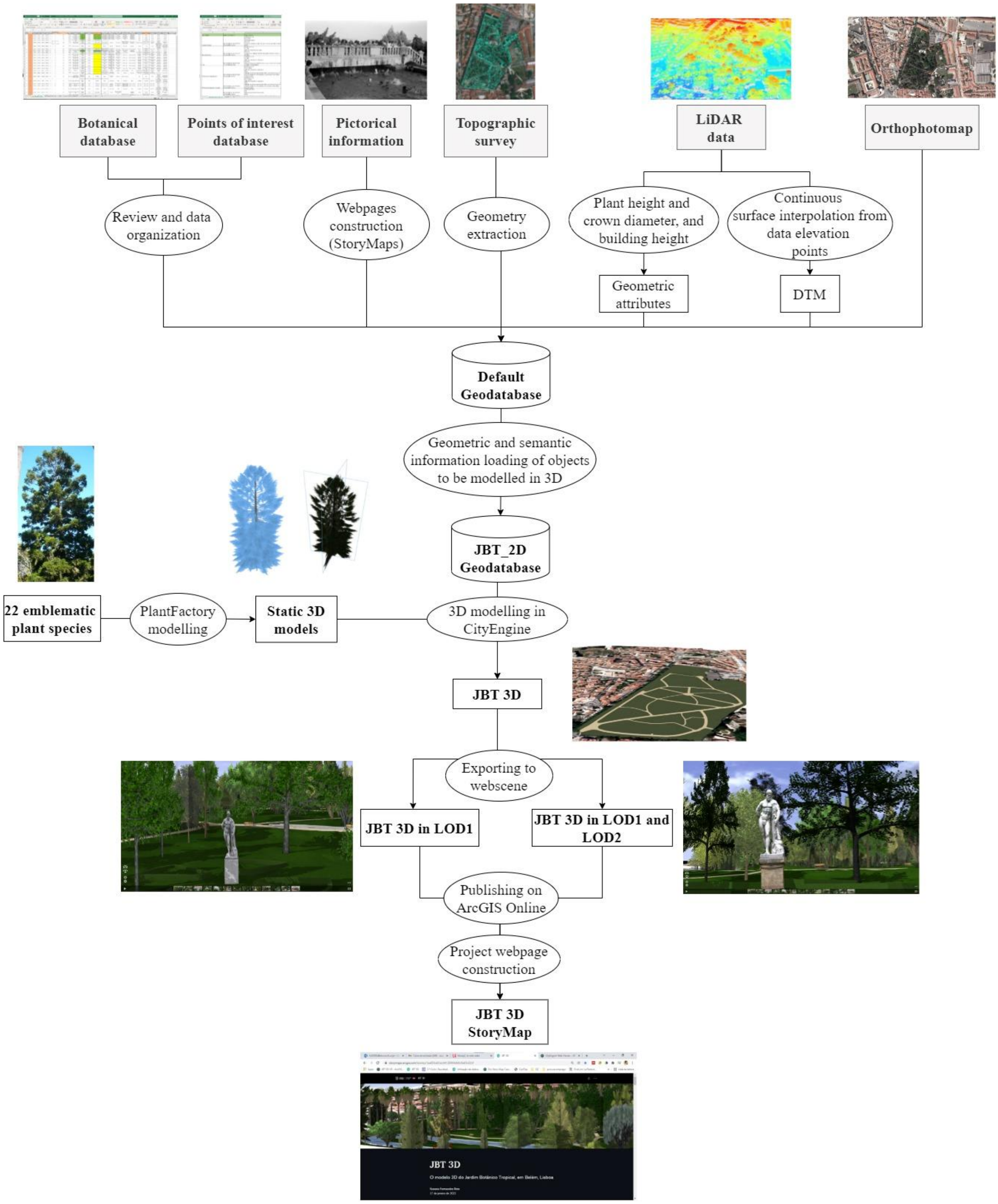


Figure 1: Workflow of the methodological approach of the project JBT 3D: (top) used data sets and pre-processing; (middle) 3D modelling of the objects and (bottom) the publication on the web.

3.1. Data used and processing

Geometric precision data of the garden real entities were obtained from: 1) the field survey of the plants and their approximated location carried out in 2014 by M.C. Duarte, I. Moura and M. Pinheiro (Duarte, Moura, Pinheiro, Nunes, & Palminha, 2016); and 2) the topographical survey of the JBT conducted in 2015 and updated in 2019 (Topiaris, 2022).

Data from a LiDAR (Light Detection and Ranging) survey of Lisbon in 2016, were used to estimate tree height and crown diameter to represent plants at scale. This data served to produce a Digital Terrain Model (DTM), a Digital Surface Model (DSM), and to estimate building height above ground. Also, a Canopy Height Model (CHM) was calculated, which is the difference surface between DSM and DTM over plant cover, yielding tree heights above the ground.

Database information associated with all sets of objects existed in table format containing several attributes and organized with redundancy.

Processing methods to obtain the adequate data format for 3D modelling in CityEngine of each class of objects are presented next.

Terrain – A 0.5 m x 0.5 m spatial resolution DTM, including the garden and a surrounding area, was used. The DTM was produced using the points classified as ‘ground’ from the LiDAR dataset. A realistic texture for the surrounding area was obtained from a 2015 orthophotomap obtained from *Direção Geral do Território*.

Paths – Since this class is modelled in CityEngine as a graph, the paths spatial layer was sourced indirectly from the topographical survey using other objects as limits (e.g. flowerbeds) and drawing a centreline.

Buildings – The spatial layer of buildings footprints to be included in the model (Condes da Calheta Palace, Raw Material Pavilion, Main Greenhouse, Tea and Coffee Greenhouses, Director's House, Gardener’s House, Tea House, Macau Arch and Moon Gate) had its source in the topographical survey. Building facades were photographed systematically in the field, and the images were processed in GIMP (Kimball, Mattis, & GIMP, 2021) to remove perspective effects and all elements of noise (sky, cars, plants, people, etc.). These images were used as textures in the 3D modelling process, one image for each homogeneous facade element. Semantic attributes for the buildings were obtained from the table of points of interest (which also included statues, busts, and some ponds). Building height over the ground was obtained from the CHM and was introduced as an attribute to the spatial layer. An attribute referring to the roof shape to be modelled in 3D was also included. Finally, for each building, a web page was created in ArcGIS StoryMaps format with detailed information and the corresponding URL was introduced as an attribute in the table containing semantic attributes of the points of interest.

Statues, busts, ponds and water channels – Spatial layers for each class containing their location in the garden were obtained based on the topographic survey dataset (points for statues and busts; polygons for ponds and water channels) and semantic attributes were provided in the same table of points of interest already used for the buildings. Also, for each point of interest a web page was created in ArcGIS StoryMaps format, including animations of the photogrammetric models of statues and busts, and more detailed information was created; the corresponding URL was included in the semantic attributes table.

Flowerbeds – This spatial layer was sourced indirectly from the topographical survey creating polygons interactively using other objects as limits (e.g. sidewalks). The resulting polygon layer was then converted to a multipatch format using a TIN (Triangular Irregular Network) relief surface obtained from the LiDAR dataset as the base. The multipatch format transformed each polygon into a 2.5 D object that could adapt better to the 3D relief of the terrain.

Plants – The plants spatial layer was obtained by georeferencing the plants in the collection database. Due to the high density of individuals in some parts of the garden, a case-by-case approach had to be followed. This allowed assigning the corresponding identifier in the plant database to the precise location of the plant. Semantic attributes of plants were obtained from a previously prepared database where information is organized in two tables: one for species attributes, and the other for specimen attributes. Considered species attributes include: taxonomy (updated according to POWO, 2021), habit, native distribution, traditional uses, a common name in five European languages (Portuguese, Spanish, French, English, and German), threaten status (IUCN, 2021), and inclusion in CITES convention (UNEP, 2021). Native distribution was mapped based on POWO (2021) and each map (created using World Administrative Divisions Esri Map Package) was exported as an image in ArcGIS Online. To represent plants at scale, height and crown diameter estimates were obtained using the LiDAR dataset. This is a common practice in monitoring forest ecosystems where remote sensing techniques are extensively used, and several methods have been developed to automatically obtain forest-related parameters (Guimarães et al., 2020). A recent study concluded that differences in results obtained with different algorithms were caused only by tree architecture and how trees interact with each other independently from the algorithm used (Hastings et al., 2020). Even knowing that the high complexity of plants in the JBT could limit automatic results, we decided to perform one of the most used methods based on watershed segmentation tools (Guimarães et al., 2020). This method carries out the segmentation of the inverted CHM by watersheds using markers (Chen, Baldocchi, Gong, & Kelly, 2006; Zhao & Popescu, 2007). The markers are points corresponding to the effectively detected plants in the CHM, which were confirmed in loco.

Urban equipment – Spatial layer with location points of benches and wastepaper bins were sourced in the topographical survey, completed with observations made in loco and in Google Street View.

3.2. Data integration and spatial database model

All final products resulting from the processing tasks of all classes of objects, being spatial data layers or tables containing semantic attributes, were stored in JBT_2D geodatabase. The conceptual data model representing the database composition was built using a UML (Unified Modelling Language) class diagram (Fig. 2) and is

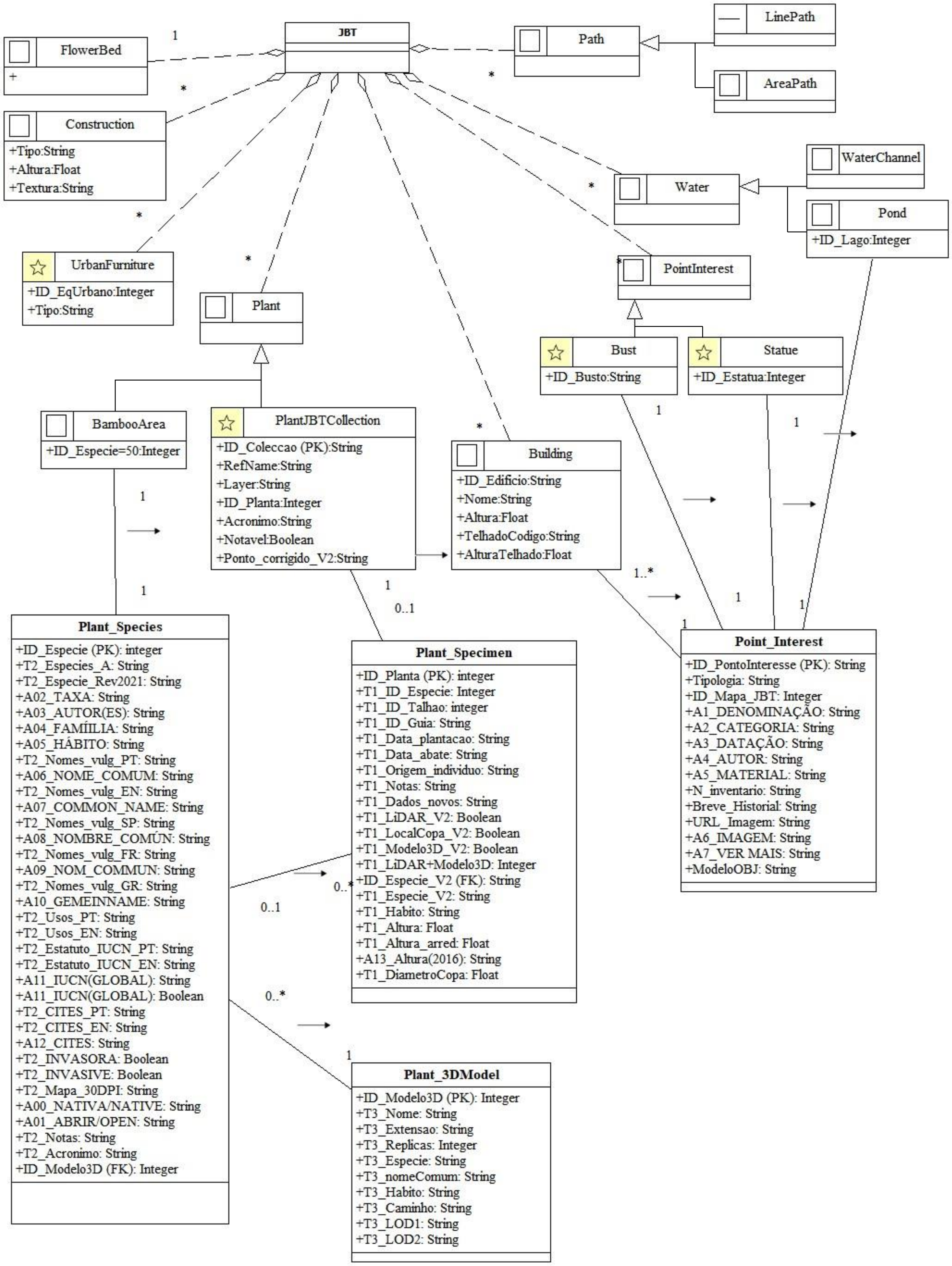


Figure 2: UML diagram of the database model of the JBT_2D. The names of the classes were translated into English for readability, but the names of attributes are the original ones. Straight lines represent the relations between classes, including the corresponding cardinality representing the number of rows of each class that can be involved in the relation.

intended to ensure not only efficient data storage with minimum redundancy but also to allow an easy update, with a reduced probability of errors.

Semantic modelling consisted of associating conventional classes to the corresponding georeferenced ones by joining operations between tables according to the data model. The resulting spatial layers were saved as new feature classes to be imported into CityEngine in order to proceed with the 3D modelling.

Georeferenced classes (e.g. PlantJBTCollection) are represented at the top half of the model (Fig. 2) and contain the geometric data, while the conventional classes (e.g. Plant_Species) are represented at the bottom half and contain the semantic attributes of the botanical collection specimens, buildings, statues, busts, and ponds.

The class Plant_3DModel is related to the class Plant_Species in a one-to-one relationship, determining that each Plant_Species has 3D models of each Level of Detail (LOD), one in LOD1 and one in LOD2. The fields T3_LOD1 and T3_LOD2 of the Plant_3DModel class indicate the path for the files containing the respective 3D models. This solution allows associating 3D models of different detail to the same location according to the modelling context (see Section 3.3). Only the appearance of the object changes, not the attributes or their values.

3.3. 3D modelling

Geometrical modelling in 3D of spatial objects was implemented in CityEngine v. 2020.0.6332 where several scenes were created containing different versions of the model. For all scenes, ETRS89/PT-TM06 coordinate system was defined. The need for different versions results from the fact that the JBT 3D containing the plants, statues and busts represented by models with a higher LOD is quite computationally heavy. To overcome this drawback, a version with a lower level of detail was created, plus intermediate versions that allow the visualization of the JBT 3D with models in greater detail only in limited areas of the garden.

Specific modelling tasks in CityEngine for each class of objects (below) were subsequently performed. As much as possible procedural modelling using CGA (Computer Generated Architecture) rules were implemented. CGA is the language used by CityEngine for procedural modelling.

Terrain – This is the base layer and the first to be modelled by importing the DTM as a height map and using the orthophotomap as texture. A 2.5 D surface is created automatically.

Paths – These were modelled in 3D by adapting the CGA rule Street_Modern_Simple (available in CityEngine library) to implement only one-way paths, curbs, and texturize the pavement similarly to the real one (light brown dirt paths).

Buildings – Footprints were used to model buildings using CGA rules. For most buildings, a rule was constructed that enables its extrusion to the corresponding height value (*extrude* function), followed by the separation of faces (*comp* function), the roof modelling according to the real shape (*roofHip* or *roofGable* functions), and finally, the texturing of faces (*setupProjection*, *texture* and *projectUV* functions) (Fig. 3). For height and roof shape geometric attributes were used that have been previously associated to each object. For texturing facades, each of the divided surfaces was selected (*f* operation) for the assignment of a specific image. Macau Arch and some

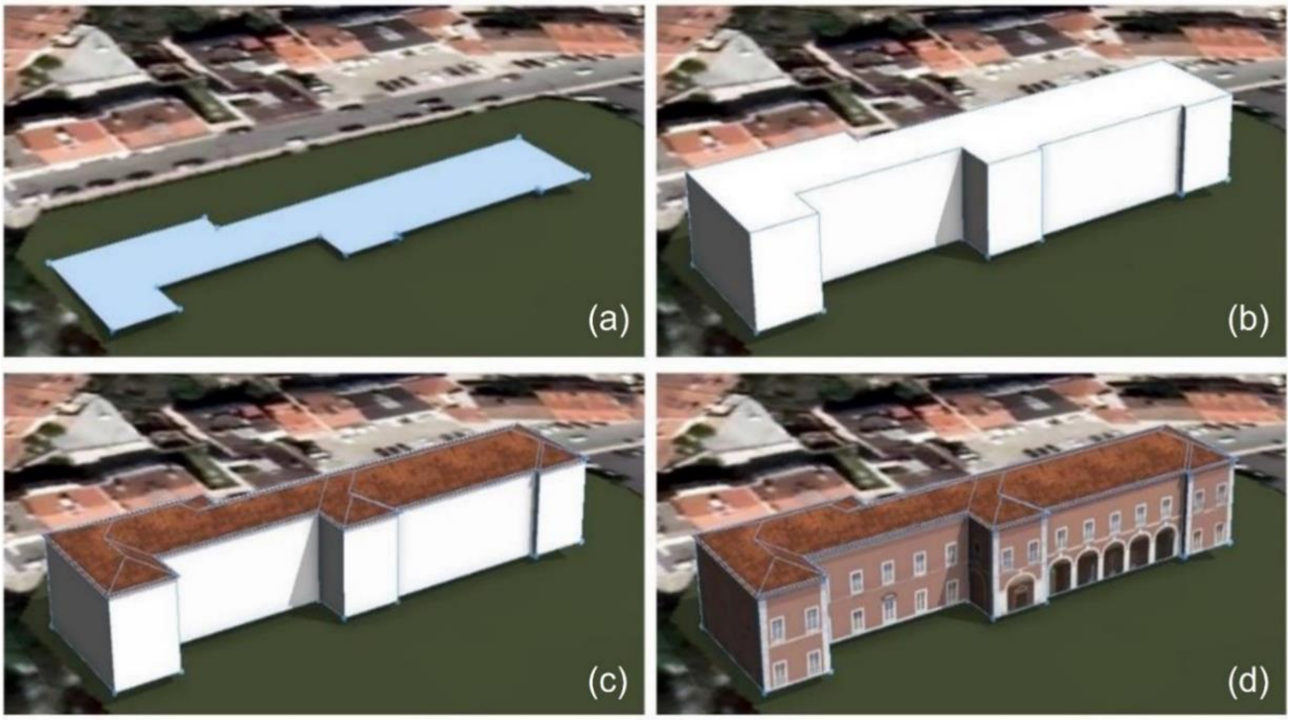


Figure 3: Phases of the 3D modelling of a building: a) footprint; b) extrusion to the height of the building; c) hip roof modelling adapted to the number of facades; d) texturing facades with edited and rectified photographs.

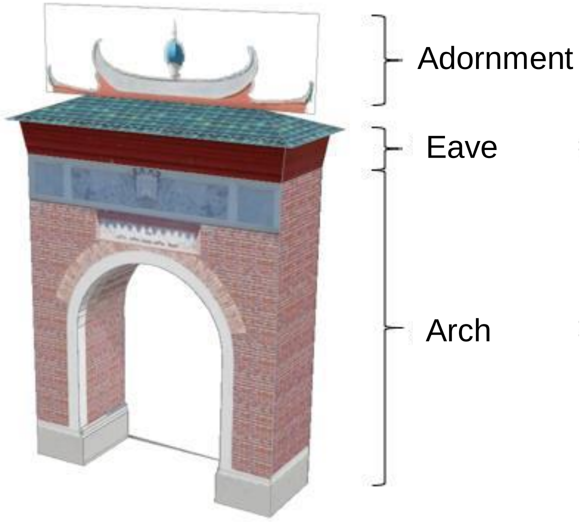


Figure 4: 3D model of the Macau Arch and its elements.

other constructions were modelled using a different procedure adapted to each case, since they had a more complex structure that could not be obtained by a simple extrusion (Fig. 4).

Statues and busts – These objects were surveyed with a Sony α230 photographic camera and modelled in 3D meshes by photogrammetric multi-view processing using Pix4D v. 4.2.26 (Pix4D, 2022) and 3DReshaper 2017 MR1 (Leica Geosystems, 2022) (Fig. 5b). Since these models are computationally heavy (LOD2), a light version (LOD1) was created in CityEngine using two perpendicular blades with projected photographs (Fig. 5a). These models were exported in FBX format and inserted as static models at the corresponding geographic locations. For statues, insertion, size, and rotation were adjusted using parameters and operations in the CGA rule, while for busts, this was made interactively.


(a) (b)

Figure 5: Statue (Hercules Farnese) in two levels of detail: a) LOD1 (blades); b) LOD2 (mesh).

Flowerbeds – Multipatch layer of flowerbeds was imported, with an offset of 0.1 m in relation to the terrain to prevent surface intersection (which causes visual artefacts), and a rule was constructed that texturizes its surface with an image of grass mat.

Ponds and water channels – Water bodies were modelled in 3D by a CGA rule which projected a water surface image. A movement was applied to the water (*set material* operation), which effect is only noticeable once the model is explored on the web.

Plants – A group of 22 emblematic plants were procedurally modelled in 3D using PlantFactory software (e-on, 2017). Photographs of plants and distinctive parts were taken with the support of ArcGIS Field Maps and used as a reference for the models (Fig. 6).

Some specimens have more distinctive leaves that had to be considered. Therefore, images of the real leaves were projected on blades (e.g. *Ginkgo biloba*) or even had to be modelled in 3D from scratch (e.g. *Araucaria* species). In some cases, an additional interactive modelling step was applied at the end of the process to turn the models more realistic, for example, by pruning (*Prune* tool), and altering the geometry or the orientation (Gizmo's tool in Touch-up mode) of branches for which *Ficus sycomorus* species is a good example (Fig. 7). At the end, all models were exported in FBX format.

For other specimens than these 22, models were selected from CityEngine 2018 ESRI.lib library, trying as much as possible to resemble the respective species. As previously, models of two levels of detail, LOD1 and LOD2, were used.

All plant models were inserted as static in the corresponding spatial location, using a CGA rule acting over layer attributes, to automatically choose a 3D model and a LOD (1 or 2) and assign it to each plant location. Two CGA rules were created, one for inserting only LOD1 models and the other enabling the control of the LOD to be inserted in different parts of the garden using global variables. Both rules insert models (*i* operation), rotate trees randomly around the vertical axis (*r* operation), control the dimension of each model using crown height and diameter estimates (*s* operation), and centre each model on the respective location point (*centre* operation). For bamboo areas, another CGA rule was created that uses the *scatter* operation to distribute a predefined number of plants on each surface with a predefined pattern (uniform or gaussian). A random factor was also applied to the rotation and dimension parameters of bamboo plants to achieve the look of a natural heterogeneity.

Urban equipment – 3D models of benches and wastepaper bins were inserted as static models, from CityEngine 2020 ESRI.lib library and TurboSquid (Shutterstock, 2021) (as free models). Insertion and dimension were defined by a rule, while orientation was adjusted interactively.

3.4. Publishing

Once the modelling process was finished some attributes were deleted from the CityEngine layer to maintain only those intended to be available for consultation by the user and those needed for the CGA construction rules (e.g. crown diameter).


(a) (b) (c) (d)

Figure 6: 3D models of trees created from scratch (top) and the corresponding real trees (bottom) for comparison: (a) *Araucaria bidwillii*; (b) *Araucaria columnaris*; (c) *Araucaria cunninghamii*; (d) *Araucaria heterophylla.*


(a) (b)

Figure 7: *Ficus sycomorus* existing plant (a) and 3D model (b) for which the modelling process was very interactive.

For each 3D scene, the adequate bookmarks (keyframes of an animation) were created and saved. The animation is automatically generated and shown as a guided tour once the user begins to explore the model on the web. Each scene was then exported to CityEngine Web Scene format (.3WS), published in ArcGIS Online, and shared with the public. JBT 3D in LOD2 was also used to export to ArcGIS 360 VR Experience format (JBT3D 360VR, 2022).

4. Results

The final output JBT 3D includes 3D models of 560 plants (142 species), their native distribution maps, and botanical attributes (taxa, family, habit, common name in five European languages, IUCN conservation status, and inclusion on CITES Appendices), as well as the determined geometric parameters (height and crown diameter) for the whole plant set. Although the heterogeneity of plants in a botanical garden prevents the successful automatic acquisition of tree dimension parameters, the used method achieved a success rate of 44% being the remaining tree crowns delineated interactively based on the CHM.

Besides the plants, eight buildings were modelled in 3D requiring the editing and perspective correction of about 60 photographs. Seven statues and eight busts, photogrammetrically modelled, and four ponds complete the statistics of the modelled objects.

A web page was produced for modelled objects containing historical information which is accessible through a link in the JBT 3D, once the respective object is selected. For each statue, the web page includes an animation of the 3D photogrammetric model where it can be analysed in more detail.

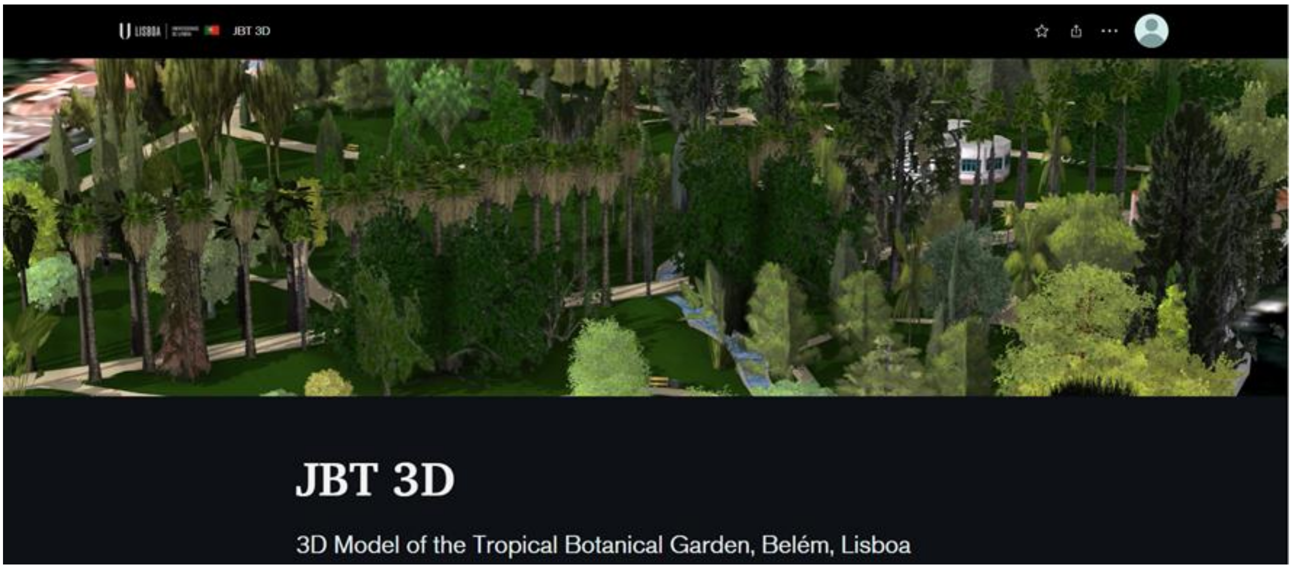
To access the JBT 3D models in different LODs and different formats, a web page (JBT 3D, 2022) dedicated to the whole project was additionally created (Fig. 8). Besides an introduction to the project, some general navigation explanations for the 3D models are given. Both Portuguese and English versions of the page are available.

Some animations of the 3D model in LOD2 are included on the project web page, as well as access to the ArcGIS 360VR format (Fig. 9). In this format, the user can choose pre-defined spots in the garden and have a look all around horizontally as well as allowing the analysis of the canopy from below. When using a cell phone or tablet to explore the website, the 360VR product allows a 360º x 90º view while the user is rotating, holding the phone in his hand without the need for further interaction.

Within CityEngine WebViewer, a guided tour is automatically started leading the user through the most iconic spots. It is possible to navigate freely through the model and to query the database using the attribute values, for instance, by scientific or common name, family or threatened status.

The objects complying with the query appear highlighted in the 3D model (Fig. 10). When exploring the 3D model, the user can select an object (plant, statue, building, pond), and a legend appears on the right-side window showing a set of attributes.

In the case of plants, the native distribution map is shown on top of the botanical attributes (Fig. 11a). In the case of the points of interest, one of the attributes, 'A7_VER_MAIS' (See_More), links to the respective web page with further information about the object (Figs. 11b and 12).



JBT 3D

3D Model of the Tropical Botanical Garden, Belém, Lisboa

Figure 8: Front page of the JBT 3D StoryMap.

(a) (b)

Figure 9: Examples of the VR360 views. The ribbon shows part of the spots with Virtual Reality scenes: a) spot of Palácio dos Condes da Calheta; b) spot of *Ceiba speciosa* and other tree species.

(a) (b)

Figure 10: Visualization of query results: a) panoramic of the garden; b) result to the query 'Palm tree' from the same point of view.

Attributes

A01_ABRIR_OPEN	https://ulisboa.maps.arcgis.co
A02_TAXA	Syagrus romanzoffiana
A03_AUTOR_ES_	(Cham.) Glassman
A04_FAMÍLIA	Arecaceae
A05_HÁBITO	Palmeira
A06_NOME_COMUM	Coqueiro-de-jardim
A07_COMMON_NAME	Queen palm
A08_NOMBRE_COMÚN	Coco plumoso
A09_NOM_COMMUN	Syagrus de Romanzoff
A10_GEMEINNAME	Romanzoffianische Kokospalr
A11_IUCN_GLOBAL_	Não Avaliado (NE)
A11_IUCN_GLOBAL1	Not Evaluated (NE)
A12_CITES	Não incluída/Not included
A13_Altura_2016_	18.9m±0.10 (estimada)
T1_Altura	18.9
T1_DiametroCopa	5.41
T3_Caminho	Plants/
T3_Extensao	.obj
T3_LOD1	_Fan_0
T3_LOD2	_Model_0
T3_Nome	Ruffle_Palm

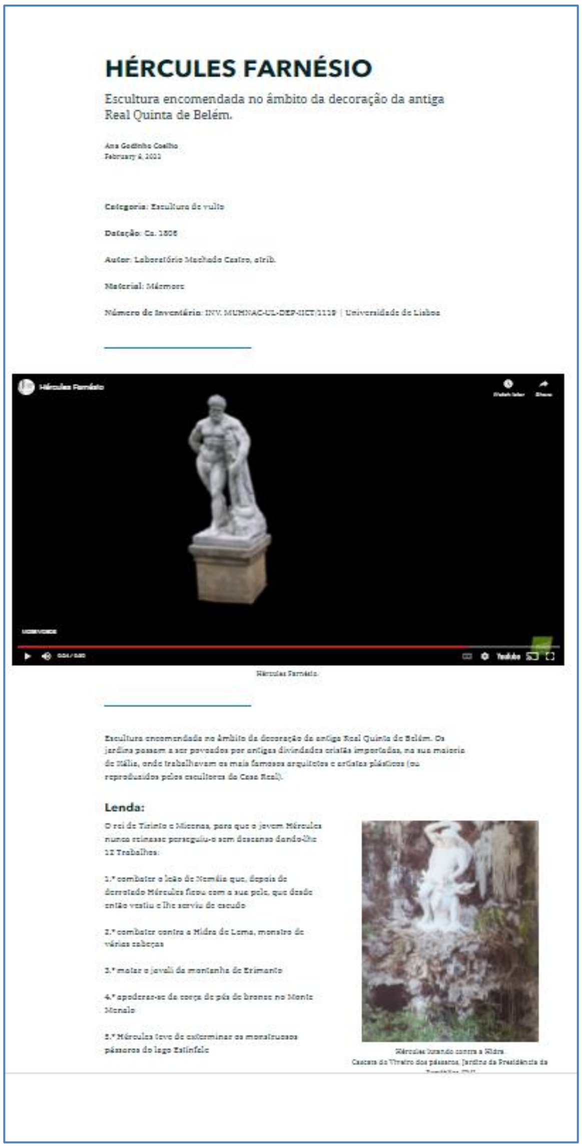
(a)

Atributos

A1_DENOMINAÇÃO	Hércules Farnésio
A2_CATEGORIA	Escultura de vulto
A3_DATAÇÃO	Ca. 1806
A4_AUTOR	Lab. Machado Castro, atrib.
A5_MATERIAL	Mármore
A7_VER_MAIS	https://storymaps.arcgis.com/stori
ID_Estatua	PIE1119

(b)

Figure 11: Selection of objects in the JBT 3D (highlighted in blue): a) a plant, map of native distribution and attributes on the green window; b) a Point of Interest and legend. The URL of the associated webpage is selectable under the attribute 'A7_VER_MAIS' (See_More).



HÉRCULES FARNÉSIO

Escultura encomendada no âmbito da decoração da antiga Real Quinta de Belém.

Ana Godinho Coelho
February 4, 2022

Categoria: Escultura de vulto

Datação: Ca. 1808

Autor: Laboratório Machado Castro, atrib.

Material: Mármore

Número de Inventário: INV. MUHNAC-UL-DEP-IICT/1119 | Universidade de Lisboa

Hércules Farnésio.

Escultura encomendada no âmbito da decoração da antiga Real Quinta de Belém. Os jardins passam a ser povoados por antigas divindades cristãs importadas, na sua maioria de Itália, onde trabalhavam os mais famosos arquitetos e artistas plásticos (ou reproduzidos pelos escultores da Casa Real).

Lenda:

O rei de Tirinto e Micenas, para que o jovem Hércules nunca reinasse perseguiu-o sem descanso dando-lhe 12 Trabalhos:

1.º combater o leão de Neméia que, depois de derrotado Hércules ficou com a sua pele, que desde então vestiu e lhe serviu de escudo

2.º combater contra a Hidra de Lerna, monstro de várias cabeças

3.º matar o javali da montanha de Erimanto

4.º apoderar-se da corça de pés de bronze no Monte Menalo

5.º Hércules teve de exterminar os monstruosos pássaros do lago Estínfalo

Hércules lutando contra a Hidra.
Cascata do Viveiro dos pássaros, Jardins da Presidência da

Figure 12: Part of the web page associated with Point of Interest with 3D model animation and historical/mythological background.

5. Discussion

The methodologies and the workflow proved to be very efficient in developing a 3D model of a botanical garden, a particularly complex environment, as well as in providing information about the represented objects, all on an online platform that allows user interaction.

The use of 3D City modelling tools for a botanical garden was a challenge. Nevertheless, the chosen software CityEngine, usually applied for urban modelling (e.g. Badwi, Ellaithy, & Youssef, 2022), was flexible enough to allow the modelling of an environment out of its scope.

The modelling from scratch of the 22 selected trees, some with very irregular geometry, was very demanding, but the used tools (PlantFactory) led to very realistic models, although heavy, as was the case of the emblematic *Ficus sycomorus* with a very intricate physiognomy (Fig. 7). The same can be said about the statues modelled photogrammetrically. When considering a whole garden with high detail and the associated semantic information, the final 3D model can easily surpass the dimension limits of the web viewers where the model shall be explored by users. So, compromises had to be made to avoid the webscene file, used for exporting the model for the CityEngine WebViewer, to reach those limits. Therefore, as in similar situations (e.g. Dylla et al., 2008), several versions of the final model were published with lower detail in some areas of the garden or in the whole garden.

Conceiving a spatial database model and implementing most geometric modelling tasks by means of CGA procedures were two fundamental measures for easy updating of data, as well as 3D models of individual objects. As in urban environments, the update of information is an essential aspect of a botanical garden and the implemented solutions revealed to be appropriate to assure not only the update of the information but also the inclusion of other types of information.

To evaluate the feedback of the users, we prepared a five questions interview, to be answered with free text, that evaluates the following aspects: visual (appealing look, realism, and positive and negative aspects); navigation and interaction; access to information; added value (for visitors and managers); improvements. The queries were emailed to botanic garden staff related to management, education and curation, botanists, and informatics experts on 3D modelling. Participants could freely explore the JBT 3D on their own platforms, computers or mobile phones, and give qualitative answers to the questions.

Ten participants gave feedback. Most users, 80%, refer to the JBT 3D as visually appealing, 70% as realistic, and one participant considers it not realistic. The positive aspect most frequently referred to was realism (50%), followed by the capacity of interaction to obtain additional information (30%), detailed view of the space (20%), easy space orientation (20%), and the automatic guided tour (20%). Other positive aspects were the exact location of plants, support for the preparation of or complement to a visit, detailed information, selection of objects, useful instructions for navigation, and high quality of 3D objects. The main negative aspect was slow navigation (20%), but others, like the long time to load the scene, lack of visual references (e.g. the garden's main entrance), the impossibility of obtaining a map containing the location and attributes of all plants, and confusing search were also referred. Navigation and interaction were easy to 90% of the users, and only one considered it difficult (10%). The most referred difficulty was slow navigation (40%), followed by insufficient instructions (10%), and difficult selection of certain objects (10%).

Access to information was successful for most participants (90%), but the information was classified as clear by only 60%, while 20% referred that information could be simplified (e.g., codes used to label attributes are not completely user-friendly). Other information that participants wished to be accessible was the flowering and fruiting season of plants; traditional uses of plants; links to pages with more information; mapping of plant location with attributes; data in different languages; videos of the garden; and animals present in the garden.

Almost all participants (90%) considered the JBT 3D as an added-value asset for visitors and for managers.

Finally, among the aspects that could be improved in the JBT 3D, the navigation speed was the most frequent answer (30%), followed by: identifying the main entrance of the garden, simplifying the information associated with the objects, instructions for navigation, clearer search, more detail on buildings, images in the project website with better quality, finish the 3D modelling of "Jardim de Macau" and "Jardim dos Catos", and migrate from the CityEngine WebViewer to the ArcGIS Online WebScene.

All in all, reactions were very positive, and the problems reported with uploading time and slow navigation clearly depend on the used platform. A solution was tried by providing the low detailed scenes (LOD1) and the partially more detailed scenes (LOD1 and LOD2 in limited areas), but smooth navigation of the more detailed scene is, at the present moment, only possible with platforms used for gaming that not everyone has. A desktop computer with an Intel i9 3,70 GHz processor and 64GB RAM showed no problems in handling the heavier LOD2 scene. The rapid hardware evolution will certainly solve the presented problems soon. Suggestions for other improvements are going to be considered in the next revision and update of JBT 3D. It was also suggested that the JBT 3D could be installed in a capable computer placed in a building in the garden, so that visitors could consult the information at some point during their visit, a suggestion already made by the authors to the Direction of the JBT. The possibility of printing a map with the locations of selected plants according to some attribute is under study. It requires the link to other platforms since those used in the project do not allow such operations.

For a cost/benefit balance, we considered the time spent on the development as the most relevant cost, since the project was developed in an academic context and informatic means and software were provided. Twelve months were spent in total by one person with a scholarship: three for botanical database organisation and updating; two for 3D modelling from scratch of the 22 most relevant trees; two for the geometric attributes collection of the trees; three for 3D modelling of buildings and other assets, edition of field captured photographs, collection of other pictorial information, elaboration of native distribution maps and selection of existing 3D models representative of the remaining tree species; one for programming CGA rules for procedural 3D modelling of scenes in CityEngine; and one for final adjustments, elaboration of Storymaps and publishing of the 3D scenes in the web through ArcGIS Online.

As for the benefits, as well as promoting and providing access to information about the JBT, the developed model can be used as a basis for other projects, such as recreating the history of the garden over time, or as a current reference for future studies. Scenes can be created where the trees appear smaller (in the past) or higher (in the future) according to the respective growing rate. The height (and crown diameter) of each tree 3D model is a parameter that can be controlled individually. The JBT 3D can also be a useful tool to assist in the management of this space, namely for interventions where some precision in the geographical location and/or dimensions of objects is essential. For example, when selecting sites for future plantations based on taxonomic criteria, queries on the location of species of the same family or genus can help to select the most appropriate alternatives. Moreover, 3D representation is particularly relevant for assessing the visual impact of planting new trees since it allows obtaining an approximate image of the three-dimensional space available at the crown level or choosing the most appropriate locations according to the sun exposure and shade cast by surrounding trees and other objects.

Despite being developed on an experimental basis, the balance seems to be positive, notably in view of its great potential to support some of the key botanical gardens' purposes; besides, adapting the project to different objectives is possible and does not mean starting from scratch.

6. Conclusions

The project 3D modelling of the Tropical Botanical Garden based on a GIS, taking advantage of tools intended for 3D city modelling, involved several researchers of different domains. While geospatial experts organized the information, created the database, and performed the 3D modelling, botanists were responsible for the correctness of botanical data, and historians contributed to the historical information of the garden. A visually attractive georeferenced virtual representation of the garden was achieved, where the user can navigate, query all objects present in the model (e.g., plants, buildings, statues, or ponds), and receive scientific and historical information about the object. For a set of objects, links are provided for dedicated web pages with further information.

The opinions of users of the application were very positive on what concerns the representation of the garden, considering it appealing and realistic and underlined the capacity of interaction to easily obtain additional information. Most of the participants consider the JBT 3D an added value for visitors and for garden managers. Negative aspects were mostly related to the computer platform that each one used to explore the scenes, which may be not ideal for this kind of products, hampering smooth navigation, a limitation that will be overcome by future developments in technology.

The JBT 3D, made accessible to the public in February 2022, follows the mobile application JBTapp (Postolache et al., 2022), launched in 2021 for visitor support. Both applications are complementary, intending to promote the visits and give access to JBT information.

Overall, challenges were overcome, and the main goal was successfully achieved: the creation of a digital replica of the Tropical Botanical Garden. Besides the realistic appearance, information about the objects is directly accessible to the user and it can be anytime enriched with new knowledge and functionalities.

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