3D MODELLING OF BULDINGS AND URBAN AREAS USING GRASSHOPPER AND RHINOCERSOS

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ABSTRACT:

3D modelling of buildings using modern tools and techniques is an important objective for the management and planning of urban areas. Rhinoceros with Grasshopper is a powerful 3D modeller in the field of architecture, engineering and construction. In this paper, 3D modelling of several case studies based on the joint use of Rhinoceros and Grasshopper are shown. In particular, different levels of geometric complexity and detail are investigated. In order to achieve these objectives, adequate canvas designs have been developed according to the different case studies examined; specifically, several cases have been analysed, starting from simple volumes up to complex geometries and even large dimensions. The input sources for the elaborations in Grasshopper can be multiple; for example, numerical cartography, geodata from Open Street Map and point clouds generated by airborne LIDAR sensors were analysed. The 3D models generated in this way have parametric characteristics that are useful for integration into Building Information Models (BIM) and Geographic Information Systems (GIS), for analysis and simulation, or for visualising projects from illustrations to photorealistic renderings.

Key-words: Grasshopper, 3D city model, Rhinoceros, Open Street Map, Point Cloud, Extrusion.

1. INTRODUCTION

The representation of the city indicates the study of the morphology and expressive language of the urban fabric, in relation to significant monuments and buildings. With the advent of the digital age, new systems for visualising and managing geodata within web platforms or specific Apps, such as Google Maps, Google Earth, Street View Map, Earthexplorer (United States Geological Survey - USGS) have enabled a new approach to urban experimentation and knowledge (Isikdag & Zlatanova, 2010; Li & Ratti, 2019). Parametric modelling is a useful tool for management and planning that can study and predict the multiple logics of urban expansion. The parameterization of buildings or individual objects can be achieved through the use of parametric software, which is able to collect information and distribute it graphically on multiple levels, providing a series of complex scenarios. For example, a building is the set of individual basic elements (such as walls, windows, pipes and floors, etc.) with certain technical and structural characteristics (Shirowzhan et al., 2020). Using the same basic elements, then, it is possible to produce diversified designs, i.e. a design that can be shared with the various professionals involved in the process. In this way, it is possible to enrich, insert, extract, update or modify the information model in an immediate and effective way. An open standardised data model and exchange format for storing 3D digital models of cities and landscapes is CityGML, which defines ways to describe most of the common 3D features and objects found in cities (such as buildings, roads, rivers, bridges, vegetation and street furniture) and the relationships between them. It particular, CityGML defines several standard Levels of Detail (LoD) for the representation of objects for different applications and purposes, such as simulations, urban data mining, facilities management and thematic surveys (Gröger et al., 2012; Dardanelli et al., 2017; Biljecki et al., 2018; Pepe et al., 2020).

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In particular, 4 consecutive well-defined LODs, applicable both internally and externally can be identified: *i)* LOD0 - Highly generalised model; *ii)* LOD1 - Block/object extrusion model; *iii)* LOD2 - Realistic, but still generalised model; and *iv*) LOD3 - Highly detailed model (Kutzner et al., 2020).

A tool for parametric modelling of buildings and urban areas is Grasshopper, which is a plug-in implemented in Rhinoceros (also simply called Rhino) software (developed by Robert McNeel & Associates, USA). This plug-in consists of a programming language for the creation of geometries visualised through the Rhino software (Kos & Snoj, 2016). The algorithms are developed within a canvas that represents the working area. Within this workspace, two macro-classes are identified: *i)* parameters, which contain the information (numbers, vectors, geometries) and; *ii)* components that perform the operations such as translation, copy, subdivision, scale, etc. Application of parametric modelling in the urban field can be found in several recent works. Rakha & Reinhart, 2012 showed an urban analysis workflow using a Rhinoceros/Grasshopper massing tool; the tool uses terrain elevation models as part of the design process to subdivide sites and generate urban forms to explore parametrically. De Jesus et al., 2018 showed the first results of geometric modelling performed in the campus of the Federal University of Bahia (UFBA), using aerial laser scanning data, integrating QGIS, Rhinoceros and FME (Feature Manipulation Engine); in Rhinoceros software, it was possible to generate an extrusion of the geometric model and in particular using plug-ins named Heron and Meerkat. Fink & Koenig, 2019 discuss about of a holistic, digital urban design process aimed at developing a practical methodology for future projects; the urban design process presented in the paper includes analysis and simulation tools within Rhinoceros 3D and its Grasshopper plug-in as quality enhancement means that facilitate creative approaches throughout the project. Silva et al., 2020 have developed a method in order to facilitate designing and building curvilinear architectures and their supporting structures using simultaneously two design paradigms connected via parametric programming. Therefore, this paper is set in the context of geometric and semantic modelling in the urban environment using Rhinoceros/Grasshopper tools.

2. METHOD

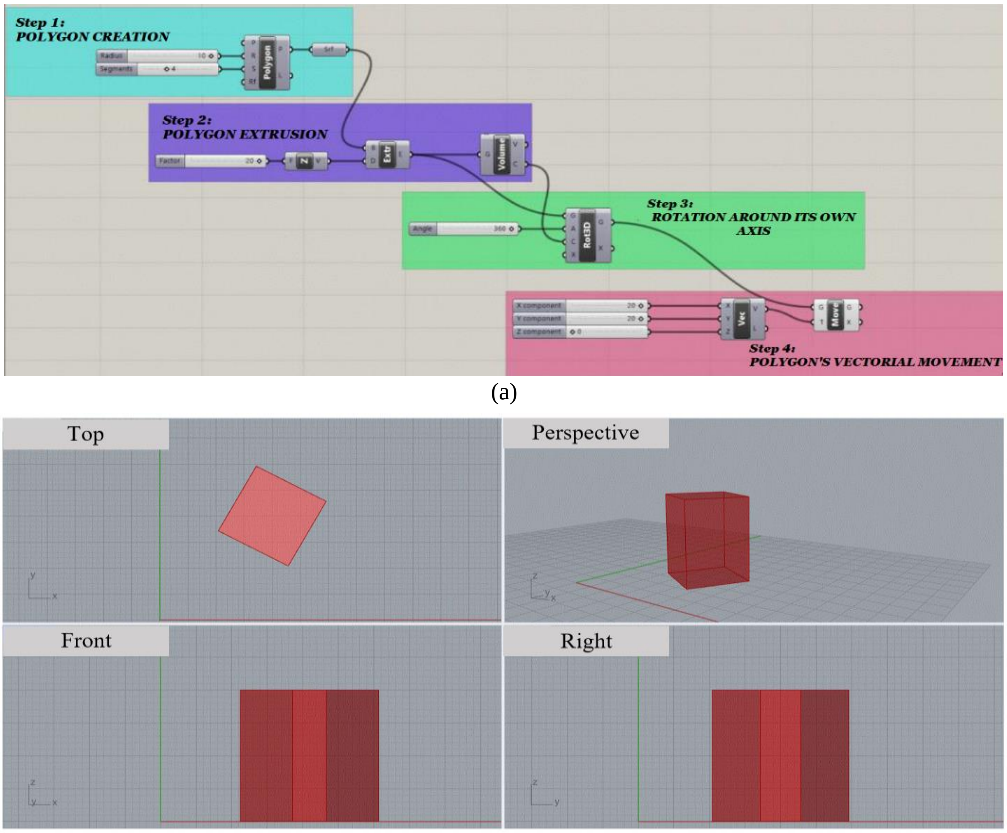
2.1. Design in Grasshopper and Rhinoceros

The parameterisation of the objects can be applied to different elements of the territory by means of the tools implemented in Rhino and Grasshopper. Indeed, programming in Grasshopper makes it possible to manage and model even complex geometries. Most of the Grasshopper interface is focused on the canvas, which is where the users performing the design of several elements and connecting them with wires. Grasshopper's components are written in Python, which is a popular language among computational designers due to its integration into many 3D modelling software and its relatively simple syntax (Peronato et al., 2017). Moreover, this environment allows one to use multiple 3D modelling functions and manage the entire design phase. For example, it is possible to build a model in Rhino and export it to a BIM (Li et al., 2012) or 3D-Geographic Information System (GIS) environment (Pepe et al., 2021). Grasshopper allows modelling using vector-type tools such as basic geometric and 3D shape sets (parametric primitives) are available that can be used to create complex objects through assembly, modification and deformation operations. It is also possible to create 3D shapes starting from two-dimensional forms and paths. In fact, through an extrusion operation, it is possible to generate the third dimension starting from a two-dimensional shape (open or closed) according to an axis that can have any inclination with respect to the starting plane. This last approach is widely used for modelling buildings in the urban environment both as prismatic solids and with rather complex 3D geometry. In order to highlight the potential of this Rhino/Grasshopper combination in urban modelling, different levels of detail and geometric complexity are discussed in the paper. In particular, 4 case studies are examined: *i)* the extrusion of simple and complex geometries; *ii)* the construction of 3D models from numerical cartographies; *iii)* the construction of 3D models using Open Street Map (OSM) data; *iv)* the construction of the 3D model from a point cloud of a church belonging to the cultural heritage and characterized by a complex geometry.

2.2. Extrusion of simple and complex geometries

The first research activity concerned the building of a rather simple three-dimensional geometry using Grasshopper. The resulting main design phases can be divided into the following activities: *i)* creation of the polygon; *ii)* extrusion of the polygon; *iii)* vector displacement of the geometry and; *iv)* rotation of the geometry around its own axis.

The first task involves the construction of a polygon on a regular square base. The code provides for the insertion in the canvas of the tool "Polygon", to which the desired number of sides (Segments) and the length of each side (Radius) can be attributed; in this way, Rhino defines the construction of a regular figure in the XY plane, centred on the origin of the axes. The next phase consists in the extrusion of the polygon by means of the tool "Extrude > Unit Z": the directional plane was then attributed through which the third dimension is obtained; in Rhino the square is developed along the Z axis characterizing the formation of a straight parallelepiped of variable height by assigning a certain value to the multiplication unit with the appropriate slider. A further attribute to be assigned is the angle at which the geometry produced is arranged in space. Through the "Rotate 3D" option, the construction can rotate around its axis according to the angle defined in the slider. Therefore, the polygon on Rhino will rotate around the XZ axis, arranging itself in space in the most appropriate way. Once built the 3D model, we can observe that it was still centred in the origin of the axes; at this stage, the objective of this third phase is to allow the figure to move in three-dimensional space. The last step, i.e. the vector movement of the solid was allowed through the "Move" tool, to which the three vector components X, Y, Z and their respective domains are associated. The representation of the canvas and the result of the modelling displayed in Rhino is shown in **Fig.** 1.

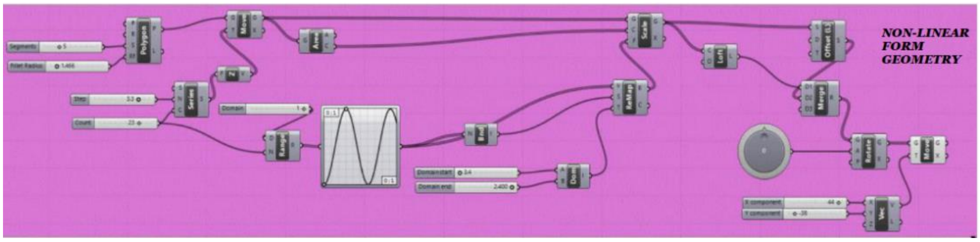


(a)

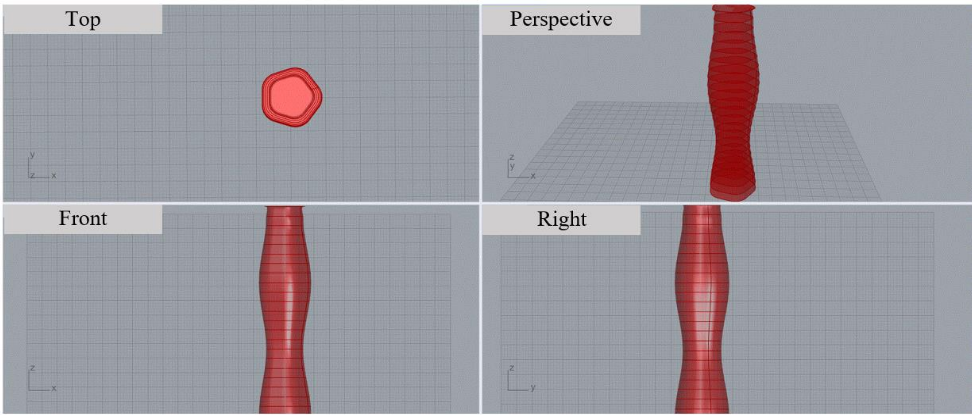
(b)

Fig. 1. Building of simple geometries using Grasshopper: code generated in the Grasshopper canvas (a); view from several perspectives, i.e. top, front, right and perspective view (b).

Once a rather simple solid was built, the possibility of realising complex 3D models was evaluated. The basic surface was acquired using the "Polygon" tool, through which it was possible to define the number of sides and relative dimensions: a pentagonal plan surface was chosen, with convex vertices using the "Fillet Radius" slider. Next, the number of floors of the building was identified and defined using the "Move > Series" command and the area ("Area") was attributed, defining the relative centres that make up, consequently, the central axis of the building itself. In order to set the sinusoidal shape of the walls, a "Graph Mapper" has been adopted, to which a domain ("Construct Domain") is associated that returns the diversified dimensions of each single floor, giving the required shape: everything is carried out by the "Scale/Offset Surface Looser" tool. Once the "Loft" surface has been applied, a first image of the tower has been reproduced; then, it has been possible to proceed with the union of the two geometries through the "Merge" command, generating a single complex. The tools "Rotate3D > Knob" and "Move > Vector XY" were used to allow the solid to rotate and move in space. The design realised in the canvas and the results of the model are reported in **Fig. 2.**



(a)



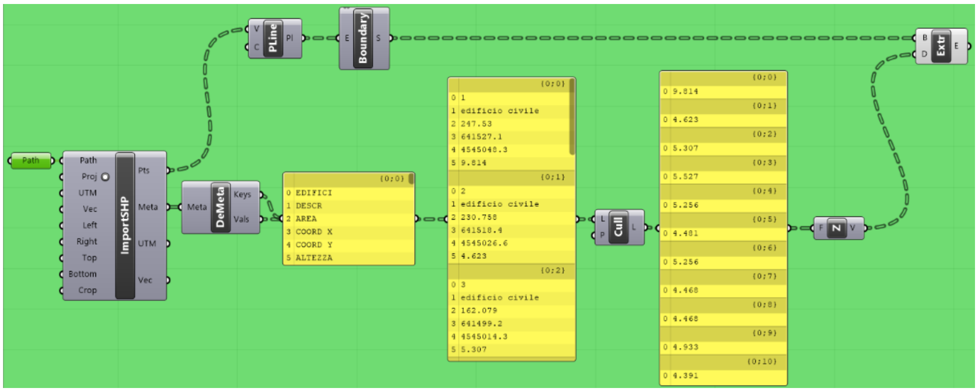
(b)

Fig. 2. Construction of non-linear geometries: code generated in the Grasshopper canvas (a); view from several perspectives: top, front, right, perspective (b).

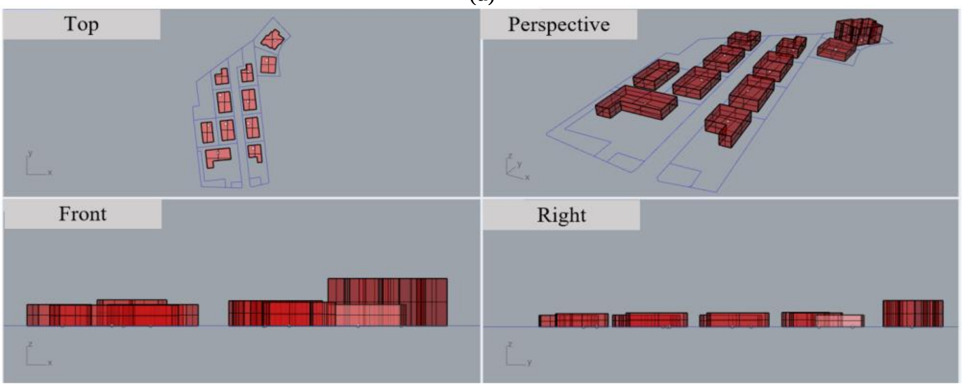
2.3. Building 3D models from numerical cartography

Using a cartography, it was possible to proceed to the design of 3D models, representing multiple buildings diversified by geometry and typology located in a precise spatial reference system. The area taken into consideration concerned part of the territory of the city of Palo del Colle (Bari, Italy); the aim of this task was to predict, starting from numerical cartography, the extrusion in space of some buildings constituting a residential area, i.e. to build in LOD1 model. The first step involved the acquisition of the regional technical map in ESRI shapefile format through the website dedicated to the thematic cartography of the Apulia region. Subsequently, using "Urbano" plugin (Dogan et al., 2020), it was possible to import this file through the use of "ImportSHP" tool: points corresponding to the vertices of each building will be returned in Rhinoceros. Subsequently, the code "Polyline>

Boundary Surface" was linked to the "Points" parameter in order to recreate the base surface of each component belonging to the shapefile. Urbano plugin introduces a fully automated workflow to load in contextual GIS, OpenStreetMap and Google Places data to set up an urban mobility model; in addition, in the version 1.2, Urbano supports terrain and allows the construction of site models with 3D terrain, buildings and roads in easy way. In this case study, the aim was to extrude the building using the properties or better the values present in the "Metadata". In order to distinguish the numerical data from the corresponding descriptions, the tool "Deconstruct Metadata" has been inserted in such a way that, by means of a "Panel", the attributes for each building are clearly visible. Among all the characteristics, the one of main interest is that relative to the heights of the buildings, therefore the "Cull Pattern" command was inserted to remove the superfluous elements from the list. Finally, the civil dwellings were extruded by associating these values to the code "Extrude > Unit Z". The representation of the canvas and the realised 3D model are shown in **Fig. 3**.



(a)



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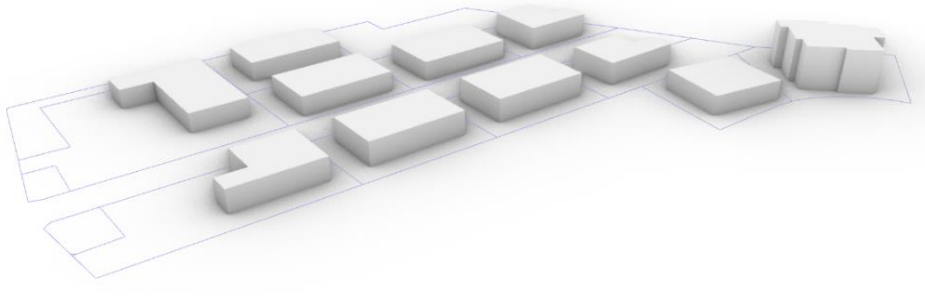
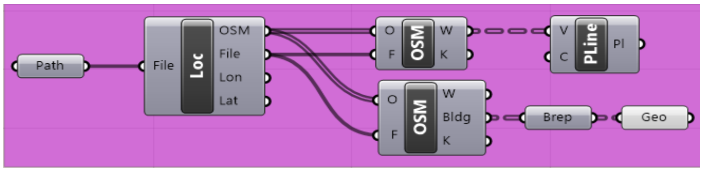


(c)

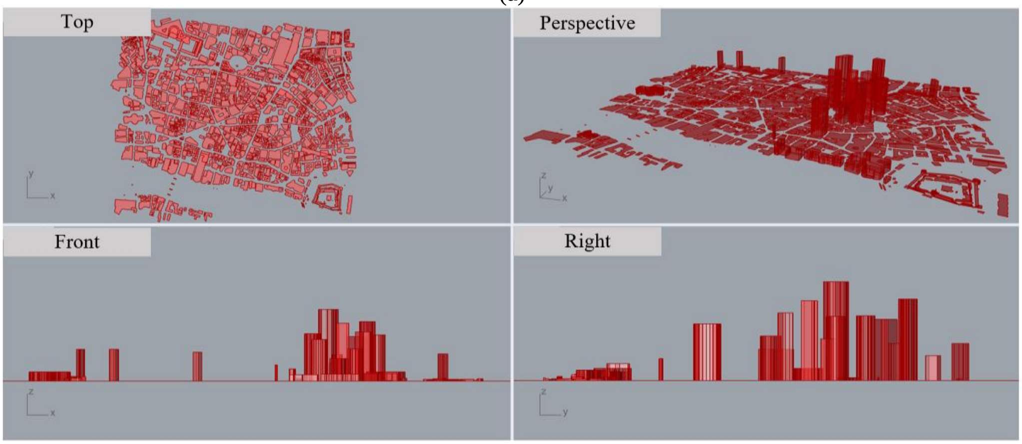
Fig. 3. Building geometries from numerical cartography: code generated in the Grasshopper canvas (a); view from several perspectives: top, front, right, perspective (b); perspective view of buildings (c).

2.4. Building 3D models using Open Street Map

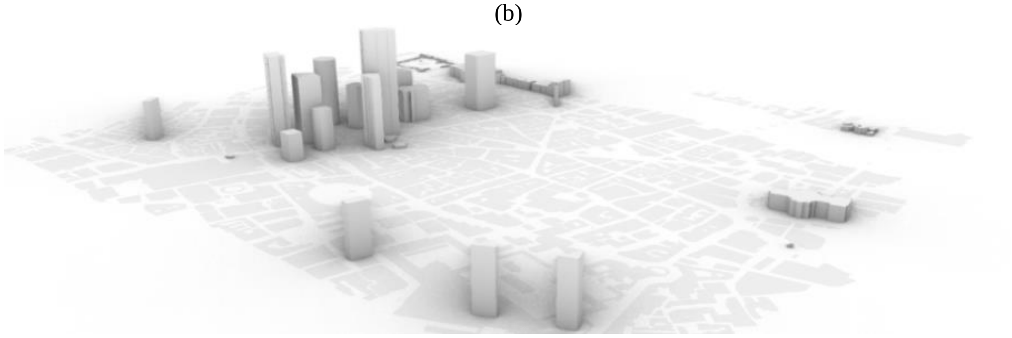
For further 3D design, geospatial data available on the OSM website were used. Since the model available from this web platform can be easily managed in the Rhinoceros/Grasshopper environment, the geospatial data are used for our purpose, i.e. to create a parametric 3D model at urban scale. The Area of Interest (AOI) can be identified through a manually adjustable window set on the OSM or by entering the relative coordinates geographic coordinates of the four vertices of the window itself. It should be emphasised that not all cities are covered with 3D models. Once the AOI was selected, the .osm file can be downloaded. OSM files are XML based and typically used to export an extent of the OSM GIS service into other applications. Once the file in .osm format was acquired, it was imported into the Grasshopper canvas using the following code: "File Path > Location > OSM Data" provided by the ELK tool (Webb, 2014). This step is performed by connecting the points together using the "Polyline" tool to outline the perimeter of the individual buildings. At the "OSM Data" command we set the "Create 3D Buildings" input to extrude the heights provided by the data acquired from the .osm file: in this phase not all the buildings of the study area will be extruded, but only the known ones. The contour surface was then created using "Geometry > Brep". An illustrative case reproduced in this project phase of part of the 'City' of London at in LOD1 is reported in **Fig. 4**.



(a)



(b)



(c)

Fig. 4. Building 3D geometries from data obtained from Google Street Map: code generated in the Grasshopper canvas (a); view from several perspectives: top, frontal, right, perspective (b); perspective view of buildings in a portion of the City of London.

2.5. Building 3D models from point cloud

The structure identified for the 3D modelling of complex buildings concerns the Saint-André Cathedral, located in the city of Bordeaux, in the south-west of France, which is situated in an important historical urban centre dating back to the Enlightenment period and which was declared a UNESCO World Heritage Site in 2007.

The modelling involved the parametric modelling of the Saint-André Cathedral. This operation consisted of three phases: *i)* data collection; *ii)* acquisition and modification of the point cloud and; *iii)* Parametric modelling of the structure.

The dataset used for structure modelling was obtained from the point clouds generated by Airborne Laser Scanner-ALS sensors and a dataset of colour images generated by nadir and oblique cameras (Costantino et al., 2021). For data collection, a photogrammetric flight over the city of Bordeaux was carried out using a twin-engine aircraft (Partenavia P68C) at an altitude of 850 m above ground level. The hybrid sensor mounted on the aircraft was the "Leica CityMapper" specifically designed for aerial urban mapping. The main characteristics of the sensor are: *i)* pulse repetition rate up to 700 KHz; *ii)* programmable return pulses of up to 15 returns, including intensity, pulse width, area: *iii)* curved waveform and slope attributes; *iv)* full waveform recording option at down-sampled frequencies; v) oblique scanner, with various scanning patterns; *vi)* real-time LiDAR waveform analysis, including acquisition of waveform attributes.

The main data used in the geometric modelling of the structure was derived from the point cloud generated by the Leica Hyperion LiDAR ALS unit and available in LAS format. The survey produced a point cloud of 100,924 points, with a density on the horizontal surfaces (roofs and ground) of 7-8 pts/m2 and georeferenced in the WGS84/UTM (World geodetic System/Universal Transverse of Mercator) zone 30 North projection, EPSG:32630 (Nicolai & Simensen, 2008; Dardanelli et al., 2020).

Using the Cloud Compare software (Girardeau-Montaut, 2014), the point cloud was cleaned from "noise" or better all the parts that do not contribute to the parametric modelling of the building, such as the vegetation surrounding the cathedral, were deleted (**Fig. 5**).

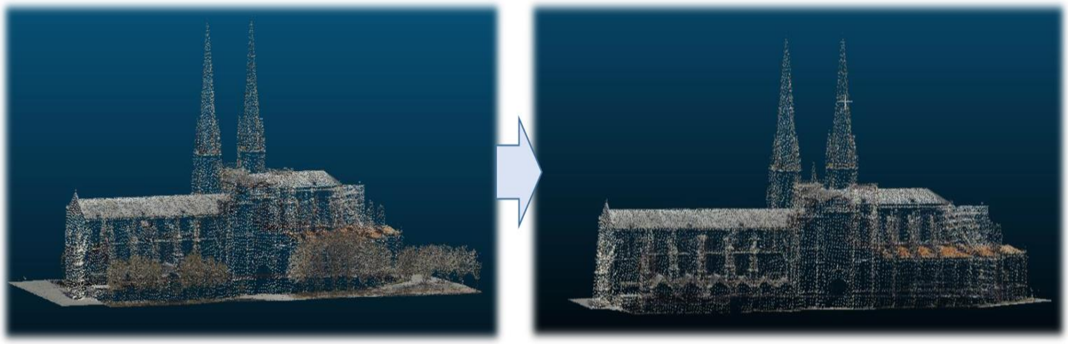


Fig. 5. Point cloud cleaned of "noise" and vegetation.

Subsequently, the point cloud was imported into Rhinoceros software. To create the parametric objects of the elements of the structure under consideration, Arena4D plug-in was used. Indeed, this latter plug-in also offers powerful point cloud manipulation tools, such as slicing, clipping, smoothing, lighting, magnification, colour ramping and exporting (Pepe & Costantino, 2021). In order to reconstruct the 3D model with different profiles, slicing command was used. In fact, this tool allows to cut the point cloud in several profiles. In Rhino environment, the different profiles were vectorised and interpolated by *Non Uniform Rational B-Splines* (NURBS) surfaces, which are mathematical representations of 3D geometry. This surface precisely defines any shape: from a simple line, to a circle, arc or curve, to the most complex free-form or organic 3D solid or surface.

In the first task, we extruded the central nave, the main towers located near the side entrances and those located along the sides of the cathedral. Then, the roof was built, which has a non-homogeneous conformation for all the layers involved; therefore, we opted for the use of the "Loft" tool, which has the objective of generating a surface along a series of selected curves. The same process was applied to generate the spires above the towers on the left-hand side of the structure and the five chevets at the top. The designed canvas and the result of the modelling in LOD2 are shown in **Fig. 6**.

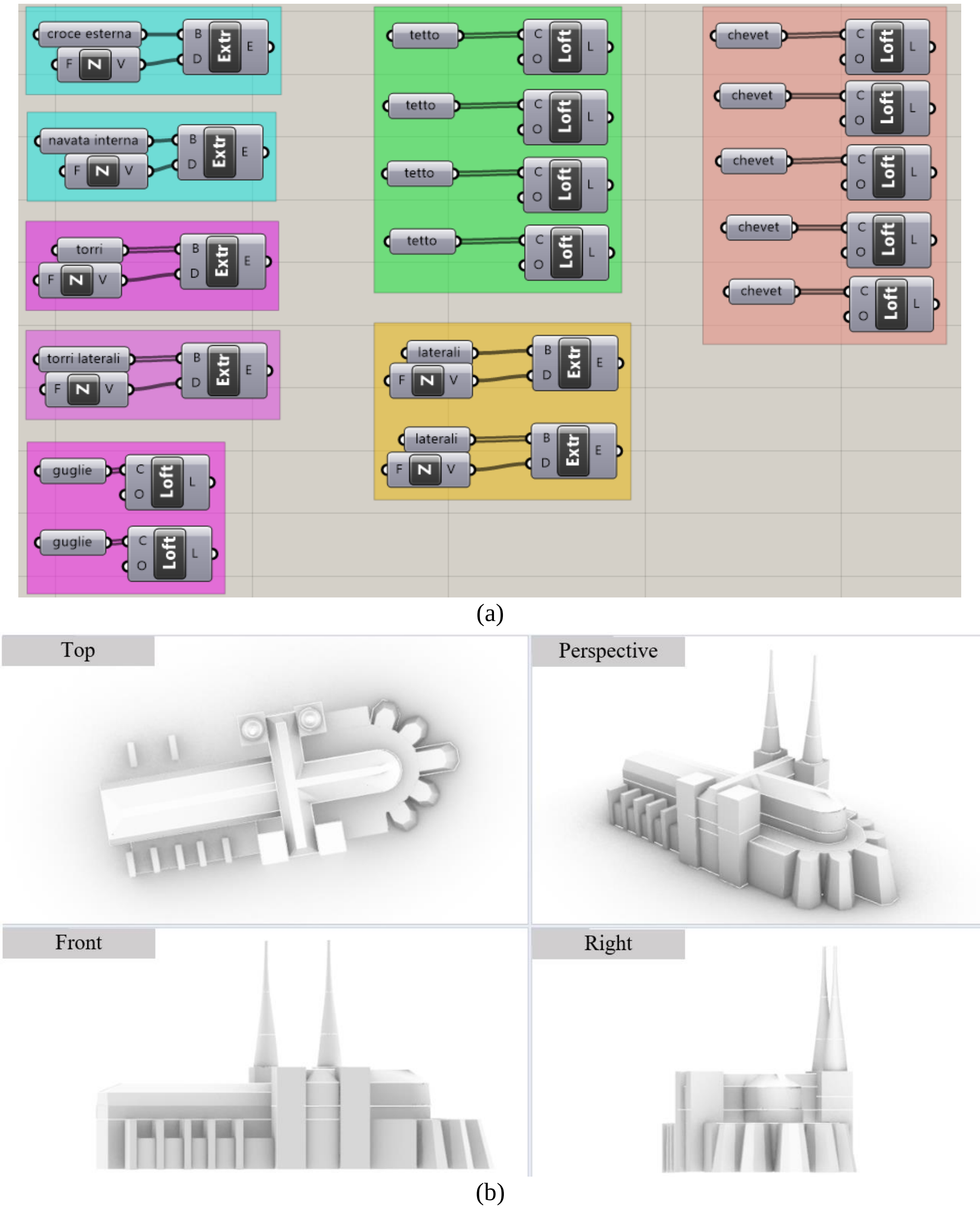


Fig. 6. Building 3D geometries from ALS data: code generated in the Grasshopper canvas for each element of the church (a); view from several perspectives: top, front, right, perspective of the building with complex geometry (Saint-André Cathedral, Bordeaux, France).

3. RESULTS AND DISCUSSION

In this paper, the 3D semantic modelling approach using Rhinoceros v.7/Grasshopper software was addressed.

In the first phase, simple elements were modelled in order to identify the level of depth, automation and sharing of the 3D models generated in this environment. The codes generated in the Grasshopper canvas formed the basis for the subsequent, more complex phases. The management in this software can be implemented using multi-sources such as, for example, numerical cartography (ESRI shapefile) or point clouds in LAS format.

The parametric approach was applied to objects, such as buildings, which can be deduced from numerical cartography; different design alternatives were experimented until generating a code that allows the immediate import of the shapefile into Grasshopper. In this way, it was possible to create three-dimensional models quickest and simplest way. Moreover, through a specific study, it was ascertained that in the case of areas of interest of relevant importance, it is possible to choose for the acquisition of geospatial data through the Open Street Map website, as it returns directly and with extreme ease a file compatible with Rhinoceros/Grasshopper. From the analysis of the geo-data, it was possible to note that in the case study of the 'City' of London only few specific buildings underwent extrusion: the most renowned ones.

Finally, an experiment was carried out on urban buildings with a rather complex geometry starting from a cloud of points generated by an airborne ALS sensor. The modelling involved several long working phases and the use of different software such as Cloud Compare and Rhinoceros/Grasshopper. Despite the complexity of the geometry, the parameterization of the structure was quite faithful to the real model, i.e. the model represented by a point cloud. Once the parametric modelling has been carried out in Rhino, through the use of a specific plug-in called Rhino.Inside, it is possible to incorporate the model into Revit (BIM software developed by the Autodesk company).

In particular, through Rhino.inside.Revit it is possible to take advantage of an integration platform between Rhino and Revit. This add-on allows Rhino and the respective Grasshopper applications to be loaded, providing a collection of new components for interaction with Revit. Rhino.inside.Revit provides a set of tools for switching between Rhino free-form modelling and BIM modelling. Using this system, through design in the Grasshopper canvas it was possible to import the 3D model of the cathedral inside the Revit software.

4. CONCLUSIONS

Programming and modelling in Rhinoceros and Grasshopper has enabled the building of high quality parametric 3D models. The different case studies have shown the ease and enormous capacity of this environment to design and plan at different levels of detail, from a single building to an entire city. Furthermore, it is possible to model even complex geometries, as shown in the case study of the Saint-André Cathedral in Bordeaux.

This process, based on the use of Rhinoceros and Grasshopper, will be increasingly used in the future to increase IT and technological efficiency in the management of individual buildings and, at the same time, of urban areas, factors which affect economic, social and, above all, environmental aspects. Furthermore, these tools represent the basic elements for the construction of 3D models suitable for subsequent analysis and cataloguing of geo-data in a BIM (or Heritage BIM-HBIM) or 3DGIS environment.

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