An effective Method For 3D Modelling of Urban Areas from Aerial Images and LiDAR data

Massimiliano Pepe [1], Domenica Costantino [2], Vincenzo Saverio Alfio [2], Ariana Grimaldi [2]

[1] Department of Engineering and Geology, University “G. d’Annunzio” of Chieti-Pescara, 65127 Pescara, Italy – massimiliano.pepe@unich.it

[2] Department of Civil, Environmental, Land, Building Engineering and Chemistry (DICATECh), Polytechnic University of Bari, 70125 Bari, Italy – (domenica.costantino, vincenzosaverio.alfio, arianna.grimaldi)@poliba.it

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Abstract

The aim of the paper is to identify a suitable methodology for the construction of 3D City Models (3DCM) from geospatial data. Recently, the use of hybrid sensors i.e. nadiral and oblique cameras supplemented by Light Detection And Ranging (LiDAR) sensors equipped on an aerial platform, are becoming useful instrumentation for mapping urban areas. In fact, the manuscript shows the use of such instrumentation for the production of a 3D City Model processed in the City Engine environment, starting from a geomatic dataset composed of a point cloud and a series of images covering a portion of the historic centre of Bordeaux (France). The results show the quality of the 3D models in LOD3, generated on the study area, in terms of architectural details, textures and semantic contributions.

1. Introduction

1.1 Survey and 3D modelling in the urban context

Three-dimensional city modelling is an important task for efficient building management, especially in historic centres.
Cultural Heritage (CH) in historic centres represents a combination of tangible and intangible elements that reflect the historical, artistic and social identity of a community, representing the historical memory, traditions, architecture and social relations that characterise the cultural heritage identity of the area. Moreover, historic city centres are often characterised by an urban fabric that tends to be irregular, with narrow, winding streets that follow the contours of the land or the original layout. Within this urban fabric, there are assets and architecture that reflect historical and social functions: buildings with historical and artistic value such as noble palaces, churches, public buildings and traditional houses. Therefore, the creation of a three-dimensional model allows a complete and detailed view of the urban morphology, facilitating the analysis and understanding of the structure of buildings, streets, squares and the surrounding environment. In this context, surveying historic centres with geomatic techniques is still a major challenge today, given the complexity of urban conformation and structure. Over the years, the construction of three-dimensional models was carried out in different ways and using different geomatic surveying techniques. The combination of these technologies makes it possible to create a digital twin of the historic centre, useful for multiple applications, from heritage conservation to urban planning (Somanath et al., 2024).
In this context, Parrinello and Picchio 2019, describe an article outlining an image acquisition methodology developed for the documentation of the historic center of Bethlehem, in the Middle East territory. Specifically, the paper shows the application of several photogrammetric survey campaigns in a portion of the historic city, acquisition issues and morphometric reliability tests of each output, to develop a general Structure from Motion (SfM) database consisting of different levels of definition of photogrammetric models of the historic center.
Bevilacqua et al., 2019, addresses the need for a 3D survey and reconstruction approach to analysing all the iconographic sources and assessing, with respect to these sources, any changes and lost architectural volumes, showing the results obtained on the case study for the reconstruction of the Palazzo di Cosimo dè Medici, on the site of the Fortezza Vecchia (Livorno, Italy) heavily damaged by bombing during the Second World War and subsequently razed to the ground.
Croce et al., 2019 address the integration and processing of different geomatics techniques for the Certosa di Calci case study to generate parametric information models from point clouds acquired through 3D surveys.

Costantino et al., 2021 show a data-driven free-form modelling method dedicated to parametric modelling of complex-shaped buildings using Airborne LiDAR Scanning (ALS) data and aerial images.

Mataloni et al. 2023, illustrates the possibility of integrating geomatic techniques in order to obtain a georeferenced point cloud of an Italian historic centre, both at the urban scale and at the scale of individual artefacts, as well as for the production of high geometric resolution orthophotos.
Franzini et al, 2023 used the Leica CityMapper-2 hybrid sensor evaluating the quality of aerial LiDAR data from a significant portion of the metropolitan of Milan (Italy) area with respect to accuracy, precision, and congruence between strips and point density estimation.
Pepe et al., 2022 apply SfM and Multi View Stereo (MVS) approach to airborne images captured by nadir and oblique cameras to build 2.5D map and 3D models for historical centre of Bourdeaux.
Lei et al., 2024 introduces a method for constructing ground-level geographic scenes utilizing mixed data from Leica CityMapper. The authors detail the primary steps and essential technologies integral to this approach, and they validate and analyse the method through a case study of actual 3D construction at the provincial level.

Therefore, this manuscript fits into the context of urban-scale 3D modelling using geospatial data from an aerial platform.

1.2 LOD concept and ArcGIS City Engine

To optimise the visualisation and management of spatial data in 3D modelling, it is necessary to introduce the concept of Level of Detail (LOD). In fact, the LOD makes it possible to adjust the complexity of the 3D model according to the observer's point of view, in other words, it represents the degree to which the element geometry and information have been considered (Zhang et al., 2022). Low LODs correspond to models with little detail, while high LODs correspond to models with a high level of geometric complexity and detail. In the field of 3D modelling, LODs can be classified as:

- LOD0: the simplest representation, often just a point or an icon to represent the building.
- LOD1: models with simple volumes, such as 3D blocks or extrusions of building footprints.
- LOD2: models with more precise geometry, but without architectural details (e.g. sloping roofs, more complex building shapes).
- LOD3: models that include details such as windows, doors and facades.
- LOD4: models with complete interiors and very fine details, often used for very close-up views.

In the field of Geographic Information System (GIS) software, Esri CityEngine is a software designed to create large-scale 3D urban models, mainly used in areas such as city planning and urban simulation, integrating geographical city data with other infrastructure data (Ibrahim et al., 2022). In addition, CityEngine uses a scripting language called CGA (Computer Generated Architecture), which enables the generation of buildings with different LODs automatically, based on user-defined rules; in this way, the number of floors, openings, colour, shapes, etc. can be controlled automatically (Watson et al., 2018). For example, CGA rules can be specified that create simplified versions of a building at greater distances. CityEngine can automatically change the LOD according to the camera distance. For example, when performing a fly-through or viewing the city from a distance, buildings are shown at a lower LOD, which then become more detailed as you get closer (Sugianto et al., 2023).

2. Data and Method

2.1 Case study

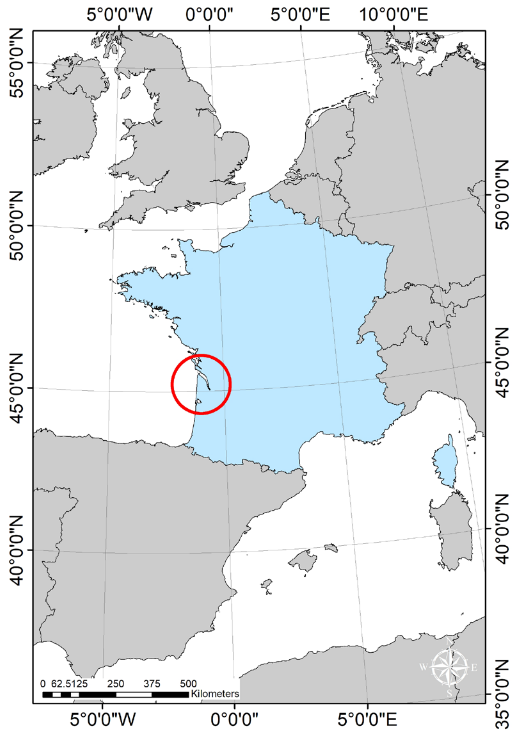
The study area is located in the historic centre of the city of Bordeaux in south-western France. The city is renowned for its distinctive historic city centre dating from the Enlightenment period, which was declared a UNESCO World Heritage Site in 2007 (Figure 1).

2.2 Methodological Approach

The methodological approach can be divided into several stages:

- Acquisition of the point cloud.
- Data processing in the GIS environment.
- LOD 2 and LOD 3 modelling.
- Texturing and informatisation of the 3D model.
- Model export.

The first step concerns the acquisition of geospatial data over an urban area. The possibility of acquiring both LiDAR data and multi-camera systems makes it possible to obtain numerous geomatic information useful for 3D reconstruction and modelling. In particular, the coloured point cloud is filtered, cleaned and segmented in order to obtain characteristic information of the buildings that make up the urban scene. Once the point cloud has been acquired, it is necessary to manage this information in a GIS environment in order to construct features with attributes.



(a)

(b)

Figure 1. Location (a) and district of the historic centre of Bordeaux analysed (b).

In other words, semantic modelling in the GIS environment enables the reconstruction of 3D models that can be linked with other databases. In this way, it is possible to obtain a detailed and accurate 3D model from the point cloud using the dedicated ArcGIS CityEngine software.
The subsequent phases finally involve the processing of the 3D model starting from LOD0 until obtaining a LOD3, also ensuring the application of textures relative to each building from the nadiral and oblique photos and, where possible, assigning informative attributes relative to the individual buildings constituting the neighbourhood under study (street, destination of use, activity name, etc.). The resulting 3D model is then validated through a comparison between the point cloud (Wang et al., 2023) and the generated model. Finally, it is possible to export the generated model in the CityGML format, guaranteeing the visualisation of the 3D model within the urban context via Google Earth.

2.2.1 Acquisition of the point cloud: In order to obtain the construction of a complete, precise and reliable 3D model, it is necessary to proceed with a metric survey that allows the acquisition of the geometric and informative data relative to the object of study.

The dataset used for modelling the structures consists of a point cloud (*.LAS), surveyed by the Leica Hyperion LiDAR ALS unit and a dataset of colour images, generated by a nadir and oblique cameras (Pepe et al., 2019).

Data collection involved a flight over the city of Bordeaux using a twin-engine Partenavia P68C aircraft, flown at an altitude of 850 meters above ground level (AGL), equipped with a Leica CityMapper hybrid sensor, which is specifically designed for aerial urban mapping.

Leica CityMapper is an aerial sensor specifically designed for aerial urban mapping and offers high performance 3D data collection, being equipped with a hybrid oblique imaging system with LiDAR aerial sensors, for the production of high-quality images even in difficult lighting conditions (Figure 2).

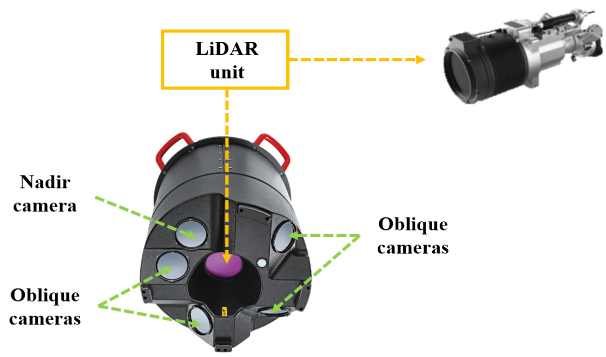


Figure 2. Leica CityMapper imaging and LiDAR sensors

In particular, the image acquisition compartment consists of a nadiral image sensor and four oblique cameras. In particular, the nadiral sensor has the following characteristics:

- Leica RCD30 CH82 multispectral camera.
- 80 MP, 5.2 μm pixels.
- Mechanical bi-directional motion compensation.

The 4 sensors relating to oblique cameras, are characterised by:

- Leica RCD30 CH81 mini RGB camera.
- 80 MP, 5.2 μm pixels.
- 45 degrees viewing angle.
- Mechanical in flight directional motion compensation.

For the LiDAR sensor, the main features are:

- Pulse repetition frequency up to 700 KHz
- Laser divergence 0.25 mrad
- Up to 2.500 m altitude range
- Oblique scanner, with various scan patterns
- Up to 40 degrees field of view
- Real time LIDAR waveform analysis
- Typical 8 p/m2 at City Mapping

The survey produced a point cloud of 100,924 points, with a density on horizontal surfaces (roofs and ground) of 7-8 pts/sqm and georeferenced in the WGS84-UTM 30 North Reference System.

Using Cloud Compare software, it was possible to subdivide the figure along the Z axis and clean the point cloud of the surrounding vegetation, since it was of little relevance to the modelling, using the “Multiple Slices” tool. This step was fundamental in order to separate the area of the roof from the rest of the building for subsequent more efficient processing and to identify the three main guiding planes, relating to the base of the building and the development of the roof, in order to guarantee precise modelling in the subsequent phases, since it was not possible to generate (at this stage) a detailed contour.

2.2.2 Modelling in ArcGIS City Engine environment: In order to import the point cloud into the CityEngine software, in the ArcGIS PRO environment a conversion from LAS format to Multipoint was carried out, and subsequently from Multipart to Single Part, in order to obtain the model in shapefile format, finally setting the relative reference system.
The modelling of the geometries was carried out starting with the most complex area, i.e. reconstructing the area above the structure and accurately modelling the individual roofs with the creation of an initial LOD0 (2D) model following the course of the point cloud and the upper guide plane relative to the roofs. By means of the Push Pull tool, it was then possible to reproduce the third dimension of the roof by joining the geometry with the second, upper guide plane, obtaining prisms, so as to obtain a LOD1 model (Figure 3a).

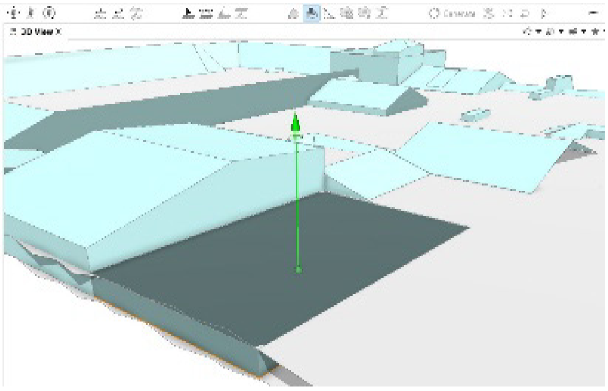
In order to represent the double-pitch roofs, a line was drawn on the upper face of the prism so as to recreate the roof ridge line, and then proceeded to the relative extrusion through which it was possible to move the ridge line along the three x,y,z directions (Figure 3b) so as to reproduce with high precision the roof course outlined by the point cloud.

Subsequently, the compatibility between the margins of the constructed geometry and the variation of the course of the point cloud was evaluated and, by applying this process for each roof of the entire complex, it was possible to obtain a LOD2 model of the roofs (Figure 3c). The same process was applied to reconstruct details and protruding elements such as gutters and windows in order to increase the degree of detail of the model (Figure 3d).

Overall, these elements present a non-homogenous and rather complex conformation, therefore, this phase required extreme precision in following the perimeter of the guide planes and the course of the point cloud.

Once the area relative to the roofs had been reconstructed by extending the lateral elements of the pitches downwards, the walls of the building were constructed by following the distance between the second guide plane of the roofs and the one relative to the base.

A LOD2 model of the entire complex was thus obtained, resulting in a geometry congruent with both the point cloud and the guide planes (Figure 3e).



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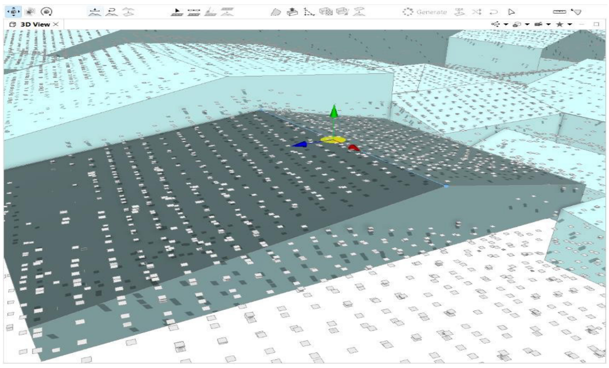

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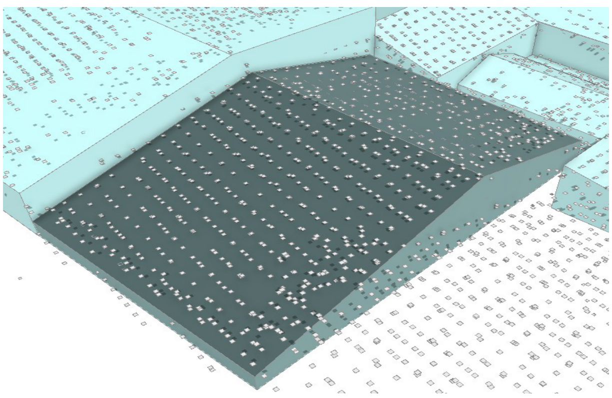

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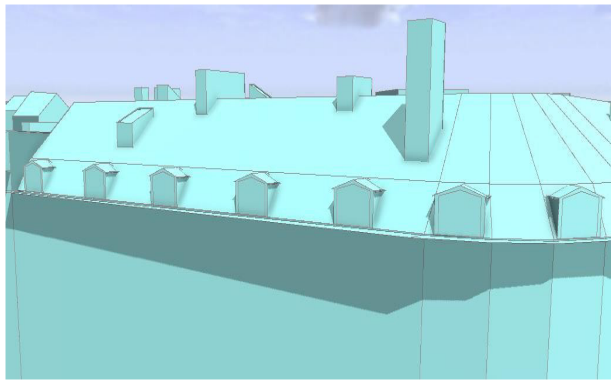

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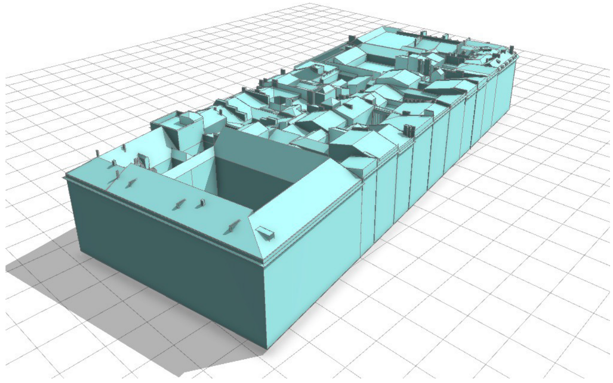


(e)

Figure 3. Modelling in City Engine: creation of roofs with the “Push Pull” tool (a), extrusion and repositioning of the ridge line (b), 3D double pitch roof congruence check - point cloud (c), detail elements (d).

2.2.3 Texturing and informatisation of the 3D model:

Finally, textures were assigned to each building; in particular, for the texturing of the roofs the Nadiral photo was most often taken as reference, while for the side façades the photos taken with the cameras in the left, right and forward positions were appropriately adopted.

Although the aerial photos are tilted, it was also possible to make angle corrections within the CityEngine software using the Crop Image tool, with the aim of ensuring a considerably more precise and reliable display of the texture. This tool generates a manually adjustable frame on the image of interest in order to return a new cropped figure orthogonal to the observer.

Once the images of roofs and side walls had been edited, it was possible to apply the texture to each geometry with the Shape Texturing tool.

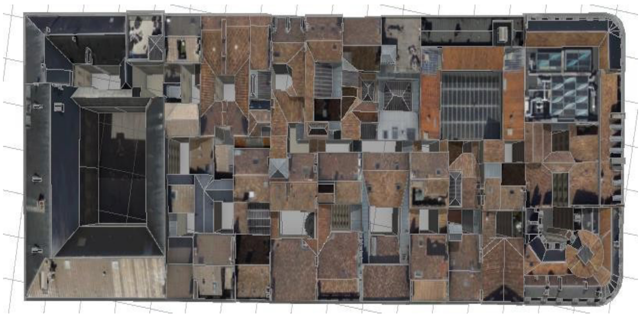
This process was, however, rather complex both for the south-west façade due to its extreme proximity to the adjacent building, and for the innermost areas of the complex. Therefore, it was not always possible to apply the texture to which it belonged, but rather one of similar or analogous architecture acquired from adjacent structural elements.

3. Results

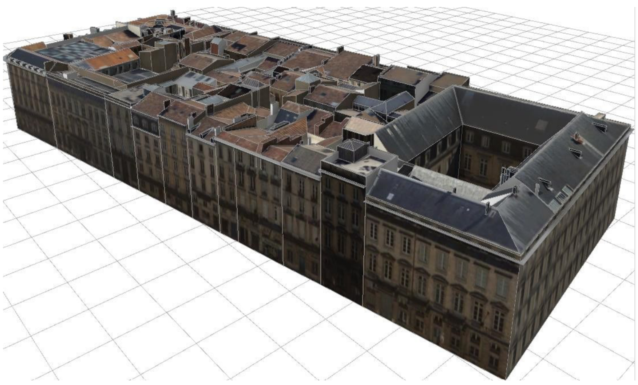
The final elaboration is therefore rather true to the trend of the point cloud and comparable with the starting photogrammetric images, obtaining a degree of detail of the LOD3 type (Figure 4). Within the CityEngine software it was possible to assign all the information related to the individual shapes constituting the element under study, in order to recreate an information database.

The information relating to the individual buildings was acquired by consulting the Open Street Map (OSM) and Google Maps software, and these were matched in order to obtain a complete picture of the activities and uses affecting this complex.

Finally, it was possible to export the 3D model according to the standardised CityGML data model, in KML format. This step ensured the georeferenced positioning of the structure within the open browser Google Earth Pro, so that its visualisation within the city context could be appreciated.



(a)



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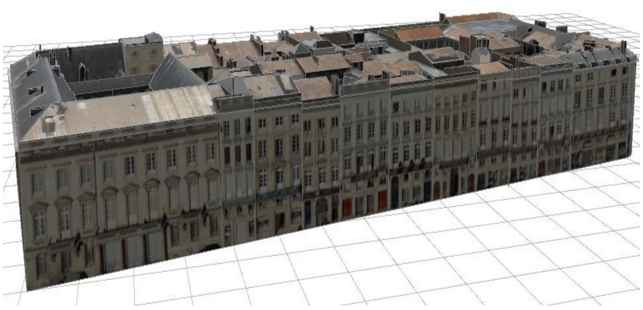

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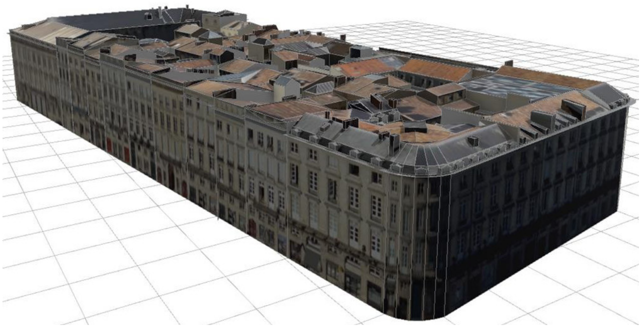

(d)

Figure 4. Textured model results in LOD 3: Top view of the analysed historic centre (a) and 3D perspective views (b, c, d).

In order to estimate the accuracy and precision of the 3D model generated with the illustrated methodological approach, a comparison using the Cloud to Mesh (C2M) algorithm in Cloud Compare software was performed (Girardeau-Montaut, 2016). The C2M algorithm implemented in Cloud Compare software is a method used for accuracy analysis and validation of 3D models by comparing scanned data with a generated or simulated 3D model (Gura et al., 2024).

In fact, by selecting the mesh as the reference entity, the C2M algorithm calculates the distances from the point cloud to the mesh, configuring the parameters related to "Maximum distance", i.e. setting a maximum distance (in mesh units) within which the distances between the point cloud and the mesh will be calculated, "Signed distances" to determine positive and negative distances based on the position of the cloud with respect to the mesh surface, and "Flip normals" in the case where the mesh normals are inverted with respect to the direction of the cloud.

Therefore, through this processing, it was possible to calculate the Euclidean distance between the original point cloud and the generated 3D model. In this case study, the Root Means Square Error (RMSE) value of 0.008 m and the Standard Deviation value of 0.567 m, were obtained. This means that the methodology proposed in this study makes it possible to obtain not only detailed 3D models from the point of view of reconstructing architectural elements, but also accurate and valid from a metric point of view.

4. Conclusion

In the present work, the different potentials of the 3D City Model were addressed.

Subsequently, the relevant knowledge was put into practice and an experiment was conducted on an urban complex from a point cloud generated by an airborne ALS sensor and several cameras.

In this work, all the steps necessary to obtain a 3D model with a high level of detail of LOD3 from hybrid sensors data were described.

The relative modelling involved multiple work steps and the use of various software such as Cloud Compare, ESRI ArcGIS and finally ESRI ArcGIS City Engine, the latter being fundamental for the purposes of three-dimensional modelling.

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Through the various steps described in the preceding paragraphs, the software’s considerable potential in being able to manage the various levels of definition (from a LOD0 to LOD3) and to guarantee the inclusion of semantic and informative data relating to the individual structural elements was thus discovered.

However, a significant problem encountered is due to the application of some textures that are not framed within the photogrammetric images due to the complex location of the structure in the urban complex: this has compromised the quality of the visualisation of some facades such as the one to the south-west. Therefore, on the whole, a rather detailed 3D model was nevertheless obtained that can be compared with the point cloud and the photogrammetric starting data. The modelling of the structure was therefore quite faithful and comparable with reality.

This process is the basis of 3DCM and/or BIM modelling, which are a fundamental part of the design process in order to increase the sustainability of buildings and, at the same time, of urban areas, factors that influence economic, social and, above all, environmental factors. In addition, the construction of 3D models of entire urban contexts, integrated with semantic information, descriptive and contextual data on the model elements, could improve the understanding and usefulness of the information contained in the three-dimensional representation of cities.

In this way, all studies and developments related to urban planning, infrastructure monitoring and even emergency management would also be facilitated.

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