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FROM DATA TO 3D DIGITAL ARCHIVE: A GIS-BIM SPATIAL DATABASE FOR THE HISTORICAL CENTRE OF PAVIA (ITALY)

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SUMMARY: *Historical city centres are called to be witnesses of the past while supporting modern life. The competing needs for conservation and transformation involved in their development introduce a complex and multidisciplinary problem, which can be handled only by using proper tools. In this framework, the definition of shared digital archives able to collect and organize heterogenous data is believed to be the first step for the creation of an effective knowledge base, capable of activating analyses and supporting decision-making processes. The study presented here starts from the discussion of the requirements that an information system on historical centres should meet, and proposes a workflow based on the interoperability between GIS (Geographic Information System) and BIM (Building Information Modeling) aimed at the realization of a spatial relational database founded on CityGML. The OGC (Open Geospatial Consortium) standard was chosen in view of its capacity of representing the objects with their geometrical, topological and semantic properties, by specifying their relationships in a hierarchical environment. With the idea of introducing a repeatable model, the whole process starts from easily retrievable data on the city and makes use of standard data models, classification systems, programming languages and, as much as possible, of open software and contents. In order to test and validate the process the case study of the historical centre of Pavia (Italy) is presented as an experiment at the urban scale, while a single historical building complex is modelled for the assessment of the compliance to higher Levels of Detail. The workflow used to manage and display the information employs Visual Programming Language (VPL) and follows a four stages process: the retrieval of the input data, the informative modelling (GIS or BIM), the conversion in CityGML and the inclusion in the relational database. As a result, a three-dimensional spatial relational database in a standard data model is defined, capable of harmonizing, storing and organizing building information on historical city centres.*

KEYWORDS: *3D Digital Archives, CityGML, GIS, BIM, Spatial database.*

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1. INTRODUCTION

In recent decades a renewed attention is being paid to historical centres, highlighting the dual role that are playing in the urban development: as a cultural value, to be protected and enhanced, and as active parts of existing cities, to be planned and upgraded (Strange, 1997). The recognition of this dichotomy introduces a convoluted problem, which calls the municipalities to manage these cities as complex systems, subjected to competing needs for conservation and transformation. Within this context, where many different subjects and points of view are involved, the administration should be conducted with an integrated approach, in order to avoid the risk of losing the coordinated objectives. The delineation of such a multidisciplinary issue, whose area of influence extends from the territory to the building level, requires the implementation of multi-scale tools and the definition of digital archives accessible by a variety of stakeholders, in which common problems can find shared solutions (Cecchini et al, 2018).

Moreover, along with the increase of the complexity in the management of city centres, the volume of heterogeneous information to be handled is steadily growing, making the theme of data modelling and storage crucial for the success of the process (Egusquiza et al, 2014). At the same time, the diffusion of digital survey techniques and the improvements made in the field of data processing for three-dimensional reconstruction, provided the tools for defying informative models whose usefulness goes beyond visualization (Musialski et al, 2013). With the newly acquired information technology, it is possible to define digital archives where "information is also semantically specified in a shared and explicit way, so that it can be universally understood and correctly interpreted" (Noardo, 2018).

In this framework, the creation of a spatial database able to describe the built environment by making a combined use of GIS (Geographic Information System) and BIM (Building Information Modeling) could be a valid support for the achievement of more informed and effective decision-making processes in the management of historical city centres.

However, currently there is a lack of methodologies and instruments able to collect and harmonise different data sources on the urban landscape, mainly caused by persistent interoperability issues between BIM and GIS (Liu et al, 2017). More specifically, tools that enable data-exchange are available, but an effective interoperability based on semantic is not yet provided (Karan et al, 2015). An integration of BIM and GIS in a common environment - which is a step forward the chance of importing and exporting data between the associated platforms - would offer the opportunity of using the strengths from both the informative systems (de Laat and Van Berlo, 2011), covering a wider range of applications.

The research objective is the definition of a repeatable procedure, capable of overcoming interoperability obstacles for the achievement of a spatial relational database aimed at information management on historical city centres. In this paper, the requirements that should accompany information systems on built environments will be discussed and a solution for the achievement of a multi-scale informative city model integrating BIM and GIS will be proposed with reference to the case study of the city of Pavia (Italy).

2. REQUIREMENTS AND TOOLS

The first application cases of information systems to the built environment are strongly related with GIS, which was originally conceived in a two-dimensional version and only later upgraded by adding the third dimension (Zlatanova et al, 2002). The implementation of 2D GIS to cultural heritage has already been treated in literature: from the first applications in the 90s in the field of archaeology (Moscati, 1998) to some examples applied to historical city centres (Restuccia et al, 2011; Giannopoulou et al, 2014). Moving to 3D GIS, only fewer case studies are available (Almeida et al, 2016; Parcero-Oubiña et al, 2014), showing an increase within the framework of the reconstructions after the series of earthquakes that struck central Italy in 2009 and 2016 (Bartolomucci et al, 2012).

Despite their important value, the retrieved studies appear to be strongly linked to their local application, fragmented and never mutually compatible. Indeed, the implementation of GIS is extremely flexible, and thus suitable to a huge amount of case studies, but it is limited by a lack of standardisation, which leads to the definition of many *ad hoc* systems that are not easily reusable. In the light of these considerations, it is clear that those studies are missing a durability element, which is not linked to the discipline itself, but that is related to the information management and to the proper selection of tools. Even though GIS is the main reference point, it appears to be too limited to sustain the increasing complexity of processes related to the management of information on historical city centres. In order to be effective an information system designed for this purpose should in fact fulfil the following requirements (Egusquiza et al, 2014; Costamagna and Spanò, 2012; Wüst et al, 2004):

- Multi-scale definition: development in an environment and with a code that allows the movement between the territorial and the building scales by adapting the level of detail of geometries and information, and the computational load involved in the analysis;
- Multi-level definition: possibility of providing several levels of access to the data with the corresponding privileges in order to meet the needs of different classes of stakeholders, from the citizenry to the administrations;
- Semantic syntax: inclusion of both geometry and data properly related and georeferenced and ability of semantically classifying objects by describing their relationships in a hierarchical system. The platform will be required to carry out functions above and beyond the simple visualization, and therefore the definition of rigid and well-known rules for its management is mandatory;
- Interoperability: use of flexible and widespread file formats with the aim of easily interacting with other informatic tools. Since the topic of the management of cities is multi-disciplinary, the possibility of moving information across different platforms without losses and misunderstandings is paramount. If possible, the involved codes should be open in order to simplify the diffusion and the implementation of the system;
- Using of international standards: municipal, regional and national border crossing by adopting standard data models, classification systems and languages. The necessity of planning tools based on shared standards is underlined by the European Commission, which issued the INSPIRE (Infrastructure for Spatial Information in Europe) directive in 2007 with the aim of promoting and encouraging the use of open and shared formats in the field of spatial data (European Parliament and the Council, 2007).

In this project, the targets were met by creating a database founded on CityGML: an extendible open standard issued by the OGC (Open Geospatial Consortium) for modelling, storing and exchanging spatial data. Its purpose is to give a common definition of the basic entities, attributes and relationships that constitute a three-dimensional city model. To do that, CityGML organises the information by describing city objects with their geometrical, topological, semantical and appearance properties (Kolbe et al, 2005) and includes the chance of multi-scale and multi-level representation because of its definition in five Levels of Details (LODs). It is compliant with the with the ISO/TC211 standard on geographic and spatial information, integrated with the INSPIRE data model and suitable for interoperability with BIM, due to its semantic structure which is consistent with IFC (Industry Foundation Classes), the open standard for information modelling.

Currently, the main fields of application of CityGML include planning, risk assessment and energy analyses. Some cases have already been tested for its application to cultural heritage (Gröger and Plümer, 2012), but the opportunities in this field are not yet properly exploited (Dore and Murphy, 2012; Mignard and Nicolle, 2014).

Since CityGML data model was not originally thought for the management of real estates with heritage value, some shortcomings in this application can be retrieved. However, its characteristic of extensibility allows the definition of thematic expansions (formally Application Domain Extentions – ADE), which can be used to add customized classes and attributes. In the case of cultural heritage, different proposals were recently formulated (Biljecki et al, 2018). In this work the one defined by Noardo (CHADE - Cultural Heritage Application Domain Extension) (Noardo, 2016) was used by reason of its focus on the topic of management.

3. METHODOLOGY

3.1 Integration of GIS and BIM

The importance of integrating GIS and BIM has already been widely recognized as an opportunity of defying effective multi-disciplinary workflows in building processes (Liu et al, 2017). In recent times the diffusion of open standards in both fields - namely IFC for BIM and CityGML for 3D GIS - moved a significative step forward for the research of new solutions for interoperability (Liu et al, 2017).

The two systems were designed for different purposes: GIS for the management of large dataset on existing natural and built environment and BIM for the detailed representation of new constructions. However, there are many contact points between the two: suffice is to mention the characterization of Levels of Detail and Levels of Development and the definition of relationships between entities in a hierarchic structure. Precisely because of their ability to represent reality at different scales, they should be considered as complementary tools (Saygi et al, 2013) in a multi-scale flux of information, where it is crucial to be able to move from general to specific and vice versa without losing control and coherence.

This approach is leading to the definition of Urban Informative Model (UIM): intended as an extension of BIM for larger areas of interest (Mignard and Nicolle, 2014) with a view that many advantages could arise from the representation of the interaction between buildings and their environment. From a forward-looking perspective, once the CityGML model of an historical centre will be published, each stakeholder could enrich it with the models of its competence, benefiting from the insertion in the urban context. This also derives from an idea that is deep-rooted among the academic community about the need for a common platform in which to store and harmonize 3D cultural heritage models created by different subjects (Koller et al, 2009). In this paper the integration will be tested for a single building complex: the former Certosina Monastery, built in Pavia (Italy) from the 13th century.

The process presented here is founded on the integration of GIS and BIM with the aim of defining a comprehensive informative system, which will converge into a proper database for the management of the information on historical city centres. The workflow will follow four main steps applicable to both the strands, at urban and building scale: after the retrieval of survey data, a three-dimensional model will be defined using GIS or BIM, translated into CityGML and finally embedded in a relational database (Fig. 1).

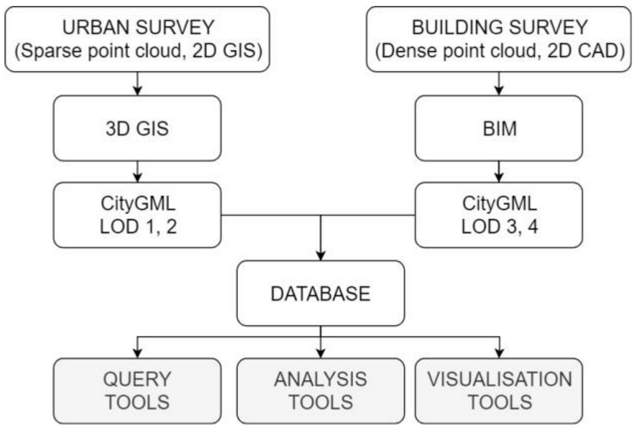

FIG. 1: Scheme of the workflow presented here. The blocks filled in grey represent some possible tools that can be linked to the final database.

3.2 Creation of the CityGML model at broader LODs

Operationally, the starting point for the creation of the model was the retrieval of the geographic contents on the city of interest. In the idea of defining a repeatable workflow, availability and accessibility of spatial data was taken as a fundamental aspect. In this direction, two datasets were identified. The first one, collected from the Territorial Information System (SIT - Sistema Informativo Territoriale) of the Municipality of Pavia, is a two-dimensional cartography representing the built environment through three informative layers (maximum extension, footprints and volumetric units). The other one, provided by the Italian Ministery of the Environment (Ministero dell’Ambiente e della Tutela del Territorio e del Mare) consists in a point cloud with 4 points per square meter, resulting from a LiDAR (Light Detection And Ranging) survey campaign of 2008-2009. The data sets were put together in a GIS environment by homogenising their reference and projection system in WGS 1984 UTM Zone 32N (EPSG:32632) (Fig. 2).

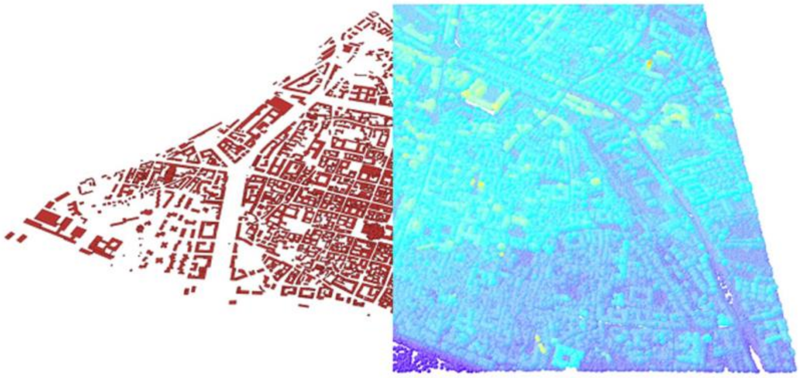

FIG. 2: Datasets available for the city of Pavia. On the left the two-dimensional cartography and on the right the point cloud.

The next step was the extraction of the building solids. The difficulties encountered in this operation were mainly related with the urban context typology. In the case of historical centres, the urban fabric is extremely compact with no chance of distinguishing the object boundaries from the digital survey. Moreover, there is a strong impact of vegetation on the clarity of the point cloud itself, due to the presence of many trees along the streets and inside the gardens. The Shapefile with the building footprints allowed to overcome these problems, giving the chance of subdividing the point cloud in classes containing homogeneous elements by comparing the position of the polygons with the points of the cloud. By working inside ArcGIS, the points were classified between Ground, Buildings and Vegetation. Then three raster layers were derived in order to describe the resulting surface (DSM – Digital Surface Model) and to emphasize the trend of the ground (DTM – Digital Terrain Model) and the presence of buildings (nDSM – normalized Digital Surface Model). Subsequentially, the three-dimensional model of the built environment was extracted by using of a series of geoprocessing tools in ArcGIS. The reconstruction of the roof shapes was the most complex and delicate passage: it was carried out with an algorithm able to test several roof forms (flat, hip, gable, dome and vault) on each footprint and to choose the fittest one based on the points of the survey. Even though this process is recognized as globally effective (Macay et al, 2013), some adjustments made by hand were necessary, especially for the buildings with very complex shapes.

The building extraction carried out in ArcGIS returned a number of 3D Polygons equal to the one of the records in the building footprints layer. However, in order to transfer the information in a CityGML data model, a conversion into Multipatch geometry is required, in order to break down the solids in their constituent faces. After this passage, the Shape file was handled with Safe FME, a powerful data conversion application. Here, with the aim of organizing the database by homogeneous technical elements and to trace the semantic structure of CityGML, the surfaces constituting the buildings were classified between Roofs, Floors and Walls according to their slope and Z values. In the same passage the parent-child relationships between surfaces, building parts and buildings was registered by linking the IDs of the objects. This is the starting point for the creation of the CityGML ontology.

Each surface was also tagged by using the Table 21 of OCCS (OmniClass Construction Classification System), which allows to describe and classify the building system on the basis of its elements intended as components, assemblies, or construction entities that fulfils a predominating function of the construction unit. OmniClass is a standard classification system for the AEC (Architecture, Engineering and Construction) industry which implement the ISO 12006-2.

The second part of the workflow focused on the transformation of the GIS towards CityGML. This operation was made with the software Safe FME by designing a VPL (Visual Programming Language) script (Fig. 3). The urban model was defined in two different LODs (Level of Detail) with reference to the classification given for buildings in the encoding standard (Gröger et al, 2012) (Fig. 4): LOD1, which includes the solid models of the buildings simply extruded from their footprints to the maximum high, and LOD2, which contains also the geometries of the roofs and their dimensional features.

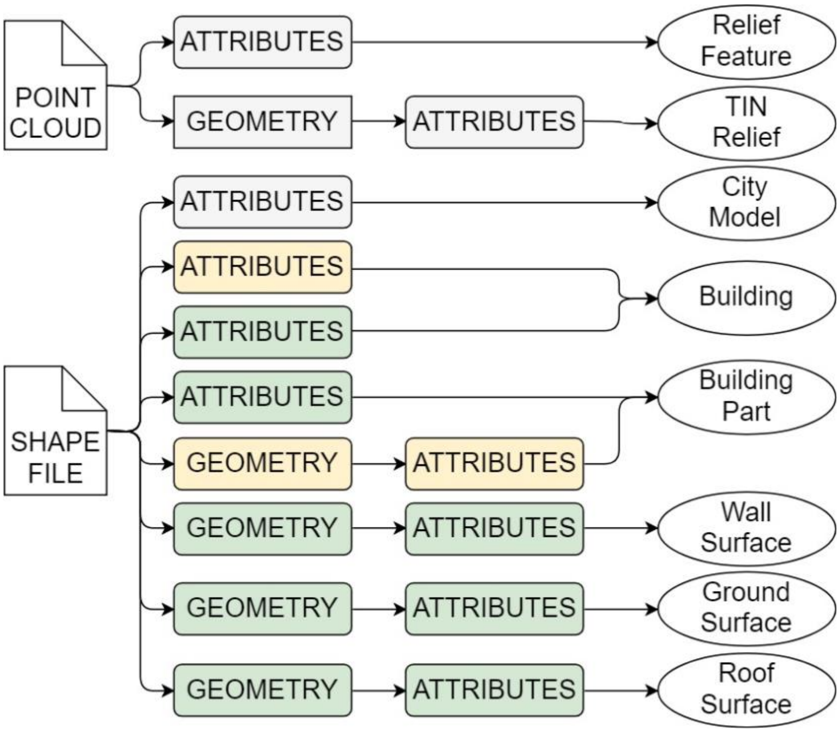

FIG. 3: Schematic representation of the VPL script for the definition of the CityGML model. In yellow the operations related to LOD1 and in green the ones related to LOD2.

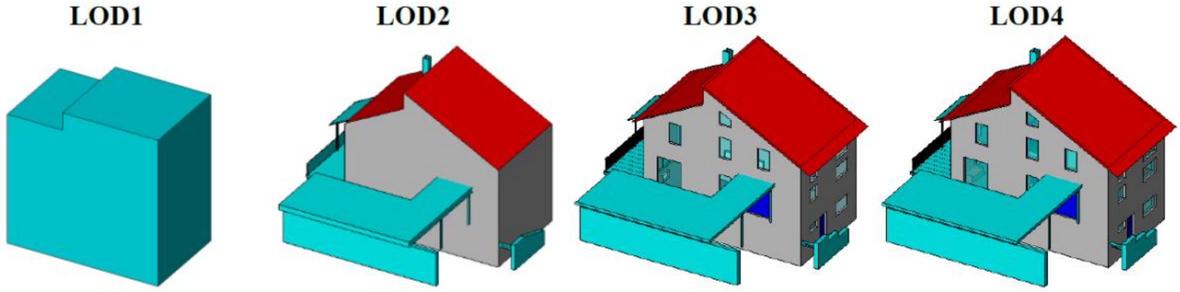

FIG. 4: Five Levels of Detail (LoD) defined in CityGML (source: Gröger et al, 2012).

For the definition of the buildings, six semantic classes were mapped from the 3D Shapefile: CityModel, Building (LOD1 and LOD2), BuildingPart (LOD1 and LOD2), RoofSurface, GroundSurface and WallSurface. The model of the ground, instead, was achieved directly by importing the point cloud inside FME and transferring it to the semantic classes ReliefFeature and TINRelief. The script was divided into nine parts to collect and write separately the information related to each semantic class. For each of them the algorithm acquired from the input data both geometry and information and defined the network of relationships between them. In accordance with the specifications, spatial data have not always been associated with information. In fact, in the CityGML model, geometry is represented only in the lowest classes of each LOD, while the others are composed of purely non-geometrical information (Fig. 5). LOD1 geometry was produced by extruding building footprints and stored in the Building Part class. On the contrary, LOD2 geometry was defined through the surfaces of each building part and written to WallSurface, GroundSurface and RoofSurface classes. The hierarchical structure of the model is granted by the series of parent-child relationships that link all the entities.

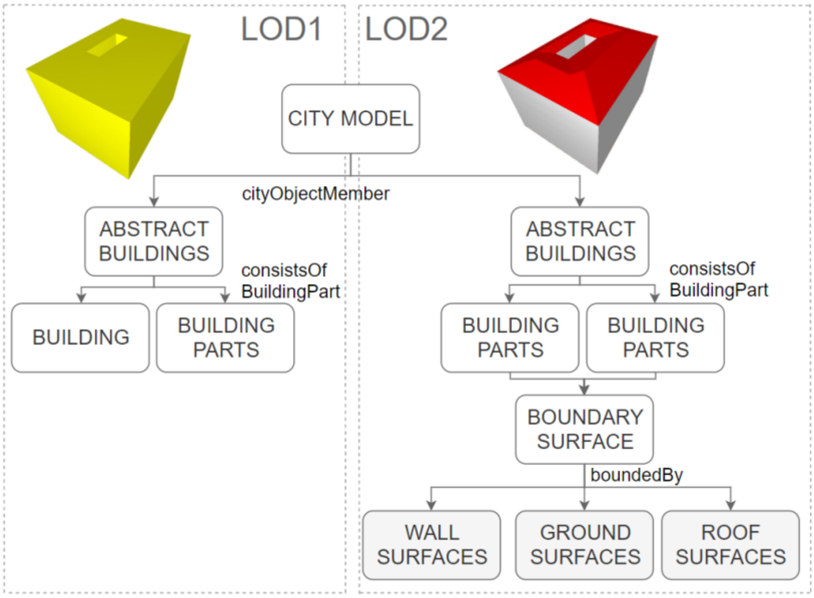

FIG. 5: Scheme of CityGML file with LOD1 and LOD2. The semantic classes filled in grey are the only associated with geometry.

The resulting model is composed by 1853 buildings, 3514 building parts and 47714 surfaces (Fig. 6). The informative data set includes all the parameters defined by the CityGML scheme, which is integrated with the CHADE (Fig. 7). For a detailed description of the Data Types of each object, please refer to (Noardo, 2018). The procedure for the implementation of the Application Domain Extension followed the best practice suggested by the OGC (Open Geospatial Consortium) (Van den Brink et al, 2012), which involves the automatic generation of ADE from UML (Unified Modelling Language) diagrams.

FIG. 6: 3D model of the city of Pavia (left) with an extract of the semantic tree (right).

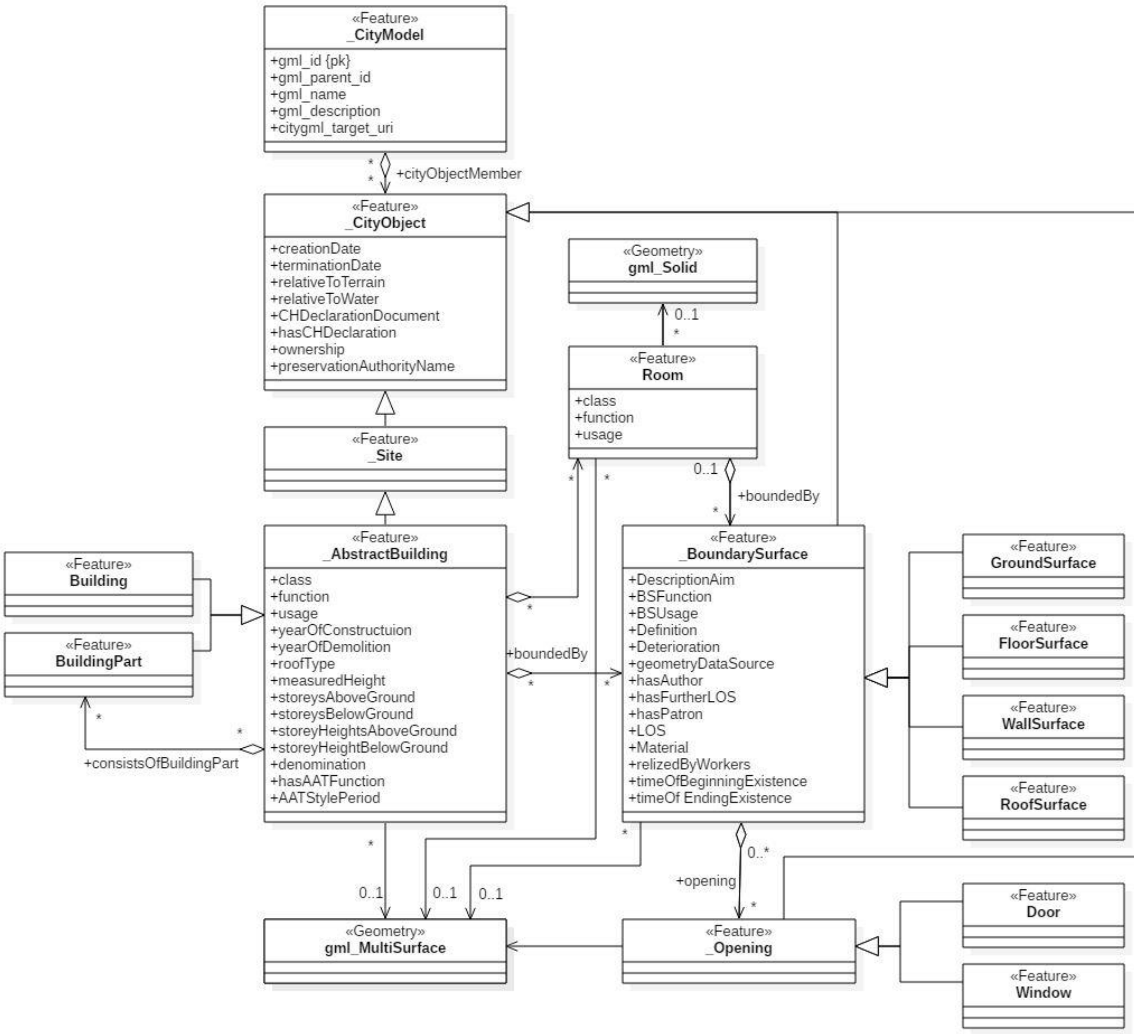

FIG. 7: CityGML UML scheme for the Building module integrated with the attributes of the CHADE.

3.3 Integration of BIM for upper LODs

As it was already seen, the dataset retrieved for the city of Pavia allowed to define a CityGML model in LOD1 and LOD2. However, in order to increase further the level of detail, urban data become too sparse and rough. That's why it is paramount to integrate urban models with others designed to store information at lower scales. As it comes from its name, BIM focuses on buildings, specifically by describing their exterior and interior features. It usually represents constructions with a higher precision than GIS, and for this reason, in the transition from IFC to CityGML, most of the process concerns the simplification of both geometry and information. From a theoretical point of view, a Building information Model exported via IFC meets the requirements of a CityGML LOD4, but effectively this is only true unless one considers a clean-up operation on the model categories (Donkers et al, 2016). Moreover, as it can be drawn from literature (Cheng et al, 2013), the difference between LOD4 and LOD3 is based on the presence of the internal elements of the building. The LOD3 model can therefore be achieved by filtering the geometries on the basis of a specific parameter that labels each model entity as internal or external

However, the differences in the way of describing building systems between the two data models go beyond the number of items or their level of detail, since it is rooted in a slightly different representation of the ontologies. By comparing the broad scheme that highlights the hierarchical organization of the main entities in the two file formats (Fig. 8), it can be observed that IFC decomposes the building more finely than CityGML. This introduces the problem of defying an effective mapping system between the classes, which won't always fit a one-to-one relationship.

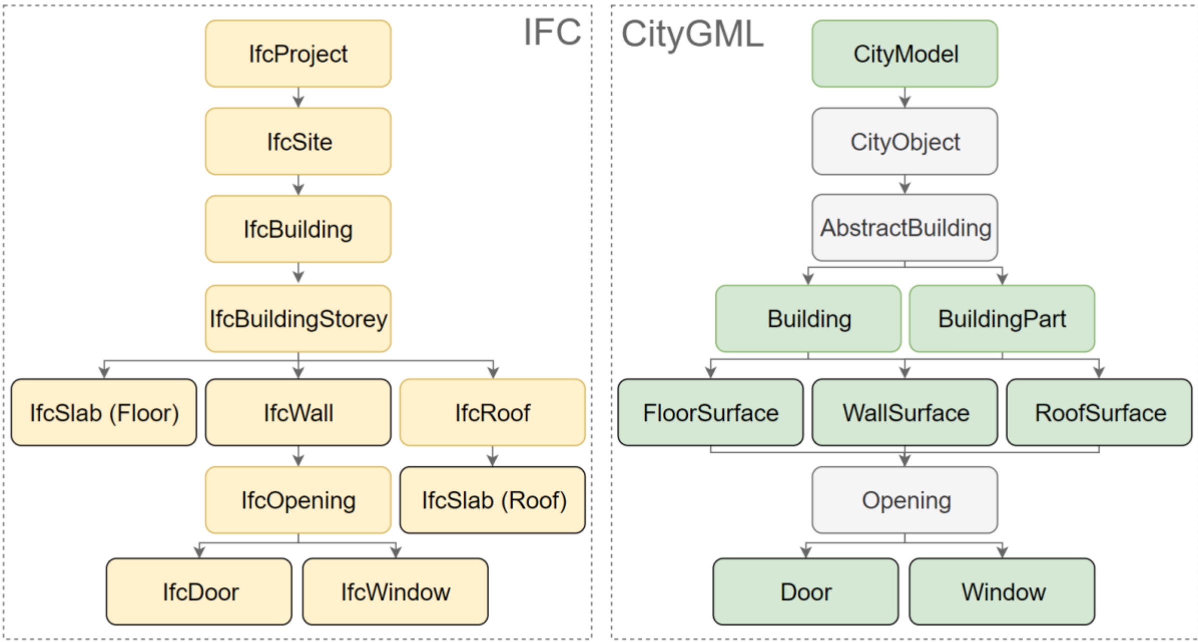

FIG. 8: Comparison between the hierarchical scheme of IFC and CityGML. The blocks with the black contour carry geometric information. The blocks filled in grey shall forward the attributes without a proper identification

In this study a test was made for a single building complex: the former Monastery called "Certosina", dating from the 13th century but heavily transformed over time and currently used by the University of Pavia. The building was firstly modelled by using the software Autodesk Revit 2018 and then exported in IFC 2x3 Coordination View 2.0. The process of conversion from IFC to CityGML was carried out inside Safe FME, starting from LOD4 and downgrading as it was described before. As it can be seen from the schemetic representation of the script (Fig. 9), some adjustments were required for the alignment of the classes from BIM to CityGML. Due to the lack of some intermediate classes in the CityGML scheme, the set of parent-child relationships had to be rearranged. This has, in some cases, led to the necessity of merging two IFC classes and organizing the information by linking some instances with their "grand-parent" in order to rebuild a valid ontology (Fig. 10).

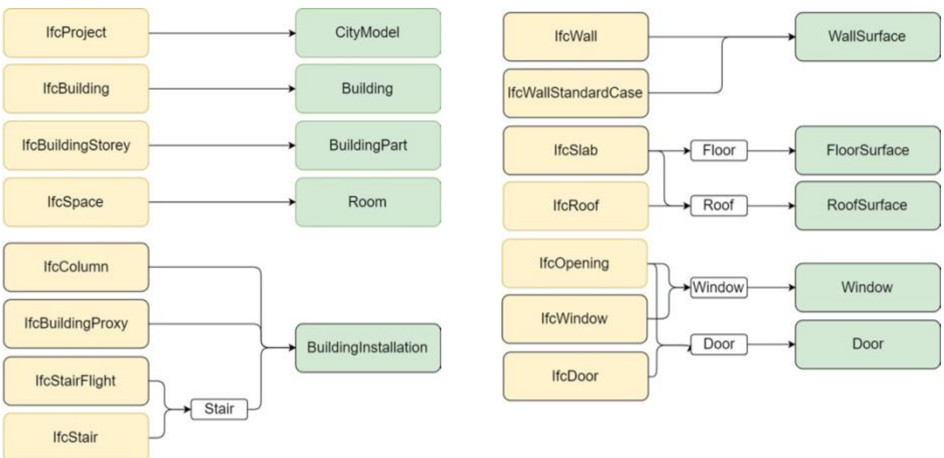

FIG 9: VPL script schemetic representation for LOD4 generation. In yellow the IFC classes and in green the CityGML ones. The blocks without the black contour do not carry geometric information.

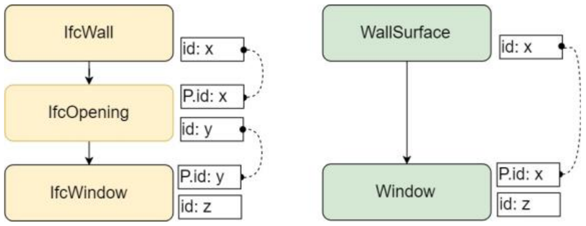

FIG 10: Alteration of the parent-child relation that happens when a class shifts between IFC (yellow) and CityGML (green).

The resulting model is shown in Fig. 11. As it can be seen, even though the geometries are globally well reconstructed, some issues are still evident, in particular with reference to those objects that are cut or extended with relation to other entities. By analysing the process, it was observed that this problem concerns the export in IFC from Autodesk Revit 2018, and not the translation phase towards CityGML. One solution could involve a different definition of the shapes of these objects, for example by using the "Edit Profile" function, but the problem is still under review.

The downgrade from LOD4 to LOD3 was achieved by filtering all the elements on the "Function" parameter, which identifies internal and external entities, and by excluding from the outputs the CityGML class Room.

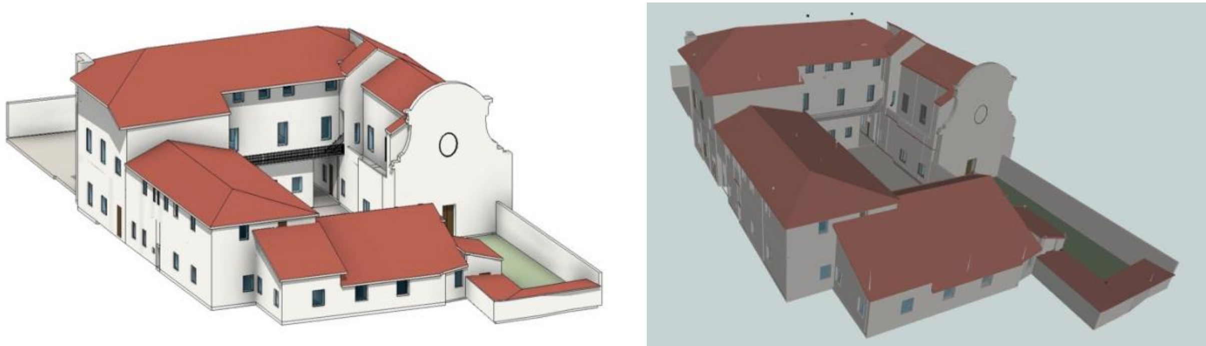

FIG 11: 3D view of the IFC model imported in Revit 2018 (left) and the CityGML model as resulting from FME inspector (right).

3.4 Implementation of the database

The last phase of work involved the creation of a database capable of incorporating the CityGML model, in order to constitute a reliable storage for the information and a solid starting point for the construction of a knowledge base on historical city centres. With this aim the PostgreSQL DBMS (Data Base Management System) was chosen and the PostGIS extension was activated for the management of geographic objects. The database scheme was defined starting from the UML diagrams representing the CityGML and the CHADE scheme (Fig. 7), which were translated into DDL (Data Definition Language) commands of SQL (Structured Query Language) by using Sparks Enterprise Architect. In this way each CityGML class became a table in the database, and the relationships between the objects were translated into external reference with the use of foreign keys. The data migration from CityGML to the database was achieved through a set of VPL scripts. The operation was taken without any complication, since each information written in CityGML was able to find an exact match in the database scheme.

4. RESULTS

The achievement of a relational database able to manage multi-scale information about historical city centres starting from easily retrievable data is an important goal. A thus defined digital archive can be embedded in third-party commercial and open solutions to allow an extensive exploitation of the data. As a function of its standard structure the information can in fact be correctly interpreted without misconceptions, so that multidisciplinary uses can be planned.

Once defined, the database can be queried with a vast set of applications for consultation, visualisation or analysis purpose, with or without reference to the geometric entities. In this study, in order to ensure a use in close connection with the geometries of the model, a link with the GIS open solution QGIS was established. From the software, the database can be interrogated through a SQL shell and the results can be visualized in the graphic environment, obtaining geometric outputs that help the communication to different types of stakeholders.

Finally, the content of the database can be exported in the KML/COLLADA file format, which allows its navigation in Web application such as Google Earth, ESRI ArcGlobe and ArcGIS Pro, NASA Worldwind, and CesiumJS (Yao et al, 2018). This opens the way to a series of Web services, which may act as a preliminary graphic interface for the consulting of the database by the less experienced users.

FIG. 12: Extract of the city model of Pavia imported in Google Earth environment.

5. CONCLUSIONS

The collection and the storage of big amount of heterogeneous data involved in the management of historical city centres request the implementation of spatial databases able to link information and geometrical features in a well-organized semantic structure. The research presented in this paper starts from the discussion of the requirements that an informative system designed for this purpose should met and shows a fully interoperable workflow. From a set of widespread available geographic data, a spatial relational database is achieved. It constitutes the core of a three-dimensional digital archive on historical city centres, able to manage different scales and data models for a complete description of the built environment. The whole process uses open file formats and software solutions in order to be easily implementable in both professional and academic contexts.

The case study of the city centre of Pavia demonstrates a practical example of the chances of integrating GIS and BIM and ensure the success of the theoretical framework. The urban model is defined in CityGML LOD1 and LOD2, while the model of the former Monastery complex called "Certosina" is built in Autodesk Revit 2018 and converted into CityGML LOD3 and LOD4. Both the models are integrated in a PostgreSQL database, linked to the GIS open software QGIS for visualization, query and analysis purpose.

Despite the operability of the whole system, it should be mentioned that at the state of the art there is a lack of effective tools able to handle three-dimensional Urban Information Model, causing important restrictions to the opportunities that might arise from their implementation. In this sense, the model presented here is complete in its geometric and informative definition, as well as in the description of the relationships between objects, but it results still underperforming in its final uses. To make an example, big amount of data can be exchanged to various types of stakeholders through the extraction of thematic maps. However, at the current state the non-experienced users will not be able to produce the maps themselves, since skills in the field of GIS or SQL are required due to the lack of proper Graphical User Interfaces (GUI).

Future works will address mainly this issue, exploring the possibilities of embedding the spatial relational database inside user-friendly information technology tools, with the aim of achieving effective multi-level instruments that make the users independent in the consultation of the information.

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