Architectural heritage semantic 3D documentation in multi-scale standard maps

# Architectural heritage semantic 3D documentation in multi-scale standard maps

Francesca Noardo[1]

[1]Politecnico di Torino – DIATI, c.so Duca degli Abruzzi, 24, 10129 Torino, Italy

francesca.noardo@polito.it

**Abstract.** The documentation of cultural heritage is acknowledged as a fundamental instrument to guarantee the monument preservation and promotion, and to educate people towards these aims. The recently evolved potentialities of information technologies and communication (standard data models, ontologies and formats, web technologies) permit the development of digital archives in which the information is also semantically specified in a shared and explicit way, so that it can be universally understood and correctly interpreted. However, some tools are missing for suitably archiving and communicating the architectural heritage information, including the representation potentialities of high-level-of-detail 3D models. A goal of this study is the suitable representation of both the thematic information about architectural heritage and its 3D geometric characteristics in an interoperable and understandable way. For this reason, the existing data models, available for the geometric and cartographic field, and for the cultural heritage domain, were considered. They are distinct standards, and some limits make them incomplete (in the spatial or semantic management). In this study, an extension is proposed of the standard data model CityGML to overcome these limits. CityGML is published by the Open Geospatial Consortium to represent urban objects and permits a multi-scale management of the information useful for the representation of architectural heritage multi-faceted, multi-temporal, complex knowledge. In the paper, the extension is described, and an example of its application on a portion of a highly detailed 3D model of a medieval church is presented.

**Keywords:** Architectural Heritage; documentation Standard; Semantics; interoperability; ontologies; 3D digital archive.

## 1 Introduction

The documentation has been acknowledged as a fundamental requirement for the cultural heritage (CH) to be known, preserved, and promoted, since the early documents arose from the awareness of the importance of CH for humanity (from the Athens Charter, in 1931 [1], onward). An important concept, already stated in the Athens Charter, is the necessity of filling in CH public inventories and archives, with multi-media materials.

In more recent years, an explicit and inclusive principle regarding the information has been stated in the so-called 'Ename Charter' [2] (principle 2: information sources). Some of the Ename Charter objectives regard the understanding and the interpretation of the 'cultural sites' (including architectural heritage) through instruments that permit their documentation with all those elements that constitute the essence of a CH item. These are shared with the research presented in this paper:

- facilitate understanding of CH;
- communicate the meaning of CH sites;
- respect the authenticity of CH sites, by communicating the significance of their historic fabric and cultural values and protecting them from the adverse impact of inaccurate or inappropriate interpretation;
- develop technical and professional guidelines for heritage interpretation and presentation, including technologies, research, and training.

It is clear how digital archiving technologies can improve inventorying multi-media documents and how communication technologies, including the internet, can presently empower the public knowledge and promotion of CH. The standards for documentation have an important role in this process, since they permit the building of interoperable information, understandable by everyone, since the rules used for cataloguing are well-known and explicit.

Critical tools to achieve interoperability and accessibility of the information are ontologies and standard data models, that specify in a clear, unambiguous, and 'open' way how to structure the data and prescribe how they have to be interpreted, reducing the risk of misinterpretation and possible consequent loss of information [3]. The ontologies [4,5,6] are formal, explicit specifications of a shared conceptualization [7], that is, the shared description of the objects and of their reciprocal relationships in an application domain, in an explicit form and in a machine-understandable language. The definition of an explicit and shared data model permits the production and sharing of open data, with the connected advantages [8], advanced analysis, enhanced queries and support to artificial intelligence mechanisms for extracting new knowledge.

The core ontology for managing CH information was developed by the International Committee for Documentation (CIDOC) of the International Council of Monuments (ICOM): the 'CIDOC conceptual reference model' (CIDOC-CRM) [9], and became the standard ISO 21127. It was initially addressed to the archiving of information concerning CH objects conserved in museums, but it is anyway a reference for classifying the CH thematic data and values, which can be found very similar also in architectural heritage. Some extensions to the CIDOC-CRM were developed: 'Monument Damage Information System' (MONDIS) [10, 11], for representing the information about preservation, decay, deterioration mechanisms, restoration and intervention; 'CRMBA', for the documentation of standing buildings [12]; CRMgeo [13], permitting the inclusion of spatial information. CRMBA has similar aims of this research; the gap with respect to the considered issues in this study is in the management of complex 3D models in connection with other multi-scale parts of the city and the landscape, which are fundamental to the monument interpretation.

Some international inventories and projects structure the data following the CIDOC-CRM. For example the ARCHES project [14, 15], by the Getty Conservation Institute [16] and the World Monuments Fund [17], develop an open source, interoperable, web- and geospatially based information system for inventory and management of immovable CH. A connected webGIS allows drawing a simple geometry collocating the item on a base map. A complex management of geometry is however missing.

Other vocabularies compliant to the CIDOC-CRM are realized by the Getty Institute [18], to structure CH related terms and items: the Art and Architecture Thesaurus (AAT), structuring terms linked to the description of works of art and architectures; the Thesaurus of Geographic Names (TGN), which, in contrast to GeoNames (structured database for toponyms) [19], also includes historical denominations; the Union List of Artist Names (ULAN), containing names and synthetic information about CH authors; and the Cultural Objects Name Authority (CONA), describing the different denominations of a cultural item over time. Within these vocabularies, the spatial component is not present, but they can be the reference for the semantics of objects that unequivocally have a spatial connotation (e.g. all architectural parts or toponyms) or for related information (such as authors or object names).

The spatial extension employed in the cited examples is often bi-dimensional, however, with little defined geometry (points, lines or approximate polygons), because the aim is the localisation of the archived objects for access and retrieval reasons. It is not the documentation, analysis and reading of the artefact 3D geometry. One of the main aims of the CIDOC-CRM ontology and of its spatial extension CRMgeo, was the reasoning about CH objects there archived and the places connected to them (for example for historical events).

However, the spatial and geometric data represent and materialize a great and essential part of its cultural value. Therefore, an important part of the information stored in the digital inventories should be the metric information, which, nowadays, can be available in form of very dense and detailed 3D models (high measurement and georeferencing accuracies).

For exploiting the available 3D survey techniques in documentation (e.g.[20, 21, 22]), which permits the obtaining of dense, accurate, and detailed 3D geometry, some 3D models about CH are published on the web in digital archives, as a support for communication, analysis, research, education, tourism, preservation. Two examples are the Smithsonian Institution X3D archive [23] and the one developed by the CyArk Project [24]. A limit of such repositories is that they are not labelled with a standard semantics, so they could not be automatically connected to further information regarding the same represented object or related concepts. They are represented in a high level of detail, but they are not connected to their urban or landscape context, which could be extremely meaningful for defining and transmitting their value.

In this study, a solution to these gaps is proposed by extending a standard data model developed in the field of geographic information and spatial information management, in which interoperability is equally a key issue. For this reason, geospatial ontologies [25] and standard data models for structuring interoperable international digital maps were published. In particular, the 'INfrastructure for Spatial InfoRmation in Europe' (INSPIRE) European Directive was developed [26]. Similarly, international industry standards are being developed by the Open Geospatial Consortium (OGC) [27], involving major stakeholders and actors of the sector. The most important OGC data model for structuring urban data in 3D semantic digital maps is CityGML [28]. It is an open data model, aimed at the representation, storage and exchange of three-dimensional (3D) urban objects. The original aim of CityGML, beginning in 2007, was to foster the reusability of 3D city models. Its semantic definition can be equally useful for managing the semantics of data with the tools offered by informatics and artificial intelligence. Both INSPIRE and CityGML are compliant with the ISO/TC211 standard about the geographic and spatial information management and foresee the use of the OGC Geographic Mark-up Language (GML) [29] for the implementation of the databases. They present some similarities in their semantics, especially regarding the INSPIRE theme (and the CityGML module) 'Building', since the INSPIRE data model (INSPIRE DM) is based on the data specification of CityGML for this theme, even if some changes and simplifications are applied and, therefore, they are not fully compliant with each other. However, the main difference between them concerns the different scale to which they are aimed: INSPIRE DM considers wider portions of land, for supporting European environmental policies; CityGML is aimed at urban-level 3D representations.

Some studies [30], proposed how to extend the INSPIRE DM for including the CH sites, including them in 'Protected Sites' (Annex I of the INSPIRE DM). Although being an interesting research, the considered levels of detail are compliant with the ones foreseen by the INSPIRE DM, therefore insufficient for dealing with smaller parts of a monument. However, considering the relations between CityGML and the INSPIRE DM in, for example, the 'Building' theme, it is possible to suppose that the extension here proposed could be somehow translated to INSPIRE in future works. The INSPIRE DM and CityGML aim at representing a common frame for mapping data, independently from any specific application for which they can be used, therefore they can be considered as ontologies [31, 32].

Other existing systems to manage the building information are the Building Information Model (BIM) [33], born to project new buildings, and Historical BIM (HBIM), to manage existing and historical buildings with similar tools than for new-projected ones, with very detailed semantics concerning the building components [34]. However, it presents some limitations. Firstly, the managed geometry often derives from parametric modelling, that is, already interpreted data, with respect to the surveyed point cloud or a simply interpolated mesh. It could carry a loss of data if some feature is not correctly interpreted, or simply not noticed, by the modeller. Otherwise, a mesh or a point cloud represent coarser, less interpreted, data, open to geometry documentation and interpretation in following times. Secondly, the software managing BIM are devoted to best management of one single building, whereas the entire town or landscape is not included. The landscape or the urban context is however fundamental for the architectural heritage representation; also for this reason, an urban data model was chosen as starting point for this study, even if in the future the field of BIM will likely meet GML models.

### 1.1 Research Aims

In this study, a data model for structuring architectural heritage 3D high-level-of-detail data, built by extending the existing structure CityGML, is proposed as a solution.

CityGML is already meant to deal with buildings in their double dimension, in a multi-scale representation: as a part of the city and landscape, and as a higher-detailed 3D object. However, some extension is necessary in order to correctly include in the schema all the attributes and features characterizing the architectural heritage, and all the connected information useful to their understanding and study.

This schema will enable an unambiguous interpretation of the information and empower the possibility of both database interoperability and information retrieval, through the relations among the data defined in the data model. All the objectives stated in the Ename Charter can benefit from the advantages of this system.

## 2 CityGML for architectural heritage: CH Application Domain Extension (CHADE)

CityGML can be extended to include the objects and features belonging to specific application domains. These extensions employ specific characteristics and procedures of CityGML, being defined as Application Domain Extensions (ADEs). Some already official ADEs exist, which are specifically developed for buildings; for example, GeoBIM integrates some classes derived from Industry Foundation Classes (IFC) [35], which is a standard used in BIM [36].

In the model proposed in this paper, including the characteristics of surface complexity is also attempted. Moreover, some attention is drawn to the traceability of the archived data, in order to allow technicians to interpret the information and evaluate its degree of fuzziness.

The proposed CH Application Domain Extension (CHADE) for the building module of CityGML is summarised in Fig. 1 and then analysed in detail in the subsection 2.1. The extension has been developed and tested on the building module. Once its validity is proved, its concepts and classes can also be applied to the other CityGML modules (Bridge, CityFurniture, Transportation, Tunnel, and so on).

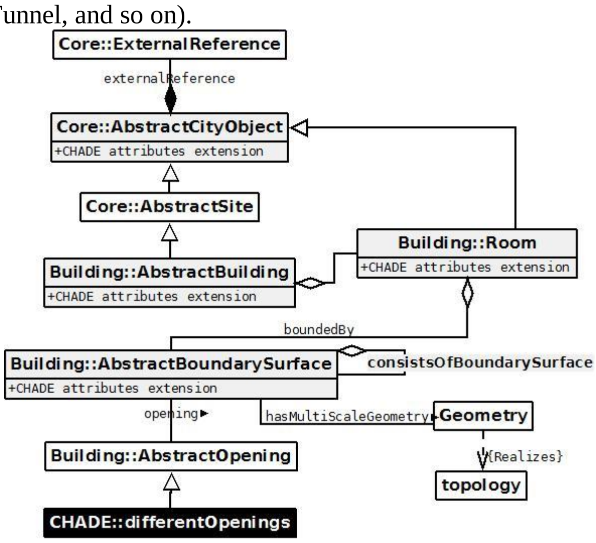


**Fig.1.** Synthesis of the CityGML CHADE in a UML diagram. The CityGML classes are shown in white, the CHADE extensions and the inserted relations are shown in grey (black for the whole class) [38].

The described model was implemented by modifying the UML schemas in a proprietary commercial software, 'Sparx Systems – Enterprise Architect', using the method defined as best practice by OGC [37]. The whole extension implementation process is described in more detail in [38, 39].

### 2.1 Granularity, Flexibility and Traceability for the documentation

The CHADE extension is here described, from the more general objects to the smaller details. Firstly, the attributes of the Core class 'AbstractCityObject' (the 'Core' is the more general part of CityGML) were extended for the identification of the monument and some important information for its study (Table 1). In particular: if a CH declaration exists (hasCHDeclaration), what the related documents are (CHDeclarationDocument), who the owners are and what the preservation authority is. Some of these have been borrowed from previous research [40]. Some attributes were added in form of complex attributes (composed by a number of other attributes) defined as new 'DataTypes' in the model. In Table 1 the DataTypes 'Ownership' and 'PreservationAuthority' are shown, including data useful to identify and contact them.

Some explanation about the language used in this table, and in the following ones, is needed, which is the same used for implementing the model. The kind of object 'ADEElement' is the extension of the CityGML class with new properties. In the list of properties, the storage modality is included, that is: 'char' for simple text; 'boolean' for true/false attributes; 'int' for numbers; 'anyURI' when it refers to web resources; other codes indicate further DataTypes (es. 'PreservationAuthority'). In the squared brackets, the possible minimum and maximum number of attributes are indicated, when they are different from 1 (the * means 'more than 1'). This is important because some attributes can change over time in historical building documentation, and, in this way, it is possible to document them all.

| *Kind of object* | <<ADEElement>> | <<DataType>> | <<DataType>> |
|---|---|---|---|
| *Object Name* | **CHCityObject::AbstractCityObject** | **Ownership** | **PreservationAuthority** |
| *Properties* | + CHDeclarationDocument: char<br>+ hasCHDeclaration: Boolean<br>+ Ownership: Ownership [1..*]<br>+ preservationAuthorityName: PreservationAuthority | + address: Address<br>+ CF: char<br>+ e-mail: char [0..*]<br>+ Name: char<br>+ phoneNumber: int [1..*] | + address: Address<br>+ code: char [0..*]<br>+ e-mail: char [0..*]<br>+ Name: char<br>+ phoneNumber: int [1..*] |

**Table 1**– Extension of the core class 'CityObject' and the two new objects in form of DataTypes 'Ownership' and 'PreservationAuthority'.

The CityObject can also be connected and linked to further external resources through the CityGML 'ExternalReference' class. This permits the relation of the model with further databases concerning the same object.

Also the attribute list for the 'AbstractBuilding' class is extended (Table 2). The denomination of the building is inserted, since it can be essential to describe and identify a specific Monument. Moreover, the function of the building has to be defined, also including the historical functions for permitting the study of its evolution. For archiving both these attributes, two new entities are added as DataTypes, since they are complex when regarding a historical item, changing over time. The building denomination ('BldgDenomination'), simply include the denomination of the documented monument, in a language depending on the Source of the data, and refers to a specific time. The building function ('BLDG_Function') DataType includes the function name (at present in English, specific future works with historians could further evaluate using different languages in order to avoid losing meaning nuances). The reference to the Getty AAT vocabulary follows (terms subclasses of 'single built works by function'). Again, the source of the data and the reference time are stored. Finally, an attribute "AATStylePeriod" is added, in order to explicit the belonging of the building (or part of it) to a specific artistic or cultural movement. This can help in facilitating associations with further archived objects. The values for filling in the attribute must be borrowed from the AAT vocabulary, under the hierarchical element "Styles and Periods".

| *Kind of object* | <<ADEElement>> | <<DataType>> | <<DataType>> |
|---|---|---|---|
| *Object Name* | **AbstractBuilding** | **BLDG_AATFunction** | **BLDG_Denomination** |
| *Properties* | + denomination: BLDG_Denomination [1..*]<br>+ hasAATFunction: BLDG_AATFunction [1..*]<br>+ AATStylePeriod: Code [1..*] | + AATReference: anyURI<br>+ Function: char | + Denomination: char<br>+ Source: Source [1..*]<br>+ time: time object |

| | | | |
|---|---|---|---|
| | *AbstractBuilding properties already in CityGML:*<br>+class<br>+function<br>+usage<br>+yearOfConstruction<br>+yearOfDemolition<br>+roofType<br>+measuredHeight<br>+storeysAboveGround<br>+storeysBelowGround<br>+storeyHeightsAboveGround<br>+storeyHeightsBelowGround | + hasSource: Source [1..*]<br>+ time: time object | |

**Table 2** – Detail of the extension of the class 'AbstractBuilding' and the two new objects in form of DataTypes 'BLDG_AATFunction' and 'BldgDenomination'. The properties already present in the CityGML class 'AbstractBulding' are added for completeness.

The time and the source of each data are included in the CHADE, for reference and correct interpretation of all the archived information. They are fundamental to perform historical studies, and following interpretation, preservation and promotion actions.

The considered standards (both GML and ISO/TC 211, also used by INSPIRE) already include schemas for managing the time, with issues for detailing the time considered, as a date or as a period, with different degrees of fuzziness and with the possibility to establish a sort of topology for temporal data, in a temporal reference system. These could be improved following further researches about the representation of time in architectural heritage documentation (e.g. [41]).

The 'Source' is detailed in a DataType, including: type of source; author; employed metadata standard to define it; its name (or title); reference to the source metadata (i.e. the complete sheet with the whole information, shared on a web repository); codes for its identification and retrieval (for example in local archives or libraries); and the same attribute 'time'.

Similarly, the attributes of the CityGML class 'Room' are extended, adding 'AATClass', as reference to the Getty AAT vocabulary instance defining the specific room class (e.g. 'sacraria', ID: 300007572, from the subclasses of 'room and spaces by building type'); 'RoomFunction', referring to the Getty AAT instance defining the specific room function (e.g. 'ballroom', ID:300004413) and 'RoomUsage', similar to the function, but it is referred to a contingent phase of the building, which is not the one for which the space was born. This last one can change over time; it is therefore detailed in a dedicated data type. It includes: the name defining the usage; the reference in the AAT; source and time, for permitting the traceability of the information. In CityGML the properties 'class', 'function' and 'usage' are present, but they are detailed in a codelist which is not sufficient to adequately document historical buildings.

The element of CHADE that most permits the enhancement of granularity and flexibility of the model to suitably represent architectural heritage is the extension of the CityGML class 'AbstractBoundarySurface'. In the original model, this has no attributes, and can be specialised as belonging to the main parts of the buildings (e.g. RoofSurface, CeilingSurface, WallSurface).

All the people dealing with architectural heritage know, however, that every single part of the surface has a different value and tells a different story (materials, techniques, deterioration, building time, author, meaning). It is therefore important to document every single portion of the object surface. For this reason, the change in the 'AbstractBoundarySurface' class aims at very flexible descriptions of the parts of the buildings, stratified and articulated, considering, in a multi-scale approach, even small portions. With 'portions' both clearly defined elements and 'fiat parts' (without 'bona fide', that is defined, boundaries) being intended. These two interpretations are defined as two different objects in the ontology CIDOC-CRM: respectively, they are 'E22_Man-MadeObject', and 'E25_Man-MadeFeature'. A recursive mereological 'part of'' relation is therefore added from AbstractBoundarySurface to the same AbstractBoundarySurface, which allows the articulation of the surfaces in hierarchical, semantically clear, multiscale and possibly topologically-related parts. Furthermore, several attributes are added and defined following the previously explained criteria, and some of them, being complex attributes, were defined as DataTypes. A particular attribute is 'AbstractBoundarySurface::AATDefinition' which describes the element, with reference to the Getty AAT vocabulary (Fig. 2). The hierarchy defined by the AAT vocabulary is conceived as following specific representation aims, so that the terms are grouped (e.g. the architectural elements are structural, surface, circulation, and so on). For achieving a homogeneous representation (with a consistent segmentation of the 3D model) one criteria (that is, consistent levels of the AAT hierarchy) should be chosen. The attributes "BSFunction" and "BSUsage", which can be more than one for each surface, can help in archiving the different valences of the represented component. In possible future development, it could be possible to access directly the AAT vocabulary to understand the hierarchy and the following semantics of the considered model or part of model. At present, for distinguishing explicitly the different aims of the representation (and the consequent semantic segmentation), the attribute “DescriptionAim” is added. Its values can be for example “construction elements” or “spatial composition”, obtaining the segmentations of Fig. 3.

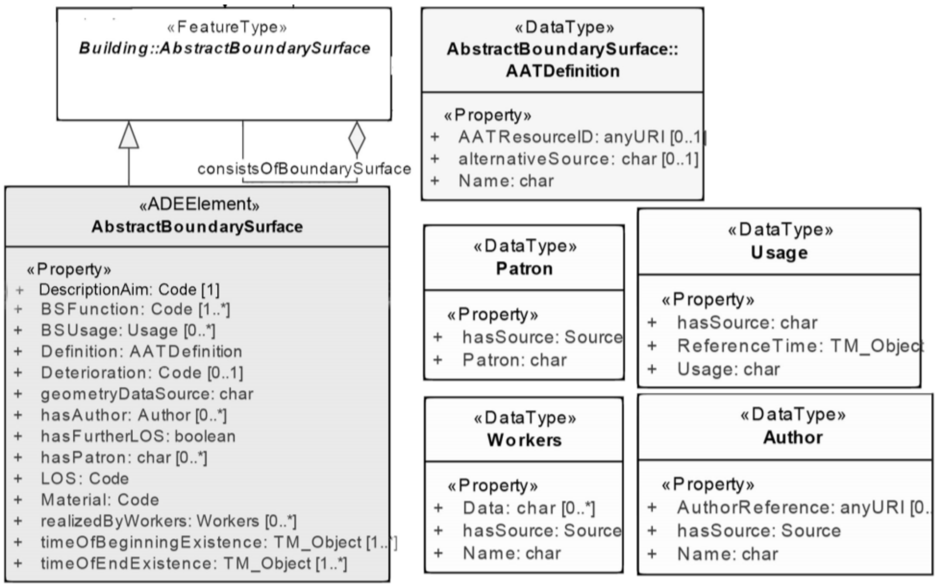
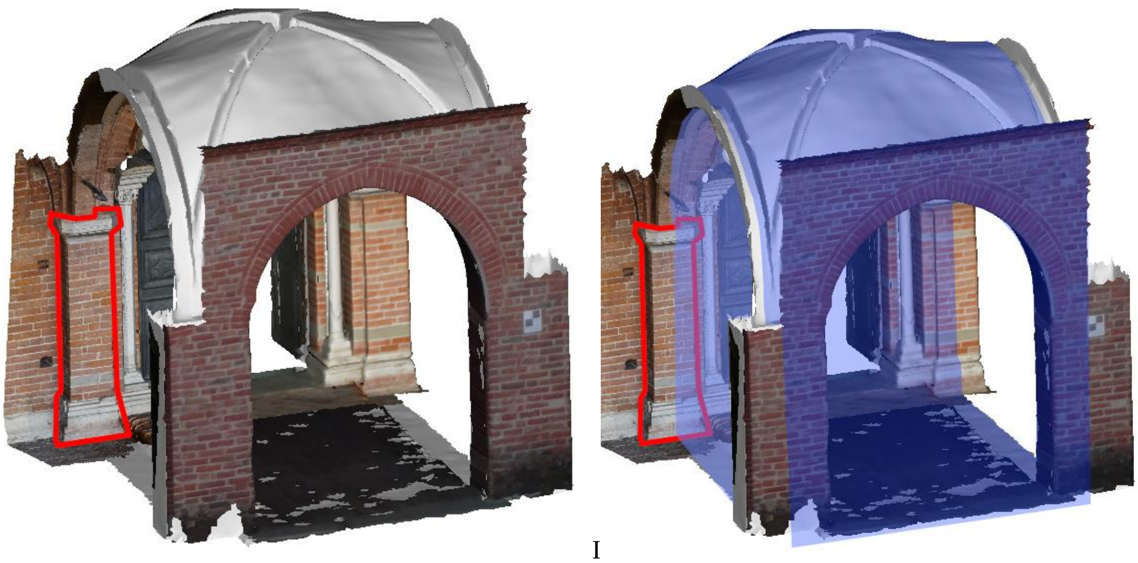



**Fig.2.** Detail of the extension of the attributes of the class ‘AbstractBoundarySurface’ and the definition of the DataTypes defining the extended attributes.



I II

**Fig.3.** For a description aim “constructive subdivision”, a pillar has to be considered as a unit (I); but it should be split into two parts when considering a bay (blue in II) for a spatial composition approach.

An innovative aspect of this model is therefore the possibility to manage each small portion of the artefact surface. These are hierarchically structured following mereological hierarchies (part-of relationships). Each part changes its meaning if considered as a singular part or as part of the whole (from the single brick surface to the whole building) [42]. For describing this hierarchy, the attribute ‘LevelOfSpecialisation’ (LOS) was added. In CityGML, the 3D geometry is classified for geometric accuracy, which mainly derives from the production methods and measurements systems. This characteristic is stored in GML models as Level of Detail (LoD) associated to each geometry. Even if it implies some consequence on the level of semantic definition, it is mainly linked to the possibilities of representation offered by the available data (accuracy and data density). The LOS permits the definition of parts and subparts that can be recognised on the same model (with homogeneous accuracy and LoD) but need to be separately specified because of the different meanings (Fig. 4). A common LOS value means also a common-aim representation (and segmentation).

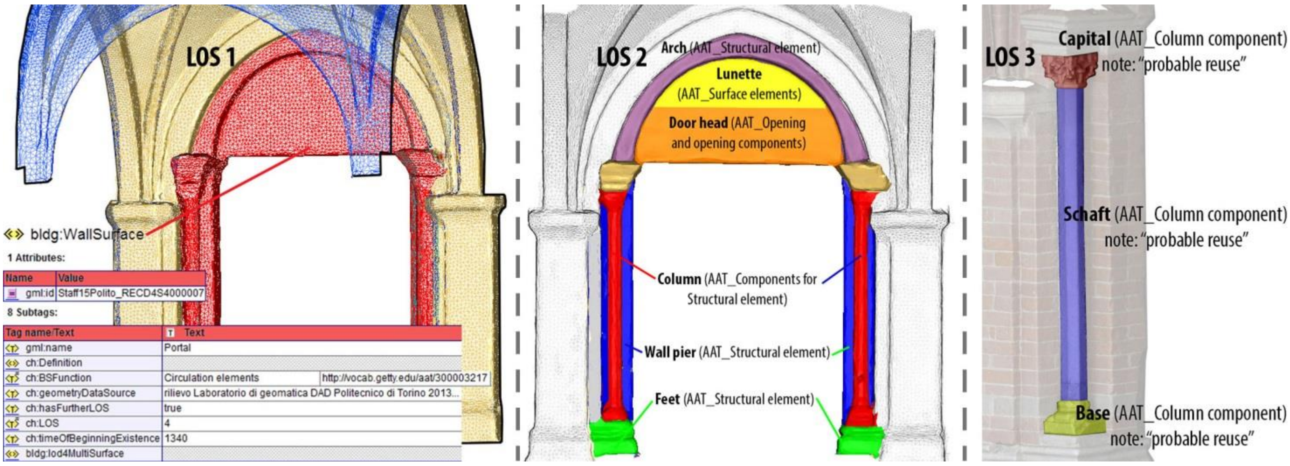


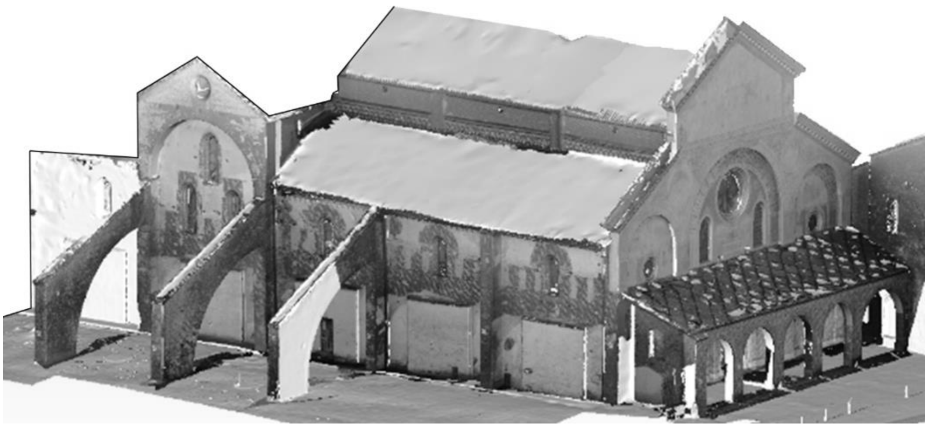

**Fig.4.** Examples of consecutive LOS specified on parts of a homogeneous-LoD 3D model. The right image (detail of the column) also has a higher LoD. The colours represent the parts into which the object is segmented.

A further extension of this class regards the number of LoDs to represent small architectonic details. They have to be increased, because the aim of CityGML is a cartographic representation (urban or regional scale), consequently the envisaged levels of detail are not high enough: from approximately 1:25,000, to a higher level of detail, useful for representing some building characteristics. However, the maximum CityGML detail, while remaining meaningful to the representation and consistent with the other levels, is approximatively 1:500 [43]. More detailed representation can be achieved using textures, permitting the addition of some details usually present in higher representation scales. To include some significant architectural heritage features in the urban representation, however, it is necessary to reach higher levels of detail, because smaller parts should also be geometrically represented without losing their complexity. Two more LoDs are therefore added: a LoD5, for approximately 1:200 or 1:100 scale, and a LoD6 for larger scales. The associated geometry class must be defined as a 'Geometric complex::GM_CompositeSurface', since it is structured and hierarchical, in the same way as the boundary surfaces should be also semantically defined. The classes useful to manage the geometry are already present in the GML and standard schemas, and can be effectively employed. Also the topological relationships among the geometric objects can be defined through the existing standards (e.g. the 'Topology' part of the standard ISO TC211 – ISO 19107:2003 Spatial Schema, or the GML 'topology'). This last described part is complex to use with current software and requires more effort.

## 3 Filling in the archive

The data to be archived can be various in format and scale. In this study, a priority is given to the geometric tridimensional data having high level of detail. These can derive from different measuring and modelling techniques, common in geomatics (e.g. [44, 45, 46, 47]). However, the 3D models must be edited and optimized for being suitably stored.

The case study here considered is a portion of the church of the medieval Staffarda Abbey (in the north-west of Italy). A dense high-level-of-detail (approximate scale 1:50) 3D model (textured mesh) was available (Fig. 5), deriving from LIDAR acquisitions integrated with data deriving from digital photogrammetry and structure-from-motion methods, using images acquired from an unmanned aerial vehicle [48]. The acquisition and processing phases are not here detailed, but they integrate the measurement of the metric data with some techniques for georeferencing the model in a known reference system [49, 50], and for controlling its accuracy, density, and quality [51]



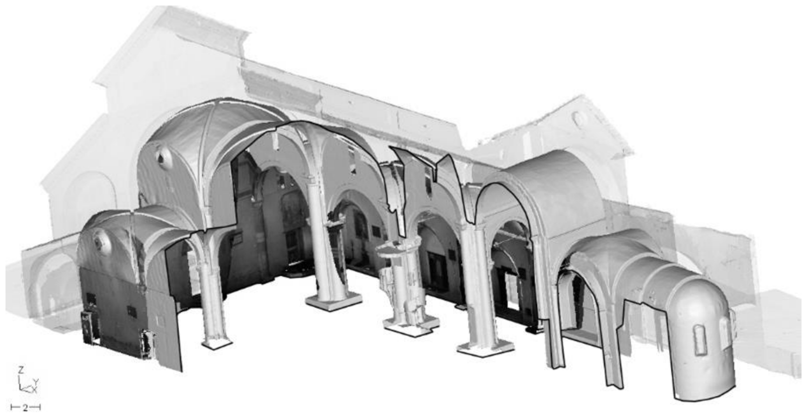


**Fig.5.** Views of the used 3D model (textured mesh) of the Staffarda Abbey church.

It is important to consider the processing phases after that the 3D model is already generated, georeferenced and optimised.

The managed surfaces are complex and composed by millions of triangles (stored as rings composing a multiple composite surface), it is obviously not possible to manually store the singular point coordinates, but some different processing permit their export in a GML format. The technical passages are described in [38].

First of all, it is necessary to reduce the number of stored points, for computational exigencies and to avoid superabundance of data in the storage. A number of algorithms are available for achieving this aim. It is however important to evaluate them in order to preserve the accuracy and original definition. This could be an interesting topic for future studies.

Secondly, the model must be segmented to allow a suitable management, both geometrically and semantically, of each part. In the segmentation different criteria should be followed: the time, for correctly mapping the stratification [52]; the meaning and role of each part, for correctly assign them a semantic value; the material, if this is meaningful for the interpretation of some part of the object; the decay, for mapping the deteriorations and pathologies [53]; and so on. A surface can be eventually repeated if it is part of more than one instance having different LOS as attributes. In this first application, each part of the model was manually segmented in a 3D modelling software. Further automatic segmentation algorithms could be analysed and employed in the future.

The prepared model must then be translated to a GML geometry, to be archived in the CityGML–CHADE compliant database. Mainly two alternatives are possible: the use of Safe Software FME (a proprietary software expressly dedicated to these operations); or the same FME algorithm integrated in ESRI ArcGIS 'Data Interoperability Toolbox' extension. ESRI ArcGIS (also a proprietary software, but often considered de-facto standards for being widely-used) is used in this case, even though the passage from an ESRI shapefile format, which is based on a relational model, does not grant the opportunity to directly specify the final structure of the data.

Because FME is a close proprietary software, however, it is impossible to modify its internal libraries to include the extended schema CityGML-CHADE. For this reason, manual editing of the resulting file is necessary to adapt the data to the new schema and to correctly define the semantics of each part. XML processing software can validate the obtained GML file.

The main difficulty consists in the inability of the existing software tools to integrate functionalities for all the managed phases and 3D formats, so several passages using specific software were followed. When possible, open source solutions are preferred, for interoperability and replicability issues. Open source software were also chosen because they can often be customized for the specific application, without being constrained to the existing structures.

## 4 Results and discussion

The built archive could be shared through the web and read by several applications or interfaces to allow consultation and analysis. Being structured in a shared and explicit way, anyone can correctly interpret the meaning of the stored information and use it for different aims. Moreover, the information can be inserted in wider landscape or city maps, permitting the analysis of the relationships between the represented monument and its broader context. This is meaningful to the definition of the cultural values of the architectural heritage emergences or small parts of them. For example, the use of similar materials or building techniques can be represented into a unique map considering the high level of detail (also a single part of a wall) and the territorial scale (enlightening the distribution of similar objects or objects features). For this reason, the proposed method permits also to include in the geographical 3D database the instances of vernacular heritage. They are often distributed in the landscape [54, 55], and can regard only a small part of a building, not noticeable for other reasons, or very small objects (e.g. pillars, small chapels describing the land) not always presenting high artistic levels, so that probably they would not be considered in more complex modelling of single monuments (such as HBIM).

Another possible study supported by information structured following the proposed data model could be the analysis of the functions of historical buildings in wide land extension, for example to compare the different development of the urban schemas.

Wider datasets could be possibly queried and analysed, once they will be filled in compliance with CityGML-CHADE.

In the test performed for this study, an open source software, FZK [56] was tested in order to read the GML archive based on CityGML-CHADE (Fig. 6). It allows the access and customization of its reference libraries for including the CHADE schema, for correctly understanding the archive. A great advantage is the possibility to read the relationships among all the objects represented in the archive, maintaining an object-oriented structure, which is more complex than the typical relational structure managed by common GIS.

Some functionality typical of the known GIS tools are included (e.g. measurement of the 3D model, thematic visualisation, computation of statistics) (Fig. 7). Notwithstanding, an extension of the capabilities of these visualization tools will be very useful for really exploiting the archive advantages and better read the archive. However, these are informatics issues, which will be solved possibly in a near future.

The cited limits are connected to the visualisation platform, however, whereas the previously structured GML file is completely independent from the platform. This is a further great advantage of this method.

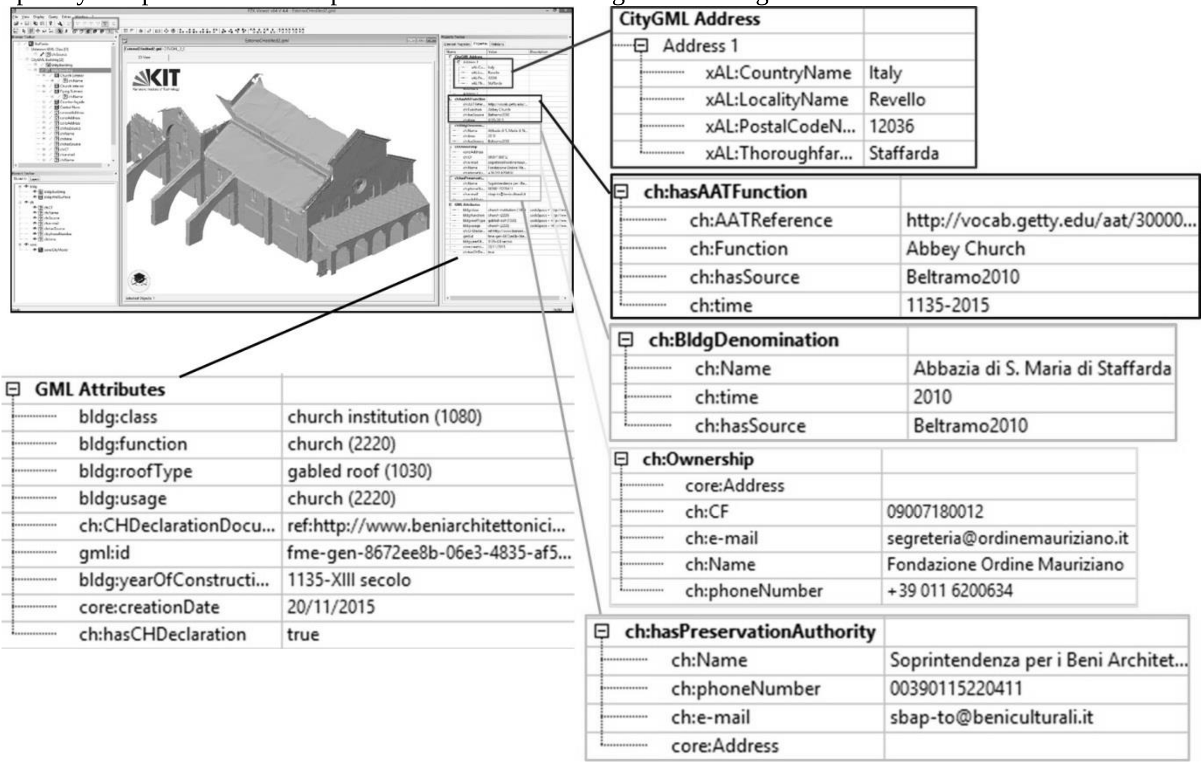



**Fig.6.** Visualization of the GML archive structured using the CityGML-CHADE in the FZK interface (black frame): on the left, the objects of the archive are listed, in the centre the 3D model is visualised and on the right, the properties can be read (in the underlined squares).

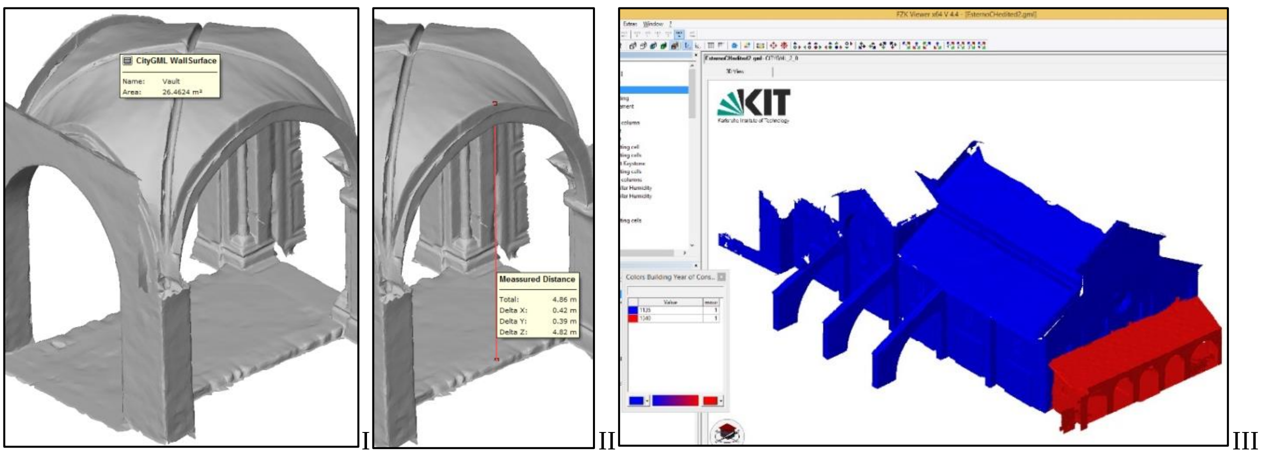


**Fig.7.** Example of direct measurement on the 3D model: areas (I) and distances (II). This can be extremely useful for architectural heritage researchers and operators. (III) is an example of a thematic visualisation of the Staffarda Abbey (based on the attribute 'year of construction').

## 5 Conclusions

Reference standard domain ontologies are essential for managing interoperable information. Architectural heritage documentation will have great advantage from employing this technology.

Multi-faceted, complex, multi-scale 3D models have to be managed by specific structures for effectively documenting architectural heritage. To reach this goal, an extension of CityGML was proposed and tested. The important aspects and issues of architectural heritage are included in the extension, from both the spatial and the thematic points of view.

The use of GML language as a base for writing the files is a definite advantage, because it can be read by humans and by a number of applications (even a simple text-editor could be effective), without being constrained to a single software tool, so that the information there contained will be hardly lost. Conversely, the required skills are not within everyone's reach.

In the extension, some fundamental aspects are addressed: the granularity of the information and its traceability, essential when dealing with historical items; the flexibility of the model, allowing adaption to the representation of such unique artefacts as monuments; and the inclusion of thematic data with eventual reference to external databases and vocabularies.

The use of a standard model permits interoperability of databases and easier retrieval of information in compliant databases. Furthermore, some automated reasoning based on the assembled knowledge could be enabled. Architectural heritage research and preservation can obviously gain great advantages by such systems, but they can also be critical for connected topics (e.g. administration, tourism, risk analysis, education).

Future work will include, in the models and in the data, a true management of advanced spatial issues, such as topology and mereo-topological constraints or geographic rules, in order to enhance analysis potentialities and transversal information retrieval.

Once also these aspects are solved, a further step towards the world-wide management and sharing of the architectural heritage documentation in a unique effective framework for their preservation, retrieval and analysis will have been made, as was recommended since the very early Restoration Charters.

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