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CityGML – OGC Standard for Photogrammetry?

THOMAS H. KOLBE, CLAUS NAGEL, ALEXANDRA STADLER, Berlin

ABSTRACT

Virtual 3D city models are an important data source for an increasing number of applications. Today, most 3D city models are created using data and methods from photogrammetry, remote sensing, and surveying. New applications of 3D city models require additional information about the city objects besides geometry and radiometry. Especially the ontological structure including thematic classes, attributes, and their interrelationships has to be represented and reconstructed. This means that photogrammetric software systems will have to be able to generate and handle more complex models as in the past. Since complex geodata products like cadastre objects or 3D city models are seldom produced in one step, additionally an appropriate data exchange format is required that avoids information loss during the processing chain starting from initial geometry registration, leading over semantic qualification and finally to the end-user applications.

In this paper we discuss the requirements along the processing chain in detail and raise the question to which extent CityGML, the new international standard of the Open Geospatial Consortium for the representation and exchange of virtual 3D city models, can support the manual and automated steps for the acquisition of 3D city models.

1. INTRODUCTION

Virtual 3D city models are an important data source for an increasing number of applications. On the levels of municipalities, states, and countries many developments already aim at the long-term extension or replacement of the corresponding 2D geo-base data by three-dimensional objects and coordinates. Today, most 3D city models are created using data and methods from photogrammetry, remote sensing, and surveying. Often existing 2D data from digital cadastre or landscape models are used to determine the planimetric extension of the geo-objects, while the height information and vertical structures are acquired using photogrammetric analysis. 3D geometry can be given as point clouds (from laser scanning or high resolution and overlapping stereo photogrammetry) or as manually or automatically extracted polygons in 3D space.

Current and new applications of 3D city models like environmental and training simulations, urban planning and facility management, disaster management and homeland security, and personal navigation require additional information about the city objects besides geometry and radiometry. *Semantic 3D city models* comprise besides the spatial and graphical aspects particularly the ontological structure including thematic classes, attributes, and their interrelationships. Objects are decomposed into parts due to logical criteria (and not due to graphical or purely geometrical considerations!) which follow structures that are given or can be observed in the real world. For example, a building will be decomposed into different (main) building parts, if they have different roof types and their own entrances like a house and the garage.

Thus, while in the past simple and pure 3D geometry and radiometry models have been sufficient, e.g. for visualization purposes, the new generation of 3D city models and their applications require the acquisition or generation of complex structured models. It also means that the photogrammetric software systems will have to be able to generate and handle these complex models. This includes the ability to exchange the corresponding datasets without loss of information.

2. WORKFLOW FOR THE GENERATION AND USAGE OF 3D CITY MODELS

Complex geodata products like cadastre objects or semantic 3D city models are seldom produced in one step. They mostly result from photogrammetric or remote sensing capturing methods for 3D geometry and radiometry along with – or followed by – methods for 3D object (re)construction and further object qualifications (Brenner, 2003). The sequence of these tasks forms a processing chain (see fig. 1), which can at least be decomposed into the following steps:

- Geometry acquisition.
- Data qualification and interpretation (e.g. 3D object reconstruction and classification).
- Data refinement (e.g. adding of semantic information; establishing of geometric-topological consistency; integration of datasets from different sources; geodetic homogenization).
- Data preparation for specific applications (e.g. augmentation of 3D models by application specific information; e.g. for driving simulators integration with the simulator control data).
- Usage of the data within specific applications.

Manual or automated processing of data within each of these steps leads to an increase of information and, thus, to an added value along the process chain as illustrated below.

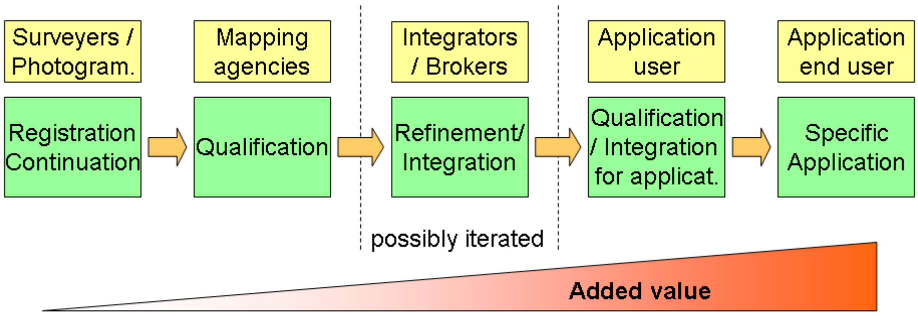

Fig. 1: Processing chain for the generation and usage of geospatial information models, e.g. 3D city models.

Although systems might integrate consecutive steps of the processing chain, each step is often carried out separately by various actors using different systems. Often, systems use their own data models and respective data structures tailored to specific requirements of the current step. These data models are heterogeneous in terms of their geometric, topological and semantic complexity. Among others, the following types can be distinguished (c.f. Stadler & Kolbe, 2007):

- **Models comprising only geometry, but no semantics**
  Purely geometric models are relevant to the storage of raw data or basic geometry models used as input for further data interpretation. They are typically based on 3D graphics formats like VRML, COLLADA, KML, U3D or legacy CAD geometry formats. Information about data quality, e.g. metadata regarding 3D point accuracy, usually cannot be represented with these formats.
- **Models comprising simple semantics along with structured geometry**
  Such models are often created through data interpretation processes like photogrammetric object extraction or automated reconstruction of geometric primitives from laser scanner point clouds. The extracted geometry is obtained in a high degree of complexity. When it comes to semantics only basic information like the existence of a building is indicated. Neither further classifications nor semantic decompositions are supported.
- **Models comprising complex semantics along with structured geometry**
  Here, both the semantics and geometry are modeled in high complexity. If all semantic components correlate to their geometric counterparts, the model is considered as being fully coherent.

In between every stage of the processing chain an appropriate exchange format is required which has to support the respective quality of the model. In the past, no format was available to cover the diverse qualities over all involved systems. Thus, information losses were (and still are often) inevitable. For example, semantic information generated during photogrammetric processing cannot be transported to consecutive steps using geometrically oriented data exchange formats like VRML, COLLADA, DXF, or KML. In many cases not even object identities can be preserved. Moreover, subsequent systems might not be able to interpret all information contained in a data exchange format. This leads to a loss of information due to limitations of the data model expressiveness of a system.

In order to avoid information loss in each processing stage, photogrammetric systems must become able to handle the complex information on the one hand. On the other hand, an appropriate exchange format is needed to transport the data in between the processing steps. The following requirements have to be met:

- Support of structured 3D geometry and semantic information. Geo-objects should have well-defined semantics to make sure that a subsequent processing stage interprets (or the user of that stage understands) the data in the intended way.
- 3D data have to be exchanged in their current state of reconstruction or qualification. This means that the data model and data exchange format would have to account for data of various complexities: from purely geometric data without semantic information to complex geometric-topologically sound and spatio-semantically coherent data.
- Due to varying requirements of applications on the one hand and the diversity of data sources and registration techniques on the other hand, different reconstructions of the same real world object may be created, possibly in different degrees of fidelity or *levels of detail* (LOD). In this case, it should be ensured that different representations of the same real world object can be represented in a merged or at least synchronized way.
- If objects are transformed or aggregated during the processing (e.g. by generalization), explicit links to the original data objects should be maintained.
- When dealing with geoinformation, the exact spatial reference is of utmost importance. Since we are reconstructing 3D city models, support of the commonly used 3D coordinate reference systems is required.
- The same object can be observed from different types of sensors e.g. an RGB camera or a thermal infrared camera. It should be possible to assign the different radiometric observations to the same 3D object surfaces.

In the further course of this paper we show how to facilitate such a workflow on the basis of CityGML, a standardized data model and exchange format for heterogeneous 3D city model data. It serves as a framework facilitating the handling of geodata from its first registration to end-user applications and allowing for iterative data enrichment. As an international standard of the Open Geospatial Consortium, CityGML has the potential to become the common basis for homogeneous communication (on 3D city models) between different photogrammetric systems and applications.

3. CITYGML

CityGML is a common information model for the representation of 3D urban objects. It defines the classes and relations for the most relevant topographic objects in cities and regional models with respect to their geometrical, topological, semantic and appearance properties. Included are generalization hierarchies between thematic classes, and aggregation and thematic relations between objects. This thematic information go beyond graphic exchange formats and allow to employ virtual 3D city models for sophisticated analysis tasks in different application domains like simulations, urban data mining, facility management, and thematic inquiries. CityGML is implemented as an application schema of the Geography Markup Language 3.1.1 (GML3; Cox et al., 2004), the extendible international standard for data exchange and encoding issued by the Open Geospatial Consortium (OGC) and the ISO TC211. It is further based on a number of standards from the ISO 191xx family, the OGC, the W3C Consortium, the Web 3D Consortium, and OASIS (Gröger et al., 2008).

The data model consists of class definitions for the most important objects within virtual 3D city and landscape models. CityGML is modularized into a core module and several extension modules. Whereas the core module comprises the basic concepts and components of a virtual city, each extension module covers a specific thematic field like buildings, digital terrain model, water bodies, vegetation, transportation, and city furniture objects etc. Implementations are not required to support the entire data model but may employ only a subset of modules according to their specific needs.

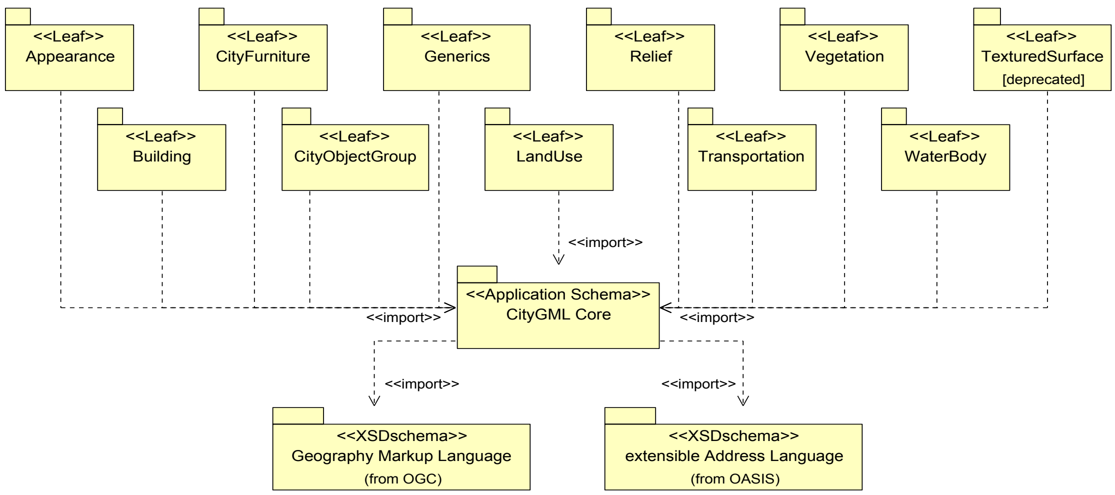

Fig. 2: UML package diagram illustrating the separate modules of CityGML.

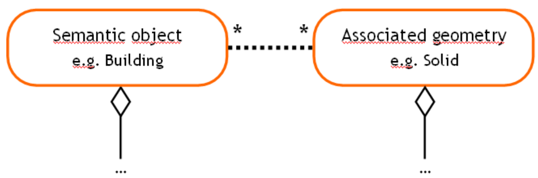

Fig. 3: CityGML's relation between semantics and geometry.

An important design principle of CityGML is the coherent modeling of semantic and geometric/ topological properties. At the semantic level, real-world entities are represented by features such as buildings, walls, windows, or rooms. The description also includes attributes, relations, and aggregation hierarchies between them. At the geometric level, geometry is assigned to thematic features representing their spatial location and extent. Complex geometry objects are decomposed into geometric primitives. So the model consists of two aggregation hierarchies in which the corresponding objects are linked by relationships.

In order to provide for a simple but yet flexible way of topological modeling, CityGML does not make use of GML's topology classes. Instead, topological neighborhood relations are expressed using GML's capability to establish XLinks from composite geometries to the shared geometry (parts). For example, a surface that is both bounding a house and a garage can be referenced by the two respective solid geometries assigned to each object. If a geometry object should be shared by different composite geometries or different thematic features, it only has to be assigned a unique identifier, which is then referenced by the corresponding GML geometry aggregate objects.

In addition to semantics and geometry/topology, objects can be assigned appearances. Appearances are not limited to visual data but represent arbitrary observable properties of an object’s surface such as infrared radiation, noise imission, or earth-quake-induced structural stress.
CityGML defines five consecutive Levels-of-Detail (LOD), where objects become more detailed with increasing LOD regarding both their spatial and thematic differentiation. Each object may have attached a separate representation for each LOD simultaneously.
3D objects are often derived from or have relations to objects in other databases or data sets. In order to express these links, each object in the city model may have external references to their corresponding objects in external data sources given as Uniform Resource Identifiers (URI).
Furthermore, explicit information which facilitate the integration of different 3D datasets / object types can be represented. The concept of the Terrain Intersection Curve (TIC) is introduced to integrate 3D objects with the digital terrain model at their correct height in order to prevent, e.g., buildings from floating over or sinking into the terrain.
To allow for the aggregation of arbitrary city objects according to user-defined criteria, CityGML employs a generic grouping concept. Groups may be further classified by additional attributes and may contain other groups as members, allowing for nested grouping of arbitrary depth.
Spatial objects of equal shape which appear many times in a city model, such as trees, can be modeled using prototypes. The prototypes are stored once in a local coordinate system and then are instantiated for each geo object at different locations using transformation matrices.
Attributes for classifying objects, such as roof types, often are restricted to a set of discrete values. To facilitate interoperability, in CityGML these sets are specified as external codelists and implemented as GML simple dictionaries. External codelists can be (re)defined by the user.
Further objects, which are not explicitly modeled as features yet can be represented using the concept of generic objects and attributes. In addition, the data model may be extended for specific applications through so called Application Domain Extensions (ADE). All datasets containing ADE can still be interpreted by applications that rely on the basic CityGML data model.

4. ADDRESSING THE NEEDS OF PHOTOGRAMMETRIC RECONSTRUCTION

Referring to the discussion in chapter 2, we will explain how CityGML addresses and resolves the issues raised along the photogrammetric processing chain.

4.1. Semantic Modeling

When using CityGML as a data model and exchange format for photogrammetric purposes not only object geometry but most notably object semantics may be stored. This includes data classification, thematic attributes, and logical relations. As described in Section 3, aggregation relations can build hierarchies on the semantic level as well as within the associated (possibly complex) geometry. Figure 4 (on the next page) illustrates the two aggregation hierarchies of a building in LOD 3. The advantage of this approach is that it can be navigated in both hierarchies and between both hierarchies arbitrarily, for answering thematic and/or geometrical queries or performing analysis. By clicking on a door’s geometry information about that door, such as its material and associated address, or about the whole building, such as the number of stories and individual storey heights may be obtained.
This form of semantic modeling enables object reconstruction systems as described in (Fischer et al., 1998 or Gülch & Müller 2001) to exchange the knowledge gained during processing. Further geometric, semantic, and topological relations which might be obtained from or required for reconstruction procedures can be modelled using the generic extension mechanisms.

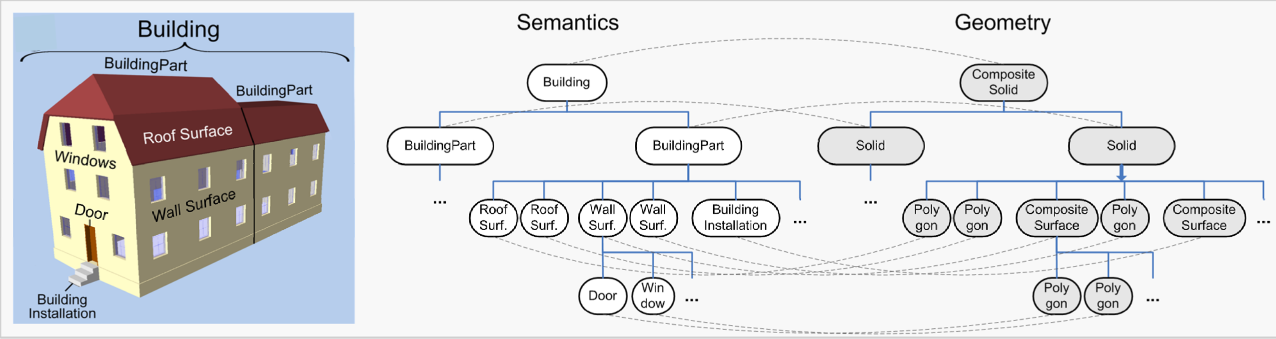

Fig. 4: CityGML model in LOD3. Semantics and geometry are coherently structured and linked on different levels.

4.2. Common information model

A common information model in the sense of a well-defined ontology and data exchange format applicable to all steps of the photogrammetric process chain must be considered a key issue to overcome information loss on the one hand and reduce ambiguity on the other hand between process steps. CityGML defines an application independent geospatial information model whose rich semantic model is the result of a consensus process involving users from a broad range of application domains. All objects have specific semantics which ensures that different users have the same understanding of the concepts. The concepts are formalised as object-oriented data models within the framework of the ISO 191xx standards family. This allows for a high degree of semantic and syntactic interoperability and the usage of CityGML as information carrier between different systems and domains.
Applications throughout the process chain can rely on a specific data quality in terms of both a well-defined thematic and spatial ontology for geo objects and at least a minimum degree of semantic information. Moreover, application specific extensions to the CityGML data model may be defined in order to meet the information needs of specific application domains.

4.3. Incremental model refinement along the processing chain

Considering the evolving quality of data along the photogrammetric processing chain, 3D models are often simple in the beginning and typically are incrementally refined in later stages of processing. For example, in a first step 3D surface geometries of buildings may be registered by stereo analysis and in a subsequent step the surfaces are grouped to create appropriate building objects. In a third step thematic information is added, and the topology of the building solids is derived or enforced. In a final step, appearance information might be acquired and assigned to the objects' surfaces. If these steps are not carried out within the same system, models with differing qualities would have to be exchanged.
Generally, models may gain in the degree of both their semantic information and spatial complexity. In CityGML data are given "enough space to grow" since their geometry and semantics may be flexibly structured. This can result in purely geometric datasets as collections of surfaces in 3D as well as in datasets with complex geometric or semantic decompositions. This flexibility allows to employ CityGML to all steps along the photogrammetric process chain. Having only one format to deal with, inconsistencies and information loss due to (incomplete) data conversions could be avoided in the future.
Moreover, CityGML provides the possibility to model links back to original data, i.e. the input data of preceding processing steps. For example, if objects are generalized into new objects, explicit links between the original and generalized objects can be maintained. These links are especially

helpful for the propagation of updates on the one side and for enquiries about the lineage of specific data items on the other side.

4.4. Appearance modeling

Fig. 5: Multiple appearances can be assigned to all 3D surfaces. Left: RGB texture; right: infrared texture.

In addition to semantics and spatial properties, CityGML features can be assigned appearance information, i.e. observable properties of a feature's surface. In most cases, this surface data is recorded by sensors, e.g. a RGB or infrared camera. CityGML appearances are represented by textures, georeferenced textures, and material representations (adopted from X3D and COLLADA) of object surfaces, but are not limited to visual data. In contrast, appearance relates to any surface-based theme, such as infrared radiation, noise imission, radio frequency absorption, and earthquake-induced structural stress. Consequently, appearance information can serve as input for both visualization and analysis tasks. CityGML supports feature appearances for each LOD and an arbitrary number of themes.

4.5. Digital terrain modeling

Photogrammetry and remote sensing produces terrain data in various forms, from non-interpreted point clouds over rasterdata to triangulated irregular networks (TIN), often including breaklines. Using CityGML's Relief module, all these forms of terrain modeling can be used to build composite terrain representations. The LOD concept even allows for the maintenance of several terrain variants in different resolutions. Digital Terrain Models (DTM) can be restricted by a validity extent polygon. Holes within this polygon allow for embedding of other DTM components, for example a high resolution TIN embedded into a large area gridded DTM.
A crucial point to the integration of 3D objects and the DTM is the correct adjustment of both the local DTM height and the height of the 3D objects. In CityGML, the intersection of the 3D object with the terrain can be explicitly registered. The Terrain Intersection Curve (TIC) delineates the intersection line of the 3D object with the terrain. It can be used to enforce the alignment of an updated DTM with the proper ground edges around the 3D object (e.g. by warping of the DTM).

4.6. Geometric-topological consistency

CityGML supports the modeling of purely geometric up to geometric-topologically sound data. This enables the implementation of data acquisition systems or data refinement processes with geometric-topological representation of spatial properties on the one hand, and the preservation of these information during data exchange on the other hand. Above, the geometric-topological consistency of concrete CityGML datasets can be inspected and ensured. In either case, redundancy of data is avoided. Furthermore, the flexible representation of geometry and topology allows for a subsequent augmentation of purely geometric datasets by topological information.

4.7. Multi-scale modeling

Different acquisition methods or applications often create multiple representations for the same real-world objects in different scales. Objects of lower resolution may also result from generalization processes. In a CityGML dataset, the same object may be represented in different

LOD simultaneously, enabling the analysis and visualization of the same object with regard to different degrees of resolution.
The specification of well-defined LOD for CityGML establishes quality classes for data acquisition. Acquisition rules can be derived from the requirements of each LOD. By providing accuracy values that have to be met in each LOD, CityGML helps in choosing the appropriate photogrammetric capturing method. The model's LOD roughly reflects the model's complexity and accuracy. Furthermore, the LODs can be considered as explicit generalization targets for 3D generalization processes (Kada, 2006).
The predefined levels vary from sole 2.5D models (LOD0) to highly detailed architectural models including interiors (LOD4). Figure 6 illustrates the semantic and geometric modeling of a building in LOD1 to LOD4 - from a simple building block to a very detailed model including interior rooms.

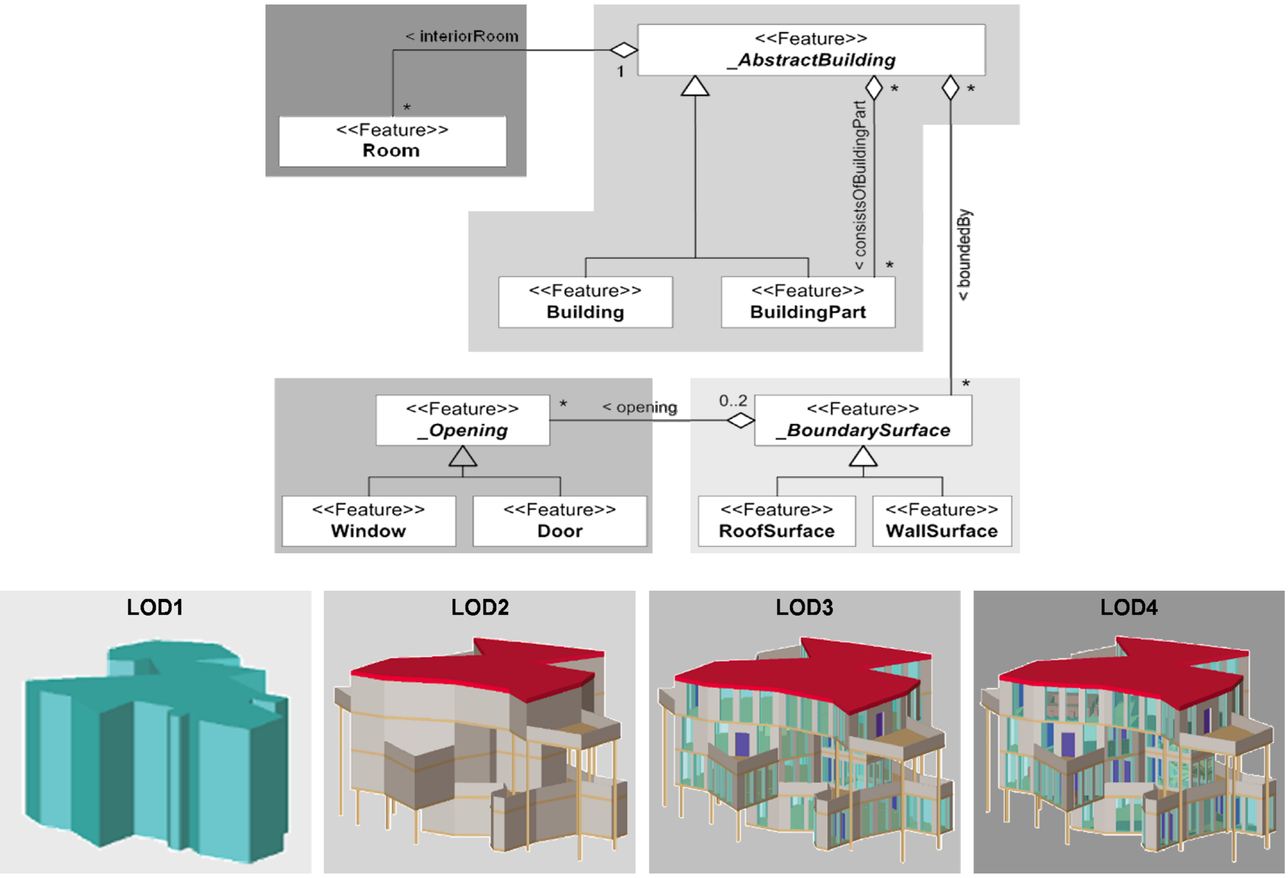

Fig. 6: Semantic and geometric modelling of a building in LOD1, LOD2, LOD3, and LOD4. Each LOD is marked by a different grey shade.

4.8. 3D georeferencing

The support of 3D Coordinate Reference Systems (CRS) is an important key to the integration of different spatial datasets. CityGML inherits GML3's spatial capabilities of handling arbitrary 2D and 3D CRS. Besides geographic and projected coordinates, it also supports compound 3D CRS, i.e. different CRS for planimetry and height. Even a mixed usage of different spatial reference systems within the same dataset is possible.

4.9. Storage, processing, and exchange

Spatial properties of CityGML features are modeled using the GML3 geometry model (Herring, 2001), representing 3D geometry according to the well-known Boundary Representation (B-Rep, Foley et al., 1995), typically using a world coordinate system. Spatial databases, like Oracle Spatial and PostGIS, as well as many (3D) GIS provide native support for GML3's geometry model enabling lossless and efficient storage, management and spatial indexing of CityGML data.
Since CityGML is realized as a GML3 application schema, it perfectly combines with the full range of OGC standards allowing for seamless integration of spatial data from different sources within Spatial Data Infrastructures (SDI). The Catalogue Service (CS-W), the Web Feature Service (WFS), the Web Coordinate Transformation Service (WCTS), and the Web Processing Service (WPS) are especially relevant to identify, access, exchange, and process CityGML resources. For 3D visualization, corresponding OGC portraying services are the Web 3D Service (W3DS; see Quadt & Kolbe, 2005) and the Web Terrain Service (WTS).

4.10. Prototypes and training data

Many cities and municipalities already model and exchange their 3D city models according to CityGML. This existing data can be used as reference and input for sophisticated simulations and analysis tasks, e.g. for automated object reconstruction processes, where sensible prototypes and statistical distributions of object parameters may be derived when taking these models as training data. The CityGML ontology defines target objects for the development of reconstruction methods (Schmittwilken et al., 2007).

5. RELATED WORK

Up to now, different 3D formats are used along the photogrammetric process chain. Most of these formats have been defined in the context of computer graphics or Computer Aided Design (CAD), e.g. DXF and DGN. In the following, commonly used formats are discussed.

5.1. 3D computer graphics formats

3D formats like X3D (ISO 19775, 2005) or U3D (ECMA-363, 2005) have their roots in the domain of computer graphics. As they are primarily focused on the modeling of the geometric shape along with its appearance and limited topology, they do not provide specific support for the representation of semantic information. However, Pittarello and De Faveri (2006) proposed two approaches to augment X3D by semantic information. Generally, they suggest representing complex spatial real world objects as multi-level aggregation hierarchies. The first approach is based on tagging X3D geometries with semantic information (properties and relations) in their metadata fields, leaving some problems to represent objects without geometries. The second approach employs the Resource Description Framework (RDF, 2004) and introduces the three different spatial aggregation concepts 'containedBy', 'sharedBy', and 'boundedBy' which are used to define zonal models. The proposed concepts allow for the representation of semantic information. However, they neither provide a framework for the definition of geographic features nor a definition of concrete objects like buildings and their semantics.

5.2. KML - exchange format for geovisualization

KML is an XML application used to encode and transport representations of geographic data for display in an earth browser (KML; see Wilson, 2008). It was brought into the OGC standardization process by Google Inc. in 2007 and has recently been adopted as an OGC standard. KML focuses on geographic visualization, including annotation of maps and images. Geographic visualization comprises not only the presentation of graphical data on the globe, but also the control of the user's navigation. KML data is organized in terms of features whereas the notion of feature is different to ISO 19109 and GML. A KML feature is an object with spatial and optional thematic properties like a name, a description, or an address. On the geometry level, KML utilizes a subset of geometry elements derived from GML 2.1.2 with a fixed spatial reference system. From its definition, KML is complementary to the OGC standards GML and CityGML. Because of its tailoring to geographic visualization it is an appropriate output format to viewer applications, but should rather not be used as exchange format for geographic data along the photogrammetric process chain.

5.3. Building Information Models and IFC

Building Information Models (BIM) are increasingly often represented and exchanged using the Industry Foundation Classes (IFC; see Liebich et al., 2007), an ISO standard describing a product model and data exchange format for the built-up environment developed by the International Alliance for Interoperability (IAI). IFC provides a rich semantic model for 3D building representation using constructive elements like beams, walls etc. Like in GML, IFC geometries are spatial properties of semantic objects. A current IFC to GIS extension project carried out by the IAI even aims at enabling the IFC schema to handle georeferencing of all building structures. However, IFC models are the result of a generative process focusing on manmade constructions. Topographic features relevant to photogrammetric processing like digital terrain models can only be modeled and exchanged as generic objects (i.e. IFC_Proxy). In contrast to a generative modeling approach, photogrammetric data is mainly acquired from observations, e.g. aerial images, laser scanner data or terrestrial measurements. Thus, an accumulative modeling principle is applied which allows the easy description of the observed features from the first data registration. These fundamental differences hinder a coherent integration of models from both domains and the use of IFC as common information model applicable to all steps of the photogrammetric process chain. However, IFC models can be converted to CityGML preserving most of their semantic information (Benner et al., 2005). Lapierre and Cote (2007) show how IFC and CityGML models can be combined in order to support emergency response planning in a homeland security scenario.

6. CONCLUSIONS

CityGML is the OGC standard for the modelling, representation, and exchange of virtual 3D city models. 3D models can be represented in up to 5 different levels-of-detail (even simultaneously) with respect to their geometry, topology, appearance or radiometry, and especially their semantics. Predefined classes have well-defined meanings, and object types which are not predefined (or objects which have not yet been classified during registration) can be represented as generic objects. Systematic extensions of CityGML by new object types and attributes are supported by the ADE mechanism.

Generally, CityGML is very flexible with respect to the data quality along the (photogrammetric) processing chain and allows that 3D models can evolve in subsequent steps while the objects keep stable with respect to their identities and already reconstructed structures. Hence, all data is given enough space 'to grow' with respect to semantics, geometry, topology, and appearance within the same framework. Multiple representations of the same real world object can be integrated and are typically mapped to also only one geo-object. Metadata for data quality like point accuracies (e.g. given by standard deviation) can be represented in GML3, and thus, also in CityGML. A first proposal for appropriate metadata elements for 3D city models is given in (Dietze et al., 2007).

The modeling paradigm of CityGML is oriented towards the representation and mapping of observable features and thus is very 'close' to the results that are obtained from data acquisition methods from photogrammetry, remote sensing, and surveying. The geometry model of GML3 implements a boundary representation and the semantic objects on the lowest aggregation level of CityGML refer to surfaces, e.g. WallSurface, InteriorWallSurface, CeilingSurface, RoofSurface, WaterSurface etc. In fact, in (Nagel et al., 2009) we argue to use CityGML as an intermediate model and exchange format for the automated acquisition of building information models from uninterpreted 3D geometry models (which can be the result of terrestrial laser scanning or architectural photogrammetric analysis followed by basic segmentation or surface generation steps). In the creation of building information models users are typically not interested in a surface-based decomposition, but in the modeling of volumetric components like walls and slabs where the spatial properties are given as constructive solid geometry (CSG) models. Since the mapping of BRep models to CSG is ambiguous, the semantic information contained within CityGML based building representations can be used to support the further interpretation. Furthermore, for a range of applications like indoor navigation or facility management CityGML models are already sufficient, and BIM models do not necessarily have to be reconstructed.

CityGML is supported by an increasing number of GIS and spatial database management systems. Besides commercial systems different free software tools, viewers, libraries, and databases are available (see www.citygmlwiki.org and Stadler et al. 2009). Many cities have started to use or are already employing CityGML to model, store, and exchange their virtual 3D models (c.f. Döllner et al., 2006). A range of applications already uses CityGML models. One of the biggest projects to name is the computation of noise immission maps according to the EU environmental noise directive which obligues all EU member countries to regularly provide maps of the noise pollution within the bigger cities. In the state of North-Rhine Westphalia in Germany, the whole process from data acquisition over qualification and enrichment of city model data by noise specific information to the noise dispersion simulation is completely based on CityGML and OGC Web Services (see Czerwinski et al. 2006).

6.1. Challenges for photogrammetric software systems

The support of CityGML – but we can say generally of complex 3D models – puts high demands on photogrammetric software tools. Such a system will have to cope with basic GML3 geometry types (i.e. simple features + Solids + TINs) and with 3D coordinate reference systems (especially compound 2D+1D CRS). It must be able to handle thematic and geometric objects separately and also aggregations of both thematic and geometric objects. The production of topologically sound models is highly recommended, since many applications require to correctly compute the volume of the 3D objects.

However, no matter whether the semantics will be structured according to the CityGML model, modern geospatial information models follow increasingly the modeling paradigm defined by the ISO 191xx standards family. For example, more and more national and international digital cadastre and landscape models are modeled accordingly and exchanged using a GML application schema (e.g. DE: ALKIS/ATKIS/AFIS, UK: Ordnance Survey Mastermap, NL: Top10NL, EU: INSPIRE Data Specifications). CityGML is only specific here in the sense that the thematic object classes follow a certain structure that is seen most appropriate for multifunctional virtual 3D city models. The modeling approach and underlying modeling paradigms are the same as with the cadastre standards mentioned above. Thus, modern photogrammetric workstations will have to cope with semantic objects, aggregation structures, and more complex geometries in the future anyway.

The modularization of CityGML may help to reduce the efforts, since implementations are allowed to support a restricted set of themes only (like Buildings, LandUse or Relief).

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