

CityGML – Interoperable Access to 3D City Models

Thomas H. Kolbe, Gerhard Gröger, Lutz Plümer

Institute for Cartography and Geoinformation
University of Bonn, Meckenheimer Allee 172, 53115 Bonn, Germany
{kolbe|groeger|pluemer}@ikg.uni-bonn.de

Abstract. Virtual 3D city models provide important information for different aspects of disaster management. In this context, up-to-dateness of and flexible access to 3D city models are of utmost importance. Spatial Data Infrastructures (SDI) provide the appropriate framework to cover both aspects, integrating distributed data sources on demand. In this paper we present CityGML, a multi-purpose and multi-scale representation for the storage of and interoperable access to 3D city models in SDIs. CityGML is based on the standard GML3 of the Open Geospatial Consortium and covers the geometrical, topological, and semantic aspects of 3D city models. The class taxonomy distinguishes between buildings and other man-made artifacts, vegetation objects, waterbodies, and transportation facilities like streets and railways. Spatial as well as semantic properties are structured in five consecutive levels of detail. Throughout the paper, special focus is on the utilization of model concepts with respect to different tasks in disaster management.

1. Introduction

Virtual 3D city models provide important information for different aspects of disaster management. First, they memorize the shape and configuration of a city. In case of severe destruction of infrastructure e.g. caused by earthquakes, immediate access to this reference data allows to quickly assess the extent of the damage, to guide helpers and last but not least to rebuild the damaged sites. Second, 3D city models enable 3D visualizations and facilitate localization in indoor and outdoor navigation. Augmented reality systems provide helpers with information that is visually overlaid with their view of the real world. Such systems need 3D city models in order to compute the positions and occlusions of the overlay graphics. Third, 3D escape routes inside and outside of buildings can be determined with an appropriate city model. Fourth, in flooding scenarios 3D city models allow to identify even affected building storeys.

In the context of disaster management, up-to-dateness of and flexible access to 3D city models are of utmost importance (Zlatanova and Holweg 2004). Spatial Data Infrastructures provide the appropriate framework to cover both aspects, integrating distributed data sources on demand (Groth and McLaughlin 2000). However, the prerequisite is syntactic and semantic interoperability of the participating GIS components (Bishr 1998).

Syntactic interoperability can be achieved by using the XML-based Geography Markup Language (GML3, see Cox et al. 2004) of the Open Geospatial Consortium (OGC). GML3 is an XML-based abstract format for the concrete specification of application specific spatial data formats. It is open, vendor-independent, and based on ISO standards; it can be extended and specialized to a specific application domain; and it explicitly supports simple and complex 3D geometry and topology. Furthermore, GML is the native data format of OGC's Web Feature Service (WFS), a standardized web service that implements methods to access and manipulate geodata within a spatial data infrastructure (Vretanos 2002).

Semantic interoperability presumes common definitions of objects, attributes, and their interrelationships with respect to a specific domain. However, no common semantic model for 3D city models has been established yet. In the following we present CityGML, a multi-purpose and multi-scale representation for the storage of and access to 3D city models. It has been developed during the last two years by the Special Interest Group 3D of the initiative Geodata Infrastructure North-Rhine Westphalia (GDI NRW). The data model behind CityGML is based on the ISO standard family 191xx. The implementation is realized as an application schema for GML3.

CityGML covers the geometrical, topological, and semantic aspects of 3D city models. The class taxonomy distinguishes between buildings and other man-made artifacts, vegetation objects, waterbodies, and transportation facilities like streets and railways. Spatial as well as semantic properties are structured in five consecutive levels of detail (LoD), where LoD0 defines a coarse regional model and the most detailed LoD4 comprises building interiors resp. indoor features. Included thematic objects, which are especially relevant for disaster management, are different types of digital elevation models, building features like rooms, doors, windows, balconies, and subsurface constructions.

The paper concludes with first results of the ongoing evaluation project "Pilot 3D", in which six groups from Germany including the municipalities of Berlin, Hamburg, Cologne, Düsseldorf, and Leverkusen implement the CityGML application schema and exchange 3D city models.

2. Related Work

3D city modeling is an active research topic in distinct application areas. Different modeling paradigms are employed in 3D geographical information systems (3D GIS, Köninger and Bartel 1998), computer graphics (Foley et al. 1995), and architecture, engineering, construction, and facility management (AEC/FM; Eastman 1999). Whereas in 3D GIS the focus lies on the management of multi-scale, large area, and geo-referenced 3D models, the AEC/FM domain addresses more detailed 3D models with respect to construction processes (Kolbe and Plümer 2004). Computer graphics concentrates rather on the visualization of 3D models.

The representation of geometry and topology of 3D objects has been investigated in detail by Molenaar (1992), Zlatanova (2000), Herring (2001), Oosterom et al. (2002), Pfund (2002), and Kolbe and Gröger (2003; 2004). The management of multi-scale models was discussed (among others) by Coors and Flick (1998), Guthe and Klein (2003), Gröger et al. (2004).

The ISO standard ISO/PAS 16739 ‘Industry Foundation Classes’ (IFC, Adachi et al. 2003) is a semantic model for buildings and terrain which has been developed in the AEC/FM domain. It defines an exchange format and contains object classes for storeys, roofs, walls, stairs, etc.. Nevertheless, since IFC is lacking concepts for spatial objects like streets, vegetation objects or water bodies, it is not appropriate for the representation of complex city models. Similar problems arise with respect to ‘green building XML’ (gbXML 2003), an AEC/FM standard for building energy and environmental performance analysis, and ‘Building-construction XML’ (van Rees et al. 2002), a standard for the mapping of construction taxonomies.

LandXML/LandGML is a standard for land management, surveying and cadastre, providing a semantic model for parcels, land use, transportation and pipe networks (LandXML 2001). Although LandXML supports 3D coordinates, it does not comprise volumetric geometries. Buildings are only represented by their footprints. Further concepts for 3D man-made objects are missing.

Computer graphics (CG) standards like VRML97 (1997) and its successor X3D model only the appearance of 3D objects. They do not provide concepts for the representation of thematic aspects, attributes, and interrelationships of the graphical objects.

Since thematic information are crucial for disaster management, CG standards are not sufficient. AEC/FM standards concentrate on man-made constructions and are lacking concepts for the representation of natural objects. Furthermore, none of the discussed AEC/FM and GIS standards supports multi-scale models resp. multiple levels-of-detail (LoD).

3. CityGML: Unified 3D City Modeling

CityGML is a profile of GML3, which implements an interoperable, multi-functional, multi-scale and semantic 3D city model. This section presents the highlights of CityGML, starting with general concepts in the first section. CityGML covers the thematic objects which are relevant for city models, including transportation objects like streets or traffic lights, or vegetation objects. However, in this section the focus is on the most important components of city models, on the building model and on the Digital Terrain Model. Both are discussed in detail.

Initially, CityGML is specified using the graphical *Unified Modeling Language (UML)* (see Booch et al. 1997). From UML diagrams, the XML schemas are derived by applying the transformation rules given in Cox et al. (2004). Thus, CityGML may be processed by standard GML3 readers.

3.1 General Concepts

CityGML implements several novel concepts to support interoperability, consistency and functionality.

Levels-of-detail

CityGML supports different *Levels-of-Detail (LoD)*, which may arise from independent data collection processes and are used for efficient visualization and efficient data analysis. In one CityGML data set, 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. Furthermore, two CityGML data sets containing the same object in different LoD may be combined and integrated.

CityGML provides five different LoD, which are illustrated in **Fig. 1**. The coarsest level *LoD0* is essentially a two and a half dimensional Digital Terrain Model, over which an aerial image or a map may be draped. *LoD1* is the well-known blocks model, without any roof structures or textures. In contrast, a building in *LoD2* has differentiated roof structures and textures. Vegetation objects may also be represented. *LoD3* denotes architectural models with detailed wall and roof structures, balconies, bays and projections. High-resolution textures can be mapped onto these structures. In addition, detailed vegetation and transportation objects are components of a LoD3 model. *LoD4* completes a LoD3 model by adding interior structures like rooms, interior doors, stairs, and furniture.

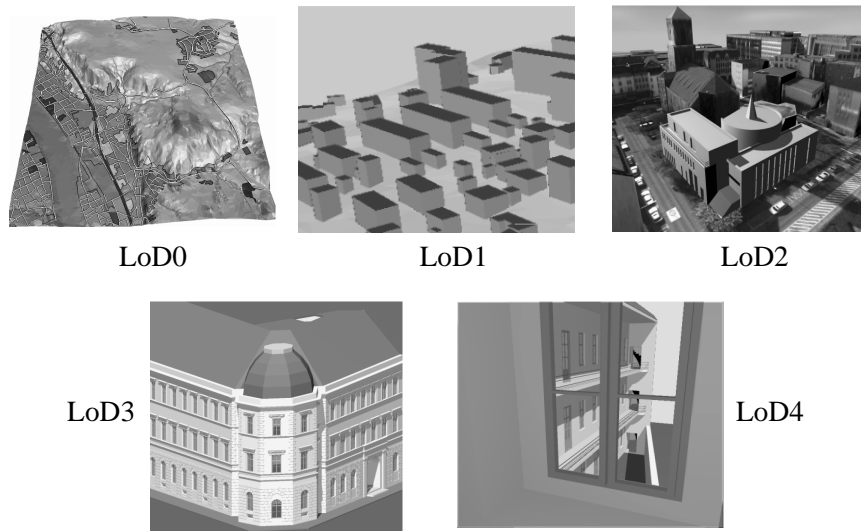


Fig. 1. The five Levels-of-Detail (LoD) defined by CityGML

The different LoD are also characterized by accuracies and minimal dimensions of objects. In LoD1, the positional and height accuracy of points may be 5m or less, while all objects with a footprint of at least 6m by 6m have to be considered. The positional accuracy of LoD2 is 2m, while the height accuracy is 1m. In this LoD, all objects with a footprint of at least 4m by 4m have to be considered. Both types of accuracies in LoD3 are 0.5m, and the minimal footprint is 2m by 2m. Finally, the positional and height accuracy of LoD4 must be 0.2m or less. By means of these figures, the classification in five LoD may be used to assess the quality of a 3D city model data set. Furthermore, the LoD category makes data sets comparable and thus supports the integration process of those sets.

Geometric-topological modeling

Spatial properties of thematic objects in CityGML are represented by a geometrical-topological model, according to the well-known *Boundary Representation* (Foley 1995). For each dimension, there is a geometric-topological primitive: a zero-dimensional object is a *node*, a one-dimensional an *edge*, a two-dimensional a *face*, and a three-dimensional a *solid*. A solid is bounded by faces, a face by edges, and an edge by nodes. An edge is restricted to be a straight line, and a face must be planar, i.e. its

boundary and all interior points are forced to be located in one plane. Edges, faces and solids may be aggregated to *CurveGeometries*, *SurfaceGeometries* and *SolidGeometries*, respectively (Kolbe and Gröger 2003). These geometries are used to define the spatial properties of application objects. The primitives and the aggregates are implemented using the GML3 geometry and topology classes, similar to the two-dimensional ‘Simple Topology’ profile of the standard ISO 19107 (Herring 2001).

The primitives node, edge, face, solid, and the aggregates must satisfy a number of integrity constraints, which guarantee consistency of the model. The interiors of the primitives must be disjoint, and if two primitives touch, the common boundary must be a primitive of lower dimension (Herring 2001). These constraints assure a clean topology without any redundancy. Since solids must be disjoint, the computation of volumes of solids does not yield erroneous results, which would be the case if solids overlap.

Coherent semantic-geometrical modeling

Another feature of CityGML is the coherent modeling of semantics and geometrical/topological properties. On the semantic level, real-world entities are represented by application objects, for example buildings, including attributes, relations and aggregation hierarchies (part-whole-relations) between objects. On the spatial level, geometric-topological objects are assigned to semantic objects, which represent their spatial properties. Thus, the model consists of two hierarchies, the semantic and the geometric-topological, where the corresponding objects are linked by relations. The advantage of this approach is, that it can be navigated in both hierarchies and between both hierarchies.

Closure surfaces and subsurface objects

A novel concept in CityGML is the *ClosureSurface*, which is employed to seal objects, which are in fact open, but must be considered as closed to compute its volume. An airplane hangar is an example for such an object. *ClosureSurfaces* are special surfaces which are taken into consideration when needed to compute volumes and are neglected, when they are irrelevant or not appropriate, for example in visualizations.

The concept of *ClosureSurfaces* also is employed to model the entrances of *subsurface objects*. Those objects like tunnels or pedestrian underpasses have to be modeled as closed solids in order to compute their volume, for example in flood simulations. The entrances to subsurface objects also have to be sealed to avoid holes in the digital terrain mode (see **Fig. 2**).

However, in close-range visualizations the entrance must be treated as open. Thus *ClosureSurfaces* are an adequate way to model those entrances.

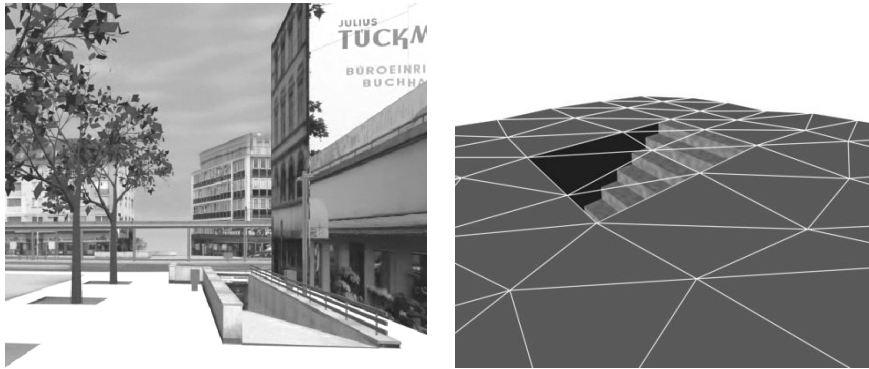


Fig. 2. Passages are subsurface objects (left). The entrance is sealed by a virtual *ClosureSurface*, which is both part of the DTM and the subsurface object (right).

References to objects in external data sets

CityGML objects often are derived from or have relations to objects in other databases or data sets. For example, a building may have been constructed from a two-dimensional footprint in a cadastre, or may be derived from an architectural model. The reference of a 3D object to its corresponding object in an external data set is essential, if an update must be propagated or if additional data, for example the name and address of a building's owner, is required. In order to supply such information, each CityGML thematic object may have *External References* to corresponding objects in external data sets (see **Fig. 3**, upper right part of diagram). Such a reference denotes the external information system and the unique identifier of the object in this system. Both are specified as *Uniform Resource Identifier (URI)*, which is a generic format for any kind of resources in the internet.

Dictionaries and code lists for attributes

Attributes, which classify objects often have values which are restricted to a number of discrete values. An example is the attribute *roof type*, whose attribute values are saddle back roof, hip roof, semi-hip roof, flat roof, pent roof, or tent roof. If such an attribute is typed as string, misspellings or different names for the same notion obstruct interoperability. In CityGML, such classifying attributes are specified as *Code Lists* or *Dictionaries*. Such

a structure enumerates all possible values of the attribute, assuring that the same name is used for the same notion. In addition, the translation of attribute values into other languages is facilitated.

3.2 The Building Model

The building model is the core of CityGML. It allows the representation of thematic and spatial aspects of buildings, building parts and accessories in four levels-of-detail, LoD1 to LoD4. The UML diagram of the building model is depicted in **Fig. 3**. The pivotal class of the model is *AbstractBuilding*, which is specialized either to a *Building* or to a *BuildingPart*. Since an *AbstractBuilding* consists of *BuildingParts*, which again are *AbstractBuildings*, an aggregation hierarchy of arbitrary depth may be realized. Since *AbstractBuilding* is a subclass of the root class *CityObject*, the relation to the *ExternalReference* (see section 3.1) is inherited. In LoD1, the spatial extent of an *AbstractBuilding* is given by a *SolidGeometry*, which in this case is a simple block. A *Building* may be part of a *BuildingComplex*, which has at least one main building.

A crucial issue in city modeling is the integration of buildings and the terrain. Problems arise if buildings float over or sink into the terrain, which is particularly the case if terrains and buildings in different LoD are considered. To overcome this problem, the *TerrainIntersection* curve of a building is introduced. This curve denotes the exact position where the terrain touches the building, and is represented by a closed ring surrounding the building (see **Fig. 4** for an example). If the building has a courtyard, the *TerrainIntersection* curve consists of two closed rings. This information can be used to integrate the building and a terrain by ‘pulling up’ the surrounding terrain to fit the *TerrainIntersection* curve. By this means, the curve also ensures the correct positioning of textures. Since the intersection with the terrain may differ depending on the LoD, a building may have different *TerrainIntersection* curves for each LoD.

In a LoD2 building, it is possible to distinguish the bounding surfaces as own thematic objects. These surfaces may be classified as *Roof*, *Wall* or *Floor Surfaces*. The geometry of these surfaces, however, is shared with the *SolidGeometry* that defines the whole building. An opening in a building is modeled by a *ClosureSurface*; this concept was already discussed in sec. 3.1. The geometry of a LoD2 building is given by *SolidGeometries*, and additionally by *SurfaceGeometries*, which represent surfaces that are part of the building, but do not bound the solids of the building. The overhanging part of a roof is an example for such a surface. A LoD2 building

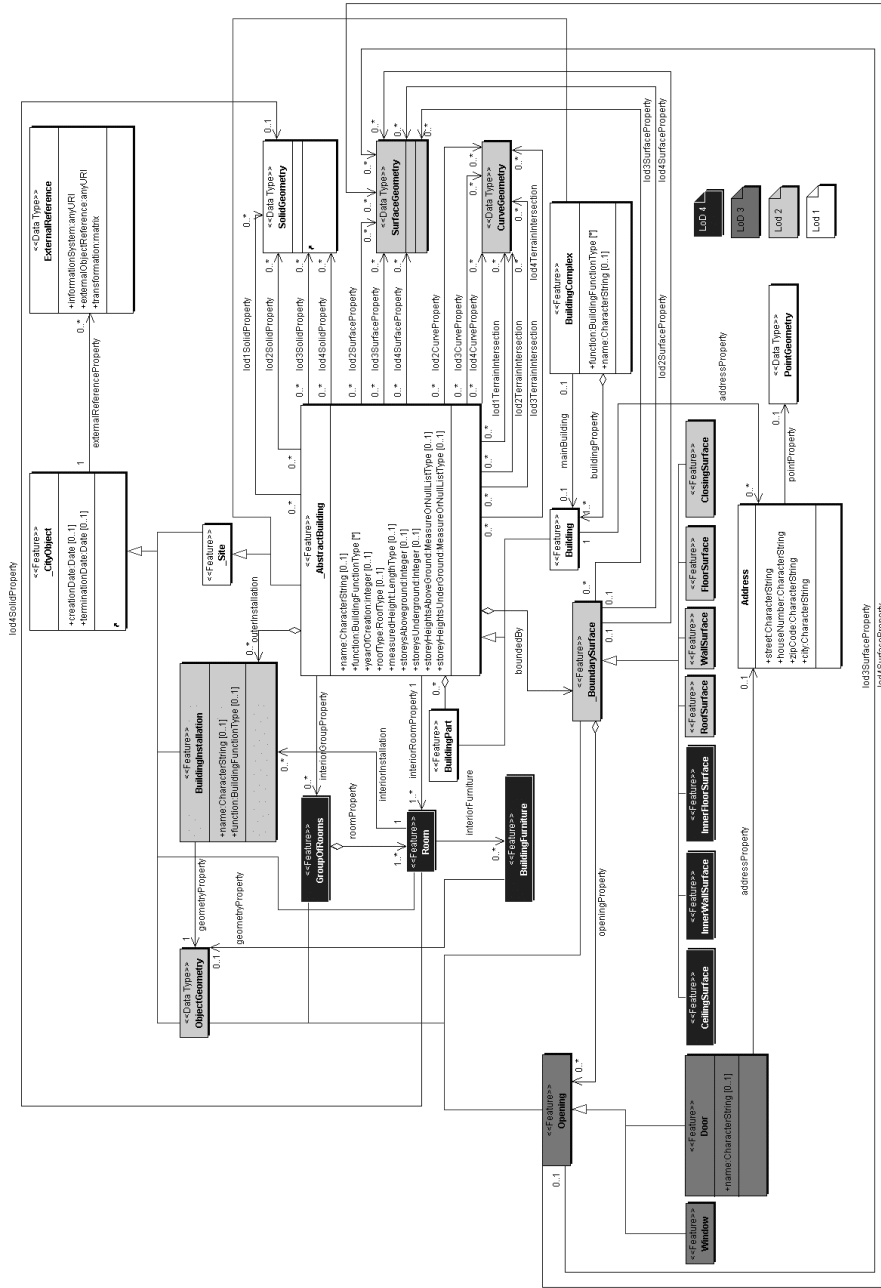


Fig. 3. UML-Diagram (Booch et al. 1997) of CityGML's building model

also may have *BuildingInstallations*, for example chimneys, balconies or outer stairs. The geometry type of a *BuildingInstallation* is not restricted. It is specified by a *ObjectGeometry*, which is the super class of the aggregates *CurveGeometries*, *SurfaceGeometries* and *SolidGeometries*. In contrast to *BuildingParts*, *BuildingInstallations* are smaller and only accessories, but not a constituent part of the building.

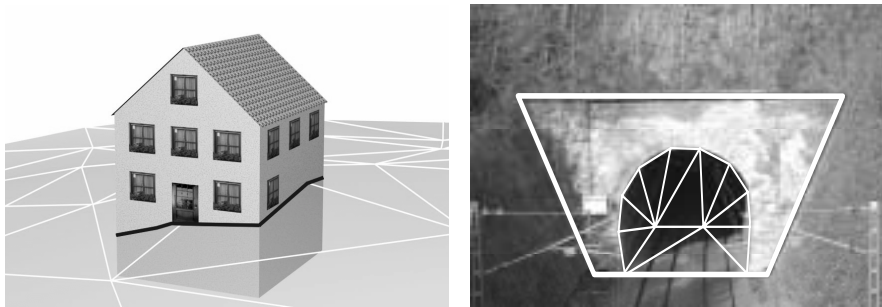


Fig. 4. *TerrainIntersection* curve for a building (left, black) and a tunnel object (right, white). The tunnel's hollow space is sealed by a triangulated *ClosureSurface*.

In LoD3, buildings additionally may have *Openings* such as *Windows* and *Doors*. The class *Opening* is a sub class of *CityObject*, thus the reference to objects in external data sets is inherited. As discussed in section 3.1, the accuracy requirements of LoD3 are much higher than those of LoD2.

LoD4 complements LoD3 by adding interior structures of buildings such as *Rooms*, which are bounded by *Ceiling-*, *InnerWall-* and *Inner-FloorSurfaces*. Rooms may be aggregated to a *GroupOfRooms*, and may have *BuildingFurnitures* and interior *BuildingInstallations*. A *Building-Furniture* is a movable part of a room, such as a chair or furniture, while a *BuildingInstallation* is permanently connected to the room. Examples are stairs or pillars. Doors are used in LoD4 to connect rooms topologically: the surface that represents the door geometrically is part of the boundaries of the solids of both rooms.

Note that all these objects inherit the references to objects in external data sets. Important data sources for LoD4 models are IFC data sets (c.f. section 2), which can be converted accordingly (Benner et al. 2004).

As discussed in section 3.1, the different accuracy requirements of LoD1 to LoD4 have to be applied to the building model as well.

3.3 The Digital Terrain Model

An essential part of a city model is the terrain. In CityGML, the terrain may be specified as a regular raster or grid, as a TIN (Triangulated Irregular Network), by break lines or skeleton lines, or by mass points. These four types are implemented by using standard GML3 elements. A TIN may either be represented as a collection of triangles, or implicitly by a set of 3D points, where the triangulation may be reconstructed by standard methods (Okabe et al. 1992). A break line is a discontinuity of the terrain, while skeleton lines are either ridges or valleys. Both are represented by 3D curves. Mass points are simply a set of 3D points.

In a CityGML data set, these four terrain types may be combined in different ways, yielding a high flexibility. First, each type may be represented in different levels-of-detail, reflecting different accuracies or resolutions. Second, a part of the terrain can be described by the combination of multiple types, for example by a raster and break lines, or by a TIN and break lines and skeleton lines. In this case, the break and skeleton lines must share the geometry with the triangles. Third, neighboring regions may be represented by different types of terrain models. To facilitate this combination, each terrain object is provided with a spatial attribute denoting its *extent of validity*. This extent is represented by a 2D footprint polygon, which may have holes. This concept enables, for example, the modeling of a terrain by a coarse grid, where some distinguished regions are represented by a detailed, high-accuracy TIN. The boundaries between both types are given by the extend attributes of the corresponding terrain objects. This approach is very similar to the concept of *TerrainIntersection* curves introduced in section 3.1.

4. Application of CityGML for Disaster Management

CityGML was designed as a data model and exchange format for the multifunctional utilization of 3D city models. In the following, we discuss the specific use of key concepts for disaster management tasks.

General modeling aspects

The coherent semantic modeling of the spatial and thematic properties of 3D objects and their aggregations is one of the most important features of CityGML. Object classes have thematically rich attributes which allow for specific queries like ‘What are the buildings with more than 10 storeys

above ground?’ or ‘Where are buildings with flat roofs which are large enough that a helicopter could land on them?’. Since the terrain model may consist of neighbored or nested patches having different resolutions, high resolution DTMs for e.g. regions with high flood risk may be embedded into large area DTMs at low resolution.

Since the geometry of all 3D objects must be represented by at least one closed solid, the computability of volumes and masses is always facilitated. For example, in flooding resp. fire scenarios it could be estimated how much water resp. smoke or gas will flow into a tunnel, pedestrian passage, or a building. The estimation of masses from volumes is also interesting for planning the removal of debris after an incident.

The possibility to provide external references can be used to associate any CityGML object and its parts with data sets of other applications like facility management systems or the cadastre, which is important to determine the owner of a building. By using external references it is also possible to relate *BuildingInstallations* (c.f. section 3.2), which are relevant for disaster management like hydrants or fire protection doors with databases that hold the technical data about these.

Building model

In flood situations resp. simulations, the representation of storey heights above and under ground allows to determine to which degree buildings are affected. This information is especially useful for planning evacuations and for damage assessment by aid organizations and insurance companies.

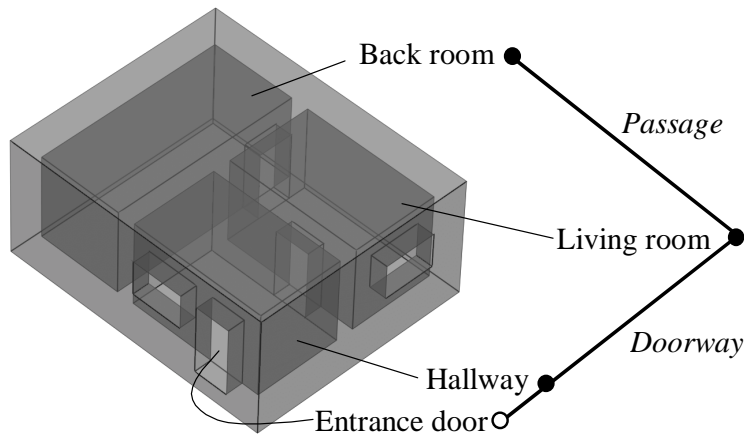


Fig. 5. Building interior (left) and accessibility graph (right) derived from topological adjacencies of room surfaces for the determination of escape routes.

Building interiors are modeled by rooms. Their solids are topologically connected by the surfaces representing doors or closure surfaces that seal open doorways. This adjacency implies an accessibility graph, which can be employed to determine the spread of e.g. water, smoke, gas, and air, but which can also be used to compute escape routes using classical shortest path algorithms. The edges of the accessibility graph can be marked by the corresponding distances and types of connection like normal door, fire protection door, open doorway etc. (see fig. 5).

5. Pilot 3D: First Implementation and Evaluation

The ‘Pilot 3D’ is a testbed of the GDI NRW in which CityGML is currently evaluated by five project teams. The teams consist of participants from academia, software manufacturers, and the cities Berlin, Hamburg, Düsseldorf, Cologne, Leverkusen, and Recklinghausen. In order to keep the implementation simple, only building models and DTMs in levels-of-detail 1 and 2 are included. Furthermore, only object geometries are exported – topology will be added in the future. Fig. 6 gives an impression of the contents and the structure of CityGML data files.

```
<?xml version="1.0" encoding="UTF-8"?>
<CityModel> <!-- declaration of namespaces omitted here due to limited space -->
  <gml:boundedBy> <!-- extent of this dataset -->
    <gml:Envelope srsName="EPSG:31466"> <!-- Gauss-Krüger 2nd meridian -->
      <gml:pos srsDimension="3">2571000.0 5677000.0 41.8</gml:pos>
      <gml:pos srsDimension="3">2573000.0 5679000.0 213.7</gml:pos>
    </gml:Envelope>
  </gml:boundedBy>
  <siteMember>
    <Building gml:id="Building0815">
      <externalReference> <!-- This is a reference to the German cadastre ALKIS -->
        <informationSystem>http://www.adv-online.de</informationSystem>
        <externalObject>
          <uri>urn:adv:oid:DEHE123400007001</uri>
        </externalObject>
      </externalReference>
      <function>31001_1010</function> <!-- this code means residential house -->
      <yearOfConstruction>1985</yearOfConstruction>
      <roofType>3100</roofType> <!-- this code means saddleback roof -->
      <measuredHeight uom="#m">8.0</measuredHeight>
      <lod2SolidProperty> <!-- building geometry for Level-of-Detail 2 -->
        <gml:Solid srsName="EPSG:31466"> <!-- Gauss-Krüger 2nd meridian -->
          <gml:exterior>
            <gml:CompositeSurface>
              <gml:surfaceMember> <!-- first roof face -->
                <gml:OrientableSurface orientation="+">
                  <gml:baseSurface>
                    <gml:Polygon>
```

```

    <gml:exterior>
      <gml:LinearRing>
        <gml:pos >2571013.0 5678371.0 64.2</gml:pos>
        <gml:pos >2571018.4 5678375.5 64.2</gml:pos>
        .....
      </gml:LinearRing>
      ..... end tags of the elements above
    <gml:surfaceMember>
      <!-- second roof face --> .....
    </gml:surfaceMember>
      ..... further faces (walls, floor)
  </lod2SolidProperty>
</Building>
</siteMember>
  ..... further Buildings
</loD2TerrainMember>
  ..... here comes the digital terrain model for Level-of-Detail 2
</loD2TerrainMember>
</CityModel>

```

Fig. 6. Excerpt from a CityGML dataset containing buildings and a digital terrain model in level-of-detail 2 (LoD2).

6. Conclusions and further Work

CityGML provides substantial information for urban disaster management tasks. Spatial objects and terrain models are represented by their geometry, topology, appearance, and semantic resp. thematic properties. The ability of maintaining different levels of detail makes it suitable for small to large area utilization. Since GML was designed by the OGC to serve as the standard exchange format for spatial data infrastructures, processing of CityGML is immediately supported by corresponding web services like the Web Feature Service (WFS), Web Catalog Service (WCAS), and Web Coordinate Transformation Service (WCTS).

The availability of data is steadily increasing as more and more municipalities decide to build up virtual 3D city models. In the SIG 3D of the GDI NRW we are currently working on the required methods and workflows in municipalities to generate and maintain LoD1 and LoD2 models in conjunction with cadastre. In the long-term, 3D cadastres could provide the main elements for 3D city models (Stoter and Salzmann 2003). LoD3 and LoD4 models currently are only available for selected areas resp. building complexes. Their automatic acquisition is still a topic of current research. However, the semantic properties of buildings and their parts as supplied by CityGML play an important role for e.g. the development of procedures for the automatic reconstruction of 3D building models from aerial images (Fischer et al. 1998).

Future work will focus on the development of more detailed models for roads, waterbodies, and vegetation. Above, concepts for the representation of history in the sense of a timeline and concurrent (planning) versions shall be integrated. On the international level, CityGML will be further discussed within the European Spatial Data Research organization (EuroSDR) and the Open Geospatial Consortium in the next months. It is intended to evaluate CityGML regarding practical issues with respect to big city models, interoperability to AEC/FM, and possible extensions to GML in the future. Finally, it would be interesting to discuss possible extensions of CityGML for the domain of disaster management.

Acknowledgements

We wish to thank the members of the modeling working group of the SIG 3D of the GDI NRW: Joachim Benner, Frank Bildstein, Martin Degen, Dirk Dörschlag, Rüdiger Drees, Heinrich Geerling, Ulrich Gruber, Frank Knospe, Andreas Kohlhaas, Kai-Uwe Krause, Ulrich Krause, Klaus Leinemann, Marc-Oliver Löwner, Hardo Müller, Hanns-Florian Schuster and Frank Thiemann. Furthermore, we like to thank our colleagues at the Institute for Cartography and Geoinformation, in particular Viktor Stroh. Thanks go to Michael Haas for assistance in preparing the illustrations.

References

- Adachi, Y, Forester, J, Hyvarinen, J, Karstila, K, Liebich, T, Wix, J (2003) Industry Foundation Classes IFC2x Edition 2, International Alliance for Interoperability, <http://www.iai-international.org>
- Benner J, Leinemann K, Ludwig A (2004) Übertragung von Geometrie und Semantik aus IFC-Gebäudemodellen in 3D-Stadtmodelle. In: Schrenk, M (ed) Proc. CORP 2004 & Geomultimedia04 (in German)
- Bishr, Y (1998) Overcoming the semantic and other barriers to GIS interoperability. Int. Journal on Geogr. Information Science, Vol. 12, No. 4
- Booch, G, Rumbaugh, J, Jacobson, I (1997) Unified Modeling Language User Guide. Addison-Wesley
- Coors, V, Flick, S (1998) Integrating Levels of Detail in a Web-based 3D-GIS, Proc. 6th ACM Symp. on Geographic Information Systems (ACM GIS 98), Washington D.C., USA
- Cox, S, Daisy, P, Lake, R, Portele, C, Whiteside, A (2004) OpenGIS Geography Markup Language (GML3.1), Implementation Specification Version 3.1.0, Recommendation Paper, OGC Doc. No. 03-105r1
- Eastman, CM (1999) Building Product Models: Computer Environments Supporting Design and Construction, CRC Press

- Fischer, A, Kolbe, TH, Lang, F, Cremers, AB, Förstner, W, Plümer, L, Steinhage, V (1998) Extracting Buildings from Aerial Images using Hierarchical Aggregation in 2D and 3D. *Computer Vision & Image Understanding*, Vol. 72, No. 2, Academic Press
- Foley, J, van Dam, A, Feiner, S, Hughes, J (1995) *Computer Graphics: Principles and Practice*. Addison Wesley, 2nd Ed.
- gbXML (2003) Green Building XML Schema. <http://www.gbxml.org>
- Gröger, G, Kolbe, TH, Plümer, L (2004) Mehrskalige, multifunktionale 3D-Stadt- und Regionalmodelle. *Photogrammetrie, Fernerkundung, Geoinformation (PFG) 2/2004* (in German).
- Groot, R, McLaughlin, JD (2000) *Geospatial Data Infrastructure - Concepts, Cases, and Good Practice*. Oxford University Press
- Herring, J (2001) The OpenGIS Abstract Specification, Topic 1: Feature Geometry (ISO 19107 Spatial Schema), Version 5. OGC Document Number 01-101
- LandXML (2001) LandXML Schema 1.0. <http://www.landxml.org>
- Köninger, A, Bartel, S (1998) 3D-GIS for Urban Purposes, *Geoinformatica*, 2(1), March 1998
- Kolbe TH, Gröger G (2003) Towards unified 3D city models. In: Schiewe, J., Hahn, M, Madden, M, Sester, M (eds): *Challenges in Geospatial Analysis, Integration and Visualization II*. Proc. of Joint ISPRS Workshop, Stuttgart
- Kolbe TH, Gröger G (2004) Unified Representation of 3D City Models. *Geoinformation Science Journal*, Vol.4, No. 1
- Molenaar, M (1992) A topology for 3D vector maps. *ITC Journal* 1992-1.
- Okabe, A, Boots, B, Sugihara, K (1992) *Spatial Tessellations: Concepts and Applications of Voronoi Diagrams*. John Wiley & Sons
- Oosterom, P, Stoter, J, Quak, W, Zlatanova, S (2002) The balance between geometry and topology. In Richardson, D, Oosterom, P (eds.): *Advances in Spatial Data Handling*. Proc. of 10th Int. Symp. SDH 2002, Springer, Berlin
- Pfund, M (2002) 3D GIS Architecture. *GIM International* 2/2002
- Stoter, J, Salzmann, M (2003) Towards a 3D cadastre: where do cadastral needs and technical possibilities meet? *Computers, Environment and Urban Systems*, Theme Issue: 3D Cadastres, Volume 27, Number 4, July 2003
- Van Rees, R, Tolman, F, Beheshti, R (2002) How BcXML Handles Construction Semantics. In: Proc. of the Int. Council for Research and Innovation in Building and Construction, CIB w78 conference 2002, Aarhus, 12-14 June
- Vretanos, PA (2002) Web Feature Service Implementation Specification Version 1.0.0, OGC Doc. No. 02-058
- VRML97 (1997) Information technology – Computer graphics and image processing – The Virtual Reality Modeling Language (VRML) – Part 1: Functional specification and UTF-8 encoding. Part 1 of ISO/IEC Standard 14772-1:1997
- Zlatanova, S (2000) 3D GIS for Urban Development. PhD Thesis, ITC Dissertation Series No. 69, The International Institute for Aerospace Survey and Earth Sciences, The Netherlands
- Zlatanova, S, Holweg, D (2004) 3D Geo-Information in Emergency Response: A Framework. In: Proceedings of the 4th International Symposium on Mobile Mapping Technology (MMT 2004), March 29-31, Kunming, China