CityGML
- 3D City Models and their Potential for Emergency Response

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ABSTRACT: Virtual 3D city models provide important information for different aspects of disaster management. In order to ensure the unambiguous interpretation of the represented objects, an ontology in the sense of a common information model for urban and regional structures has to be defined. Furthermore, 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 this aspect, integrating distributed data sources on demand. In this chapter we present CityGML, which is in the first place an ontology for the three-dimensional, multi-purpose, and multi-scale representation of cities, sites, and regions. The implementation of CityGML is based on the standard GML3 of the Open Geospatial Consortium and thus defines an exchange format for the storage of and interoperable access to 3D city models in SDIs. The class taxonomy distinguishes between buildings and other man-made artifacts, vegetation objects, water bodies, and transportation facilities like streets and railways. Spatial as well as semantic properties are structured in five consecutive levels of detail. Throughout this chapter, special focus is on the utilization of model concepts with respect to different tasks in the context of emergency response.

1 INTRODUCTION

The quality of available geoinformation is decisive for the planning and realization of rescue operations. This does not only apply to spatial resolution, geometric accuracy and topological consistency, but especially concerns the spatial dimensions of the data. Three-dimensional geodata, and in particular virtual 3D city models provide essential 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 emergency response, 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 (Groot 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 inter-relationships 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. The class taxonomy of CityGML distinguishes between buildings and other man-made artifacts, vegetation objects, water bodies, 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 data model behind CityGML is based on the ISO standard family 191xx. The implementation is realized as an application schema for GML3.

CityGML has been developed during the last three years by the Special Interest Group 3D of the initiative Geodata Infrastructure North-Rhine Westphalia (GDI NRW) in Germany. On the international level CityGML is investigated within a project of the European Spatial Data Research organization (EuroSDR) since 2006, aiming at a further harmonization in Europe and the practical evaluation with respect to large city models. A comprehensive specification proposal is currently being prepared and is scheduled to be submitted to the OGC in the next months.

2 VIRTUAL 3D CITY MODELS

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 & 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 and management processes (Kolbe & Plümer 2004). Computer graphics rather concentrates on the visual appearance of 3D models.

The possible applications of a 3D city model resp. the tasks it can support mainly depend on the concrete development of the four distinct representation aspects geometry, topology, semantics, and graphical appearance. Whereas geometry and topology describe the spatial configuration of 3D objects, the semantic aspect comprises the thematic structures, attributes and interrelationships. Information about the graphical appearance like façade textures, object colours, and signatures are employed for the visualization of the model.

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 mainly model the geometry and 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 THE SEMANTICS OF CITYGML

CityGML defines a common information model for cities and regions, including their semantic properties, i.e. the generalization hierarchy between classes, relations between objects, and spatial properties as well the appearance of objects.

To achieve interoperability, the formal specification of CityGML is based on the language GML 3.1, a standard issued by the OGC and the ISO. GML is an XML based language, which facilitates data exchange by spatial web services, in particular by Web Feature Services (WFS), see Vretanos (2002). GML 3.1 provides classes to define the spatial properties - geometry and topology - of objects. Furthermore, concepts for the definition of features including attributes, relations and generalization hierarchies are provided.

Technically, CityGML is implemented as a GML 3 application schema. It defines a profile of GML3, since the extensive geometry model of GML 3 is restricted to the classes sufficient to represent cities geometrically. CityGML has been derived from models specified in the *Unified Modeling Language (UML)* (see Booch et al. 1997) by applying the transformation rules given in Cox et al. (2004). Thus, CityGML may be processed by standard GML 3 readers and visualized by standard GML 3 viewers.

The next section presents the general concepts implemented by CityGML, while the following sections 3.1 to 3.6 describe the thematic models of CityGML which are especially relevant for emergency response applications: the building model, the transportation model, and the digital terrain model.

3.1 *General Concepts*

CityGML supports different *Levels-of-Detail (LoD),* which often arise from independent data collection processes and which facilitate efficient visualization and data analysis. 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. 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 Figure 1, taking buildings as an example. The coarsest level *LoD0* is essentially a two and a half dimensional *Digital Terrain Model* (DTM). *LoD1* is the well-known blocks model, without any roof structures. A building in *LoD2* has distinctive roof structures. *LoD3* denotes architectural models with detailed wall and roof structures, balconies and bays. 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.

Beyond buildings, the LoD concept applies to other object classes as well. The focus is on model resolution and perceptibility of object parts, but it addresses also geometrical accuracies and minimal dimensions of objects. The classification may also be used to asses 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.

Another general concept of CityGML is the *TerrainIntersectionCurve (TIC),* which facilitates the geometrical integration of buildings or other objects with the terrain. This curve explicitly denotes the exact position where the terrain touches the object. It can be used to ‘pull up’ resp. ‘pull down’ the surrounding terrain to fit the TIC. For further details see Kolbe et al. (2005).

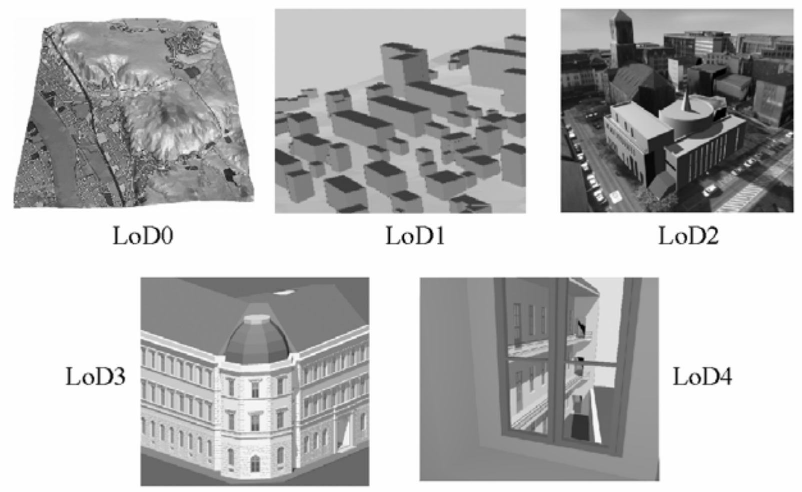

Figure 1. Illustration of the five Levels-of-Detail (LoD) defined by CityGML

3.1.1 *Geometrical modeling*

Spatial properties of thematic objects in CityGML are represented by a subset of the geometry model of GML3, according to the well-known *Boundary Representation* (Foley 1995). For each dimension, there is a geometrical primitive: a zero-dimensional object is a *point*, a one-dimensional a *curve*, a two-dimensional a *surface*, and a three-dimensional a *solid*. A solid is bounded by surfaces, a surface by curves, and a curve by points. In CityGML 1.0, a curve is restricted to be a straight line, and each surface must be planar, i.e. their boundary and all interior points are forced to be located in one single plane. Curves, surfaces and solids may be aggregated to *CompositeCurves*, *CompositeSurfaces* and *CompositeSolids*, respectively.

The primitives curve, surface and solids, and the respective aggregates must satisfy a number of integrity constraints, which guarantee consistency of the model. One important constraint is that the interiors of the primitives must be disjoint. These constraints assure that primitives do not overlap, and touch at most at their boundaries. Since solids must be disjoint, the computation of volumes can be performed much easier than it would be the case if solids overlap.

The graphical appearance of surfaces, i.e. material properties like colors, shininess, transparency and textures, is covered by concepts adopted from the graphics standard X3D.

3.1.2 *Coherent semantic-geometrical modeling*

Another characteristic of CityGML is the coherent modeling of semantics and geometrical/topological properties. On the semantic level, real-world entities are represented by features, for example buildings, walls, windows, or rooms, including attributes, relations and aggregation hierarchies (part-whole-relations) between features. Thus the part-of-relationship between features can be derived on a semantic level only, without considering geometry. However, on the spatial level, geometry objects are assigned to features representing their spatial location and extent. So the model consists of two hierarchies: the semantic and the geometrical, were 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 arbitrarily, for answering thematic and/or geometrical queries or performing analyses.

If both hierarchies exist for a concrete object, they must be coherent, i. e. it must be assured that they match and fit together. For example, if a wall of a building has two windows and a door on the semantic level, then the geometry representing the wall must contain the geometries of both windows and of the door.

3.1.3 *Closure surfaces and subsurface objects*

A new concept in CityGML is the *ClosureSurface*, which is employed to seal objects, which are in fact open, but must be closed in order to compute its volume. An airplane hangar is an example for such an object. *ClosureSurfaces* are special surfaces which are taken into account 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 Figure 2). However, in close-range visualizations the entrance must be treated as open. Thus, *ClosureSurfaces* are an adequate way to model those entrances.

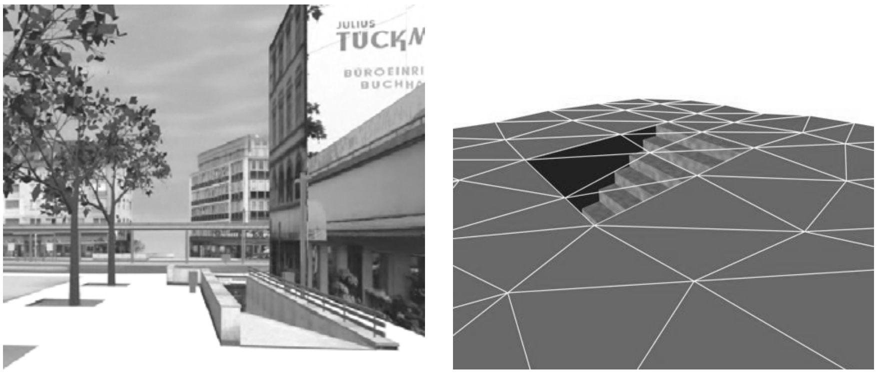

Figure 2. Passages are subsurface objects (left). The entrance is sealed by a virtual *ClosureSurface,* which is both part of the DTM and the subsurface object (right).

3.1.4 *References to objects in external data sets*

3D objects often are derived from or have relations to objects in other databases or data sets. For example, a 3D building model may have been constructed from a two-dimensional footprint in a cadastre data set, 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. Such a reference denotes the external information system and the unique identifier of the object in this system. Both are specified as a *Uniform Resource Identifier (URI),* which is a generic format for references to any kind of resources in the internet.

3.1.5 *Dictionaries and code lists for attributes*

Attributes which classify objects often have values that are restricted to a number of discrete values. An example is the attribute *roof type*, whose attribute values typically 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 *GML 3 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. Dictionaries and code lists may be extended or redefined by users.

3.1.6 *City Object Groups*

The grouping concept of CityGML allows to aggregate arbitrary city objects according to user-defined criteria, and to represent and transfer these aggregations in a city model. A group may have a name and a type, for example "escape route from room no. 43 in house no. 1212 in a fire scenario" as a name and "escape route" as type. Each member of the group is assigned an optional role name, which specifies the role this particular member plays in the group. This role name may, for example, describe the sequence number of this object in an escape route, or in case of a building complex, denote the main building.

A group may contain other groups as members, allowing nested grouping of arbitrary depth.

3.2 *Top Level Classes*

Figure 3 depicts the top level of the class hierarchy of CityGML. The base class of all thematic classes is *CityObject*, which provides a creation and a termination date for the management of histories of features, and external references to the same object in other data sets, as described in section 3.1. *CityObject* is a subclass of the GML class *Feature*, thus it inherits metadata (e.g., information about the lineage, quality aspects, accuracy) and names from *Feature* and its super classes. A *CityObject* may have multiple names, which are optionally qualified by a so-called *codespace*. This enables to differentiate for example an official name from a popular name or names in different languages (c.f. the name property of GML objects, Cox et al. 2004).

The subclasses of *CityObject* comprise the different thematic fields of a city model: the terrain, the coverage by land use objects, transportation, vegetation, water bodies and sites, in particular buildings, and city furniture. Generic city objects are explained in section 3.6, and groups have already been discussed in section 3.1.

Thematic classes have further subclasses with relations, attributes and geometry. The ones relevant for the field of emergency response are discussed in detail in the following sections.

Features of the specialized subclasses of *CityObject* may be aggregated to a single *CityModel*, which again is a feature with optional metadata.

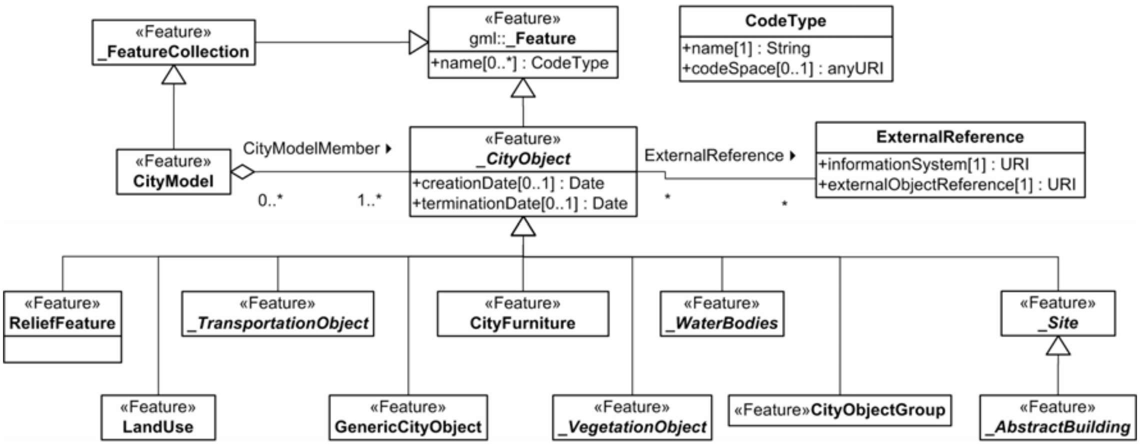

Figure 3. UML diagram of the top level class hierarchy of CityGML. The bracketed numbers following the attribute names denote its multiplicity: the minimal and maximal number of occurrences of the attribute per object. For example, a *name* is optional (0) in the class *_Feature* or may occur multiple times (star symbol), while a *_CityObject* has none or at most one *creationDate*. An *ExternalReference* has exactly one occurrence of the attribute *informationSystem*.

3.3 *The Building Model*

The building model of CityGML allows the representation of thematic and spatial aspects of buildings, building parts and accessories in four levels-of-detail, LoD1 to LoD4. The UML diagrams of the building model are depicted in Figure 4 and 5 (the diagram has been split for clarity reasons). The pivotal class of the building model is AbstractBuilding, which is specialized either to a Building or to a BuildingPart. A simple building is represented by a single building object only, while a complex building is made up of a building object consisting of BuildingParts, which, for example, differ in height, year of construction, or function. Since a BuildingPart is again an AbstractBuilding, an aggregation hierarchy of arbitrary depth may be realized.

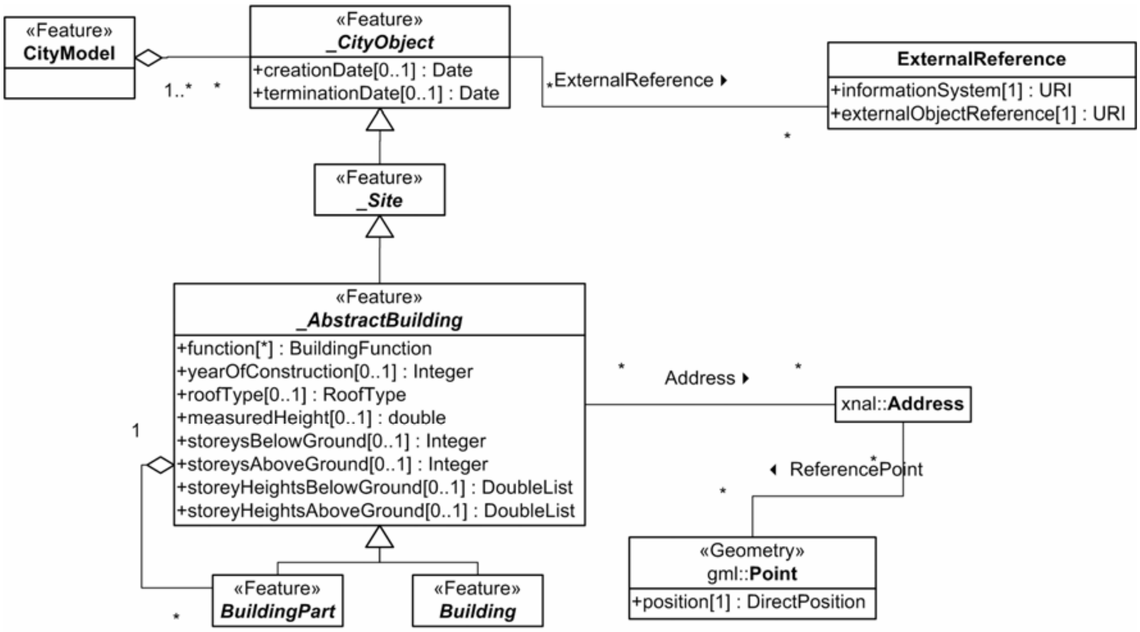

Figure 4. UML diagram (Booch et al. 1997) of CityGML's building model, part one

A building is described by optional attributes: the function of the building, for example residential, public, or industry; the year of construction, the roof type, the measured height, and the number and the individual heights of the storeys above resp. below ground. The address or the multiple addresses of a building are specified using the *xNAL address and name standard* issued by the OASIS consortium (OASIS 2003), which provides schemas for all kinds of international addresses. An optional reference point denotes the exact location of the entrance of the building, which may be needed for route planning applications.

In the coarsest LoD1, the spatial extent of a Building is given by a *SolidGeometry*, which in this case is a simple block. Since *AbstractBuilding* is a subclass of the root class *CityObject*, the relation to the *ExternalReference* (see section 3.1) is inherited.

Often Buildings are aggregated to larger *Building Complexes.* These can be represented using the grouping concept described in section 3.1. The main building of this group may be denoted by the role name of this object relative to the group.

In LoD2, there are basically two differences compared with LoD1: First, there may be a more detailed geometry replacing the coarser LoD1 geometry, and second the thematic classification of the parts of a building is more detailed. In a LoD2 building, it is possible to distinguish the bounding surfaces as own semantic 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 shape of the whole building. An opening in a building is modeled by a *ClosureSurface*; this concept was already discussed in section 3.1. A LoD2 building also may have thematic *BuildingInstallations*, for example chimneys, balconies or outer stairs. These *BuildingInstallations* have their own geometry in LoD2. The type of geometry 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 additional accessories of a building, but not a constituent part of it. Figure 6 illustrates a LoD2 building with two building characteristics and two parts.

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.

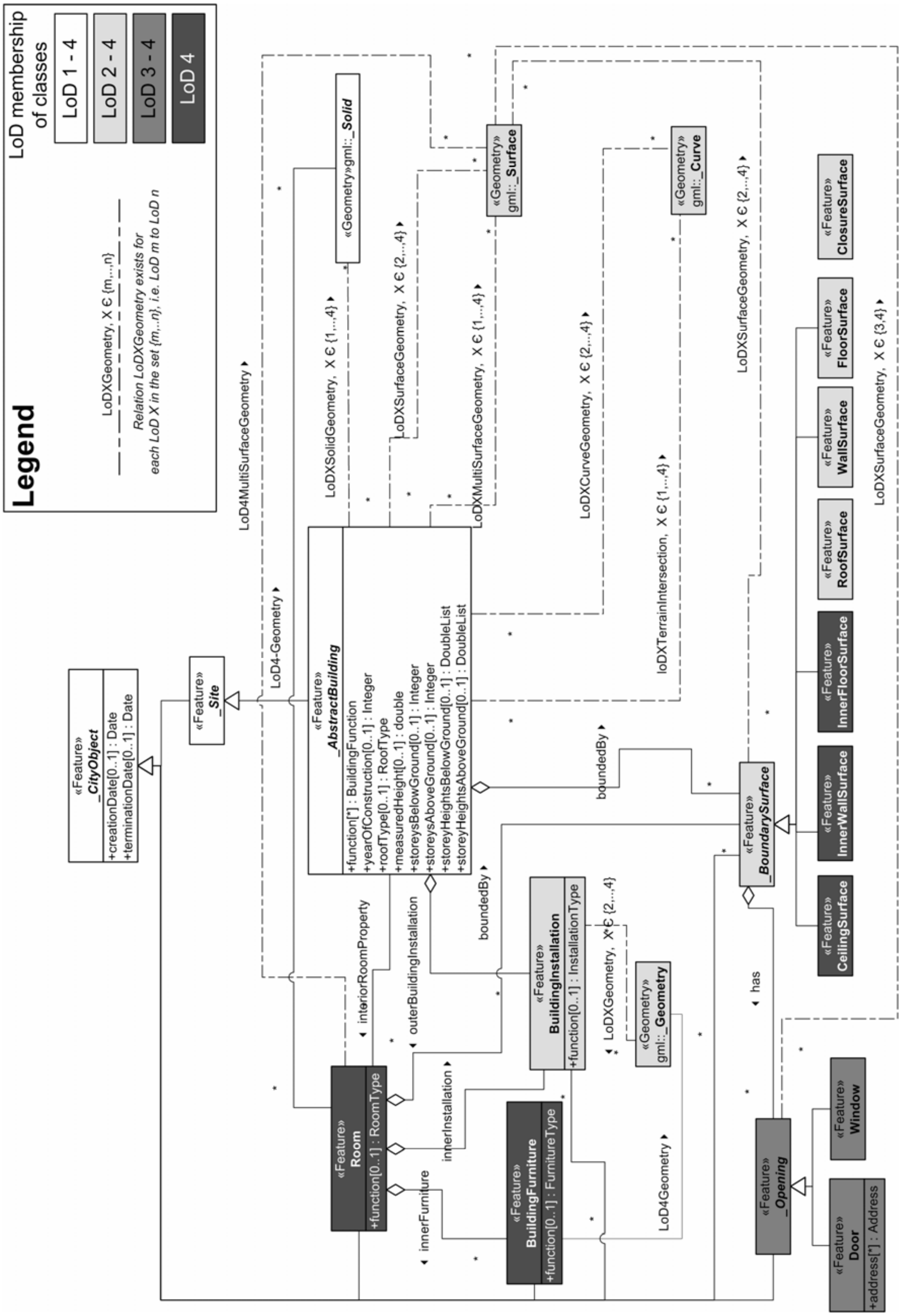

Figure 5. UML-Diagram of CityGML's building model, part two

In LoD3, buildings additionally may have *Opening* features such as *Windows* and *Doors*. The class *Opening* is a subclass of *CityObject*, it is an own thematic object and thus inherits the option to have external references. The geometry in LoD3 is given by separate solids and surfaces, which usually are more detailed than their LoD2 counterparts. In addition, curve geometries may be used to model, for example antennas, if they are not represented as thematic *BuildingInstallation.* As discussed in section 3.1, the accuracy requirements of LoD3 are much higher than in LoD2.

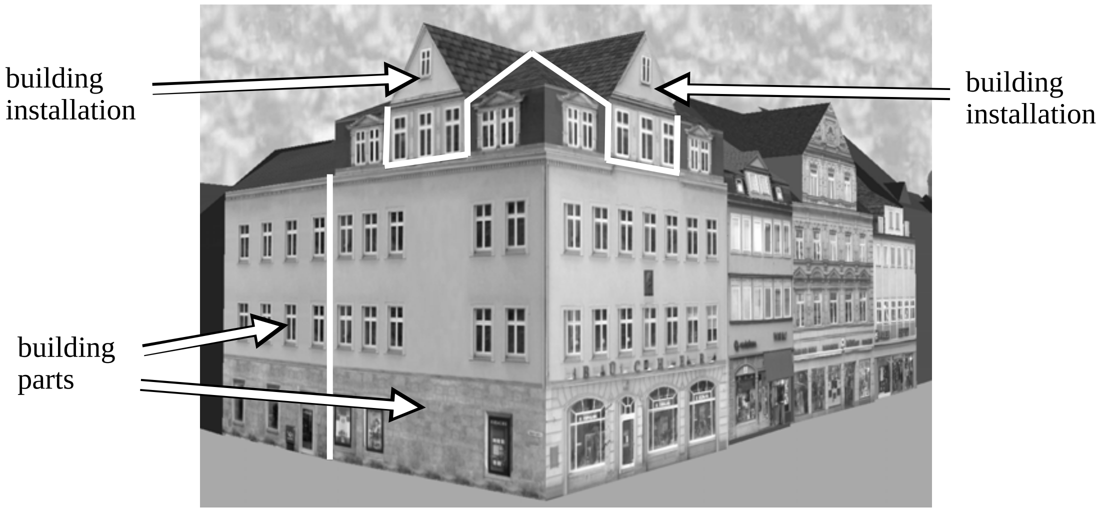

Figure 6: Illustration of a LoD2 building. It consists of two building parts with different heights. The right part has two dormers represented as building installations.

LoD4 complements LoD3 by adding interior structures of buildings such as *Rooms*, which are bounded by *Ceiling-*, *InnerWall-* and *InnerFloorSurface* features. Rooms may have *BuildingFurnitures* and interior *BuildingInstallations*. A *BuildingFurniture* is a movable part of a room, such as a chair or furniture, while a *BuildingInstallation* is permanently connected to the room. Examples for interior building installations 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. The aggregation of rooms according to arbitrary, user defined criteria is achieved by employing the grouping concept provided by CityGML.

Please 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. 2005). As discussed in section 3.1, the different accuracy requirements of LoD1 to LoD4 have to be applied to the building model as well.

3.4 *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 respectively skeleton lines, or by mass points. These four types are implemented by the corresponding GML3 classes. The UML diagram of the digital terrain model is shown in Figure 7. A TIN may either be represented as a collection of explicit triangles (class *TriangulatedSurface*), or implicitly by a set of 3D points (class *TIN*), 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 3-D curves. Mass points are simply a set of 3-D points.

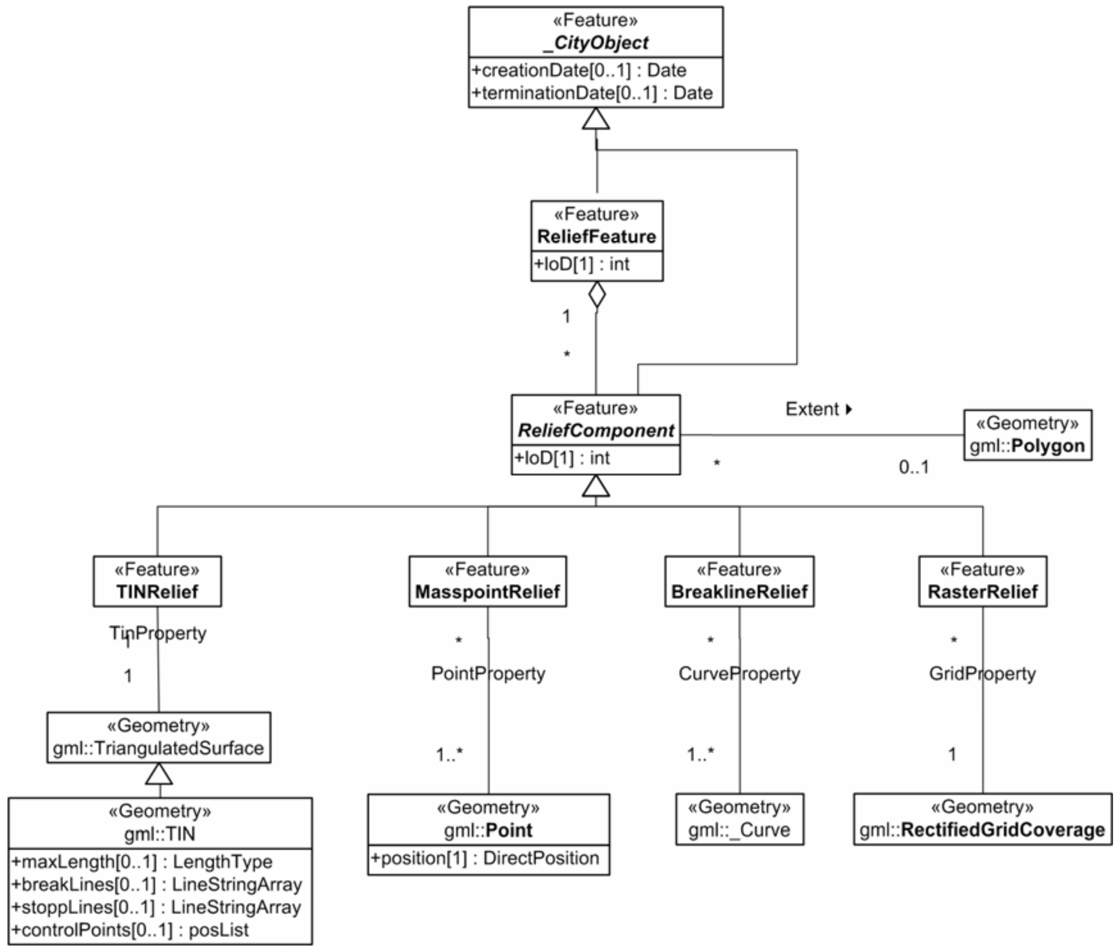

Figure 7. UML-Diagram of the Digital Terrain Model

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. 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 2-D 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 *TerrainIntersectionCurves* introduced in section 3.1.

3.5 *Transportation Objects*

The transportation model of CityGML is a multi-functional, multi-scale model, focusing on thematic as well as on geometrical/topological aspects.

Figure 8 depicts the UML diagram of the model. The main class is *TransportationComplex*, which represents, for example, a road, a square or a track. In the coarsest LoD0, the transportation complexes are modeled by line objects establishing a linear network. On this level, path finding algorithms or similar analyses can be executed. Starting from LoD1, a *TransportationComplex* has a surface geometry, reflecting the actual shape of the object, not just its centerline. In LoD2 to LoD4, it is further subdivided thematically into *TrafficAreas*, which are used by cars, bicycles or pedestrians, and in *AuxiliaryTrafficAreas*, for example green spaces or flower tubs. The function of both areas may be represented by an attribute, as well as its shape by an areal geometry. An illustration of a Transportation Complex and its parts is given in Figure 9.

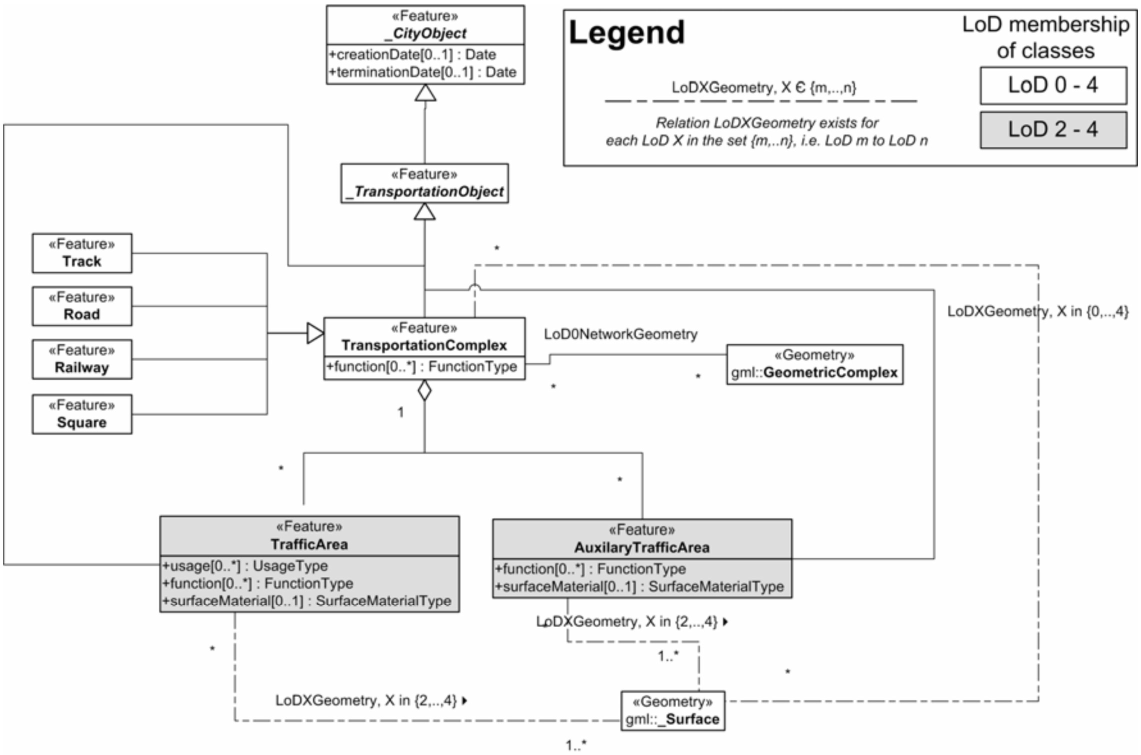

Figure 8. UML diagram of the transportation model of CityGML

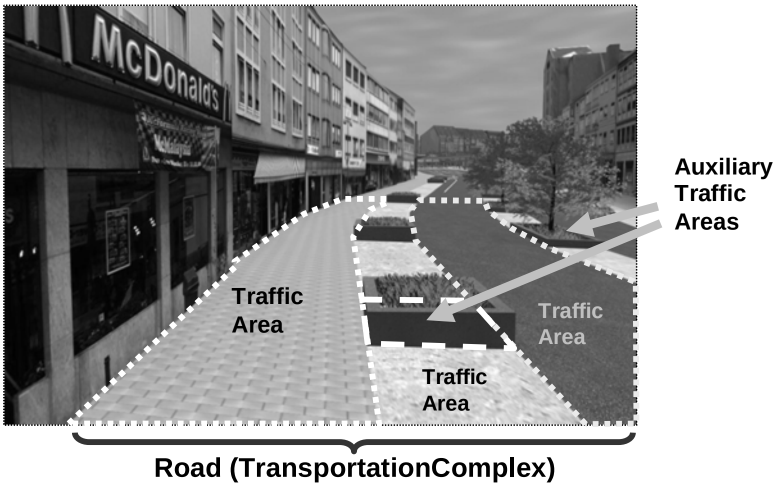

Figure 9. Example for the representation of a transportation complex, a road, which is the aggregation of traffic areas and auxiliary traffic areas.

3.6 *Further Classes*

Besides the transportation model, the building model and the digital terrain model, there are a number of other models covering further aspects of a cities' semantics. The *Water Bodies Model* represents the thematic aspects and three-dimensional geometry of rivers, canals and lakes. *Solitary Vegetation Objects* like trees and complete *Biotopes* like forests are represented by the *Vegetation Model*. *City Furniture* like traffic lights, traffic signs or advertising columns may also be represented by CityGML.

The class *GenericCityObject* allows to model features not provided explicitly by the CityGML schema. This enables the representation of objects which were not anticipated; a situation that is likely to occur in an emergency response phase. In addition, each City Object may be extended by *GenericAttributes* to represent properties of features not covered by the schema.

4 MEETING THE REQUIREMENTS OF EMERGENCY RESPONSE

CityGML was designed as a common information model and exchange format for the multi-functional utilization of 3D city models. In the following, we discuss the potential use of key concepts for tasks in an emergency response phase.

4.1 *Situation analysis, Briefing and Geovisualization*

Important tasks in the emergency response phase are situation analysis and the briefing of rescue personnel. Immediate access to geometrical and semantically rich geospatial information is essential, as both tasks involve numerous spatial and thematic queries.

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?’.

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 e. g. the owner of a building. By using external references it is also possible to relate BuildingInstallations (c.f. section 3.3), which are relevant for disaster management like hydrants or fire protection doors with databases that hold the technical data about these.

The generation of 3D visualizations of CityGML models is straight-forward, as the appearance and the geometry of 3D objects are always given explicitly. This means that the concrete 3D shape does not have to be generated or derived from implicit models by using extrusions or boolean operations on volumetric primitives (like in Constructive Solid Geometry).

4.2 *Reachability*

Reachability is of major concern for bringing helpers and equipment to a disaster area. It also influences the determination of possible escape routes for affected people. Lee (2004) and Pu & Zlatanova (2005) propose to derive a network model for building interiors from the geometry and topology of 3D models.

The LOD4 model of CityGML provides explicit information here, as 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 Figure 11).

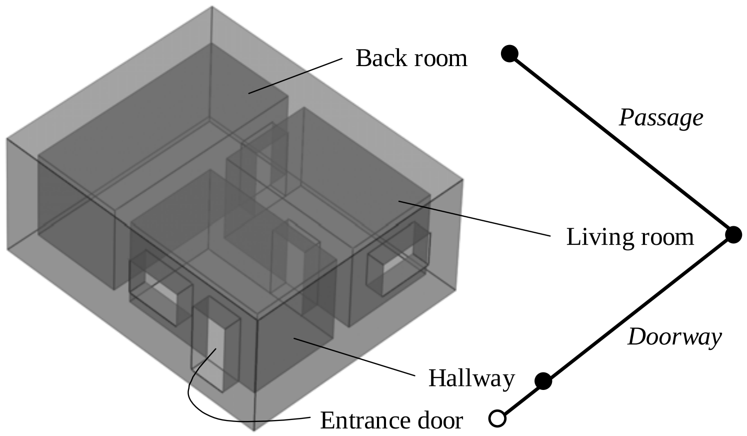

Figure 10. Building interior (left) and accessibility graph (right) derived from topological adjacencies of room surfaces for the determination of escape routes.

For reachability analyses outside of buildings CityGML's transportation modelling can be employed. It provides a linear network in LOD0 and areal traffic features in higher LODs. As these *TrafficAreas* describe the surfaces of traffic objects explicitly they can be used for trajectory planning resp. geometric route planning. In conjunction with the different types of 3D CityObjects also the extents of concrete vehicles or rescue equipment can be taken into account.

4.3 *Localization*

During rescue operations helpers always need to be informed about their current location. In this context, localization generally comprises two different consecutive steps: First, the carried navigation device has to determine the current position and heading. In the second step the location information has to be communicated to the user.

GPS and a magnetic compass (possibly in combination with a gyroscope) provide sufficient accuracy in many outdoor situations. In indoor operations or in dense urban canyons, lacking visibility of the GPS satellites and multipath effects often cause big position errors or even prevent the achievement of a position solution. For these cases, alternative approaches coming from the field of mobile robotics should be considered.

Figure 11. 3D city models provide orientation and guidance: determination of the current position using range finders and a 3D city model (left), and background and wayfinding information presented by virtual 3D banners and signposts help to guide rescue teams (right; example taken from pedestrian navigation).

Autonomous mobile robots often use range finding sensors to determine the distance to their surrounding environment (see Figure 12 on the left). The employed sensors are based on laser, ultrasonic, or radar echo registration, and at least the last two allow position determination in smoke-filled areas. Bayes filters, in particular particle filters, where shown to be very robust concerning the global position estimation with respect to a given model of the environment (*Monte Carlo Localization* MCL, cf. Thrun (2002)). Although MCL mainly needs geometry information about the surrounding surfaces, objects should be thematically divided into immobile or movable objects, because only immobile objects like walls, stairs, pillars etc. provide reliable reference information for position determination. CityGML both provides these geometric and semantic information.

In order to support the perception of one's own position and to provide guidance to the place of action, augmented reality techniques can be applied (Leebmann 2004). 3D labels and virtual signposts which are precisely overlayed in the visual field of rescue workers using head mounted displays (HMD) provide intuitive orientation and navigation cues (see Figure 12 on the right, cf. Kolbe (2004)). Labels have to be placed at specific, sensible positions and the visual overlay has to consider possible occlusions of these virtual signs by real world objects. While the latter is ensured by occlusion culling using the 3D geometry of CityGML objects, the differentiated building model of CityGML would allow to restrict label placement to specific object types or parts like building walls or traffic areas.

In the case that helpers must move through smoke-filled or dark areas, not only virtual signposts and labels but also the 3D model itself could be overlayed on a Head Mounted Display.

4.4 *Simulation*

In the emergency response phase simulation can be used to assess damaged objects, estimate possible shelters, and to predict the spreading of water, gas, fire, smoke etc. For example, Freund & Roßmann (2003) describe how a 3D simulation environment can be used to investigate different strategies for fire fighting using virtual 3D city models.

In flooding scenarios not only the digital terrain model is important, but also the built-up structures on and below the surface. Especially in urban areas water quickly spreads in subsurface hollow spaces of a city, e.g. in metro tunnels (see Herath & Dutta (2004)). As CityGML also accounts for subsurface structures, it may provide valuable information in this context. Furthermore, the representation of storey heights above and below 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.

In CityGML the terrain model may consist of neighbored or nested patches having different resolutions. This allows to embed high resolution DTMs for e.g. regions with high flood risk into large area DTMs at low resolution.

Since the geometry of 3D objects should be represented by at least one closed solid, the computability of volumes and masses is 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.

5 IMPLEMENTATIONS AND DATA ACQUISITION

5.1 *Status of CityGML*

In 2004 and 2005, CityGML has been implemented in the so-called 'Pilot 3D' testbed launched by the GDI NRW. Five project teams realized specific applications of 3D city models, e.g. fire fighting simulation, city planning, tourism, and bicycle route planning. Cross-wise data exchange was demonstrated between different applications and providers. All project teams were organized as public-private-partnerships with participants coming from software manufacturers, academia, and the German cities Berlin, Hamburg, Düsseldorf, Cologne, Leverkusen, and Recklinghausen. CityGML is now being used for system integration in the official 3D city models of Berlin (see Döllner et al. 2006) and Bonn.

In 2006, CityGML has been brought into the standardization process within the Open Geospatial Consortium. It is currently under evaluation in the OpenGIS Web Services testbed #4 (OWS-4) in an emergency response and homeland security scenario.

Examples giving an impression of the contents and the structure of CityGML data files can be found in Kolbe, Gröger & Plümer (2005). Sample datasets, UML and XML schema files, and free viewer applications are provided on the CityGML website (CityGML 2006).

5.2 *Systems and Interfaces*

A growing number of commercial systems and research tools provide interfaces to read or write CityGML datasets. In the following, some examples shall be highlighted.

One example is the commercial 3D visualization and authoring tool *LandXplorer* distributed by the company 3DGeo. Thematic and spatial properties of the data may be used for the selection of features and to determine their graphical appearance. A viewing-only version of the system can be downloaded for free (3DGeo 2006).

Aristoteles is a free viewer for 3D GML3 datasets which already supports most of the geometry types used by CityGML. It is Open Source software and has been developed at the Institute for Cartography and Geoinformation at Bonn University so far. Besides 3D visualization, the focus is on the exploration of the semantic structure and the hierarchy between features, which can be displayed and queried (Dörschlag & Drerup 2006).

CityServer3D is a client-server GIS application from the Fraunhofer Institute for Computer Graphics Darmstadt (FHG IGD), which supports CityGML as a transfer format between server and clients (Haist & Coors 2005).

Currently, a transactional Web Feature Service (WFS-T) for CityGML is being implemented within the Open Source software framework *Deegree* (Fitzke et al. 2004). The WFS is employed for data access to the 3D city models of Berlin and Bonn. Furthermore, Deegree's implementation of the OGC Web Terrain Service (WTS) can be chained with the WFS in order to produce perspective views of CityGML 3D scenes.

5.3 *Provision and Integration of CityGML Data*

There are basically two main sources for 3D city models. The first is geodesy and the second the construction domain (architectural design, civil engineering, facility management). As the modeling approach and the data models differ fundamentally in both domains, conversion of models between these domains is not straight-forward (cf. Kolbe & Plümer (2004)). Whereas the IFC standard covers the aspects of the AEC/FM domain and CAAD systems, CityGML has its roots in the field of geodesy, cadastre, and 3D GIS.

In geodesy, the trend for providing 3D city models is that models are generated from airborne and terrestrial laser scanning resp. photogrammetry (Früh & Zakhor 2004, Kaartinen et al. 2005). Many approaches also take data from 2D cadastre into account and use sensor measurements to obtain building heights. However, the automatic acquisition is still a topic of current research. 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 semantically rich 3D building models from aerial images (Fischer et al. 1998).

National and regional mapping and cadastre agencies (NMCA's) currently are incorporating 3D geo objects into the traditional cadastre and topographic datasets. In the medium term NMCAs will offer 3D city models in the context of Spatial Data Infrastructures. CityGML is intended to support these developments. In the long-term, national mapping agencies as well as 3D cadastres could become the main provider for 3D city models (Stoter and Salzmann 2003).

CityGML models also can be generated from 3D models coming from the AEC/FM domain. Benner et al. (2005) describe how the semantic properties of IFC models can be preserved and transferred during conversion.

In spatial data infrastructures, 3D city models may be assembled from different sources. The integration of these models makes it necessary to resolve geometric and topological inconsistencies. Therefore, homogenization procedures for e.g. the adjustment of the digital terrain model with respect to 3D objects, and the automatic detection and resolution of topological errors like the penetration of solid volumes have to be developed. Possible starting points are the work of Kampshoff (2005) on 3D homogenization and Koch (2005) on the topologically/semantically consistent integration of topographic objects with the DTM.

6 CONCLUSIONS AND FURTHER WORK

Virtual 3D city models provide substantial information for urban disaster management tasks. However, any application beyond 3D visualization like simulation, computation of escape routes etc., require explicit semantic models. In this chapter we have presented CityGML, a common information model for urban and regional structures. CityGML covers the four main aspects of 3D spatial objects and terrain, i.e. 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.

In emergency response, specific tasks like simulation, localization, and reachability analysis are of utmost importance. For each of these tasks it was shown, how required information are provided by CityGML.

The consistent utilization of the ISO 191xx standards facilitate immediate mapping of the data model to an application schema for the Geography Markup Language GML3. 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).

In the future, we will address the dynamic aspects of the represented spatial objects, i.e. movable resp. moving objects like a bascule bridge or the current state of doors and windows (open, closed). Furthermore, the simultaneous inclusion of different discrete water levels, e.g. low and high tide, shall be realized. Also, concepts for the representation of history in the sense of a timeline have to be integrated.

Another topic of future research is the interface between 3D GIS on the one side and CA(A)D models resp. facility management systems on the other. The essential question is how to establish a bidirectional mapping between generative (CSG) and accumulative (B-Rep) 3D geometry models. A first step was made by Brenner (2004) with the introduction of the concept of Weak CSG Primitives.

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