Chapter 3

Navigable Space in 3D City Models for Pedestrians

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Abstract

This paper explores the state of the art in 3D city modelling and draws attention to the 'missing link' between models of buildings and models of the surrounding terrain. Without such integrated modelling, applications that cross this divide are stalled. In this paper we propose a conceptual approach to this problem and set out a constraint-based solution to three dimensional modelling of buildings and terrains together.

3.1 Introduction

3D city models are increasingly considered as important resources for municipal planning and decision-making [2]; examples of 3D City models include Virtual London [2] and Virtual Kyoto [25]. An important aspect of cities is the navigable space within them. In spite of this, we have found no 3D city models which incorporate a model of pedestrian access. Navigable space for pedestrians includes space within buildings and, crucially, the connection between building interiors and exterior space. The majority of 3D city models treat buildings as solid objects which are placed upon a digital terrain model, without any essential integration between them.

In this paper, we argue that there is a need for 3D city models to incorporate topologically-connected navigable spaces, in which space internal to buildings is topologically connected to space outside buildings and in which the terrain is part of this navigable space rather than a simple surface upon which buildings are placed. Published research in this area tends to concern

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either road vehicles which operate wholly *outside* buildings (transport models) or pedestrians which move *within individual* buildings. Models which operate across multiple storeys of buildings tend to work on a storey-by-storey basis with limited topological links between layers. We describe the target application area and then present a prototype model that addresses some of these requirements.

3.2 Brief Review of 3D city modelling approaches

Many 3D city models are implemented in GIS, because this is usually appropriate for the planning application domain and the spatial scale at which this operates. Most geographical information systems (GIS) support a simple but effective modelling strategy in which 2D building footprints are extruded upwards from the terrain to a representative (often LiDAR-derived) building height. Such models can be rapidly produced, offer simple city visualisation opportunities and may be used for a limited set of analyses (Figure 1). This approach of rapid modelling has been successfully used over the Internet through customised web browser plugins and standalone browsers (e.g. Google Earth).

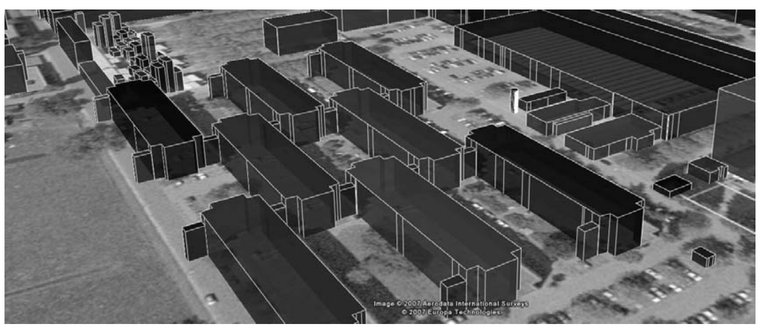

Fig. 3.1 Extruded block model of part of the Technical University of Delft campus, rendered in Google Earth. *Source: Technical University of Delft.*

In cities, there are often significant landmarks. For visualisation purposes, it is helpful if these buildings are modelled to a higher level of geometrical detail and then inserted amongst the other extruded blocks. Data for such buildings can be hand-modelled or sourced from architectural models as 3D building shells (external surfaces bounding an internal volume). This rather *ad hoc* approach provides a good level of visual realism (especially if photographically texture-mapped), and is supported by many of the software products which support the extruded block model (including ESRI's Arc-

Scene and Google Earth). Models such as these are often used as the basis for graphical applications such as walk- or fly-throughs. However, since the spatial resolution of buildings is essentially the same as their 2D counterparts the range of applications for which the data can be applied is not significantly widened.

Full and detailed 3D models of individual buildings and small groups of buildings are widely used in architecture and construction, but their high spatial resolution, their high geometrical detail and their variable types of semantic definition, often make them unsuitable for use with 3D cities. There has been much research on various aspects of 3D GIS, including different approaches to 3D geometrical modelling, the application of thematic (attribute) data, the creation, maintenance and storage of 3D topology (e.g. [26]) for data validation, algorithms for 3D spatial analysis and potential application areas [7]. However, 3D GIS is not (commercially) fully-realised for a number of reasons including the lack of availability of data and because the individual application area solutions have been developed separately, and no one tool has developed into a general cross sector tool.

Within the last decade, semantically-rich data exchange formats (e.g. IFC) and object-based building modellers (e.g. AutoDesk Revit) have been developed for architecture and construction, designed in part to facilitate the reuse of data for different stages of the design process and for different analysis tasks [6, 10, 17]. Similar approaches have been used for virtual cities; e.g. 'QUASY' [3] and 'Smart Buildings' [5]. CityGML[1]; [8] is an attempt to create a useable and formal standard for the exchange of city models, using this approach. It recognises that many existing 3D city models are rather *ad hoc* creations which neglect semantic and topological modelling aspects. It also recognises the need for a formalised set of levels of detail. CityGML is an XML-based standard which provides a set of object types (through the abstract 'CityObject' class). A building (an instance of an 'AbstractBuilding') comprises building parts, rooms and bounding objects (walls, doors, windows, ground surfaces, ceilings), depending on level-of-detail. The precise geometrical forms of these objects can each be described and classified using codes (based on the German Cadastral Standard: ATKIS). There are also objects which deal with road transport, water bodies and vegetation. Five levels-of-level exist (Figure 2): terrain-only (LoD0), extruded polygons upon a terrain (LoD1), the addition of roof structures and roof textures (LoD2), the addition of external architectural detail such as balconies (LoD3) and the addition of internal rooms (LoD4).

Semantically-rich, object-based modellers underpinned by formal modelling concepts have a number of advantages over the more ad hoc methods described earlier:

[1] In this paper, we are using version 0.3.0 of the Candidate OpenGIS standard [8, 11, 12]

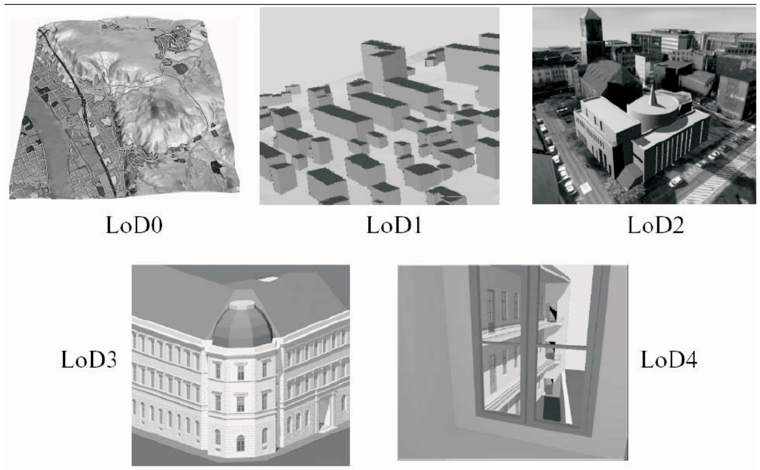

Fig. 3.2 The five levels of detail defined in CityGML. Source: [12]

1. The formalised levels of detail allow parts of buildings to be modelled at the most appropriate level of detail.
2. Interior spaces in buildings can be modelled where appropriate
3. The 3D city model is exchangeable and reusable
4. The combination of geometrical, semantic and topological information can be used to support a range of analytical tasks.

Models such these can be used to support a wide range of applications [1] such as visualisations, flood-risk modelling, scene generation from different viewpoints, the effect of an explosion or source of noise on individual building parts, analyses of land use and property value, and traffic-related analyses and impacts.

3.3 Applications

We have found support from the fire safety sector and the insurance sector for research into how city models can assist in building safety, access, monitoring and planning applications. An important theme in this application area is how spaces navigable to pedestrians are connected, including the connections between buildings and to outside space. Wayfinding, navigation, evacuation and the extent to which various individuals have access to various spaces, are all examples of questions which require an integrated model of navigable space for pedestrians. For this reason, we argue that 3D city models should not neglect navigational aspects of cities, in the same way that they should not neglect semantic aspects. Navigational aspects have a history of being considered in isolation from geometrical and semantic aspects, but all three aspects, considered together are important. There are a diverse range of issues relevant to the emergency evacuation of buildings, involving knowledge of many different aspects of the built environment. This includes [9, 18]:

1. keeping an spatial inventories of the nature and location of damage and hazardous equipment which may contribute to the aggravation of fires;
2. knowing the capacity of escape routes;
3. understanding how fire fumes might spread, how the terrain might affect pedestrian movement and how the variability between individuals may affect their movement and the movement of others.

3.4 Navigable space

Navigable space in cities can be considered to be a set of topologically-connected discrete spaces, juxtaposed in three-dimensional space. Access to these spaces is governed by the geometry of these spaces, their semantic details and a microscale description of which pedestrians have access to which spaces and under which circumstances. Such navigable details of space in cities are difficult to obtain, but some of the general-purpose semantically-rich 3D city models may provide opportunities for obtaining this information. Note that in this paper, we are *not* concerned with the *behaviour* of pedestrians in space, just where they are *able* to move – behavioural models can be built in top, in specific application domains. A review and discussion of the modelling of navigable space will follow.

3.5 Pedestrian navigation in CityGML

CityGML provides the opportunity to model both space inside buildings and space outside buildings. However, it treats these spaces differently. Interior space is modelled (at the highest level detail) as building parts and the rooms of which they comprise, whereas space outside buildings is modelled as a terrain surface. Buildings contain rooms which are organised hierarchically by building and by building part (e.g. by storey). Kolbe's [12] paper on applying CityGML to various disaster management applications, shows how the connectivity between rooms for pedestrian access can be extracted using the shared openings (doors) between rooms. However, this is both a *by-product* of the geometrical modelling (to reduce the duplication of geometrical description and *optional* [8]. Where such topology is not supplied, it must be derived through the geometrical coincidence of duplicate openings.

Other details which might affect pedestrian access are 'BuildingInstallation' and 'BuildingFurniture' feature types within the 'AbstractBuilding' model and the 'CityFurniture' concept for objects outside. These are classified with ATKIS-based codes classifying their type and function. Those relevant to pedestrian access include stairs, pillars and ramps. Kerbs are another important aspect which; these are part of the transport model.

A fully-populated CityGML model may be able to provide us with some of the information we require to obtain fully-connected pedestrian access networks, though the hierarchical way in which internal spaces are structured in the GML makes a certain amount of restructuring necessary, a task which it is likely to be achievable automatically.

CityGML has been sanctioned by the Open Geospatial Consortium (OGC), and has been evaluated in the OGC Web Services Testbed No. 4[2].

3.6 Pedestrian access models

Most published research on pedestrian accessconcentrates either on aggregate measures of accessibly for different user groups (e.g. [4, 19]), or simple network models such as those for transport modelling. Okunuki *et al.* [16] proposed some initial ideas for a pedestrian guidance system – implemented as a web prototype[3] – in which navigable space is represented as a network of single links for corridors, lifts and stairs and gridded meshes of links for open spaces. The prototype was designed to suggest a route for a user taking into account simple preferences (such as the need to avoid stairs). Lee [14] derives a 3D geometrical network by transforming polygons (representing floorspaces on specific storeys) into a connected network, using a modification of a medial axis transform. This 3D geometrical network, which extends over multiple storeys inside buildings and connects to space outside buildings was applied to building evacuation [13].

Neither of these works encodes pedestrian- and time-specific information on pedestrian access at the microscale.

Meijers *et al.* [15] developed a semantic model for describing pedestrian access within buildings. It requires the building to be subdivided into closed and non-overlapping spaces (volumes) called sections, within which pedestrian access is unhindered and whose geometry is described with a set of bounding polygons (a boundary-representation model). Each of the bounding polygons is classified according to its role in restricting or facilitating access; by persistency (presence in time), physical existence (some polygons exist purely to close spaces), access granting (classified as full, semi and limited; those classified as semi may require door keys and those classified as limited may perhaps only allow access in an emergency) and direction of passage (uni- or bi-directional). Using this polygon classification, scheme, each

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[2] The results are available in an OGC document available from http://portal.opengeospatial.org/files/?artifact_id=21622

[3] http://www.ncgia.ucsb.edu/~nuki/EllisonMenu.html

section is classified into 'end' (with one entrance/exit), 'connector' (with more than one entrance/exit) and 'non-accessible'. From these classified sections, topologically-connected graphs can be derived. This work acknowledges the need for access-granting requirements, but does not describe the details of this can be described.

3.7 Relationship of inside and outside space

Traditionally, spaces exterior to buildings and space interior to buildings have been modelled separately, in GIS and CAD-type software respectively. This is due to the different applications domains which primarily use the data, the different scales, and the different semantics. As shown, CityGML which supports the modelling of both inside and outside space models these spaces differently, using the building model for all aspects of inside space, and using the terrain, water, transportation, vegetation, city furniture and land-use models for outside space. However, unlike most of the early 3D city models reviewed in which building blocks are placed on top of a terrain, CityGML allows the 3D geometry of the interface between the building and the terrain to be described, using a 3D polyline (a 'TerrainIntersectionCurve'; Figure 4). Stoter [24] also acknowledges the importance of integrating the terrain surface with the base of buildings. From the point of view of modelling navigable spaces, the way in which the terrain meets the building at access points is of crucial importance.

Fig. 3.3 CityGML's 'TerrainIntersectionCurve' (shown in black), a 3D polyline representing where the building meets the terrain. Source: [8]

3.8 Model design and prototype

Our prototype model for representing navigable space in cities is based on Slingsby's [21] model design, which attempts to combine some of the geometrical, semantic and navigational aspects of cities. Space volumes are implicitly represented by their lower surfaces (ground surfaces), using a 2.5D approach. These surfaces are represented by polygons, tessellated and topologically structured into distinct layers. These layers are topologically-connected to each other where there is pedestrian access (Figure 4).

The three aspects of geometry, semantic and navigational aspects of the model design will be presented (full details of the implementation are in [21]).

3.9 Geometrical aspects

We use the 2.5D layered approach (Figure 4) to illustrate the importance that we attach to the topological consistency between layers, in terms of pedestrian access. It is a constraint-based surface model, in which height (e.g. spot heights) and surface morphology constraints (e.g. surface breaklines) primitives are embedded within 2D polygons. These constraints are used to generate a topologically-consistent set of surfaces defined in 3D [23]. As can be seen in figure 4, the topological model must be able to cope with non-2D-manfold joins.

Amongst the point, lines and polygon geometrical primitives, height and surface morphology constraints are embedded, as illustrated in Figure 5. There are two types of point constraint, (absolute and relative heights), two kinds of linear constraint (breaklines and vertical discontinuities called 'offsets') and two areal constraints (ramps and stairs). These constraints all affect the resulting 3D geometry. Examples of all except the ramps can be seen in Figure 5. These constraints are used to generate a 3D geometry which conforms to these constraints and is topologically consistent [23].

These layers and constraints are defined independently of real-world (semantic) meaning. The semantic model allows objects and semantic information about the objects to be defined on top of the geometrical model. Their 3D geometrical forms are parameterised in the object descriptions.

Note that the geometrical model here is only used to represent discrete and connected *navigable spaces*, structured into constraint-controlled 3D surfaces.

3.10 Semantic model

The semantic aspect of the model allows feature types (objects) to be defined and attributed a published meaning, taking their geometries from the

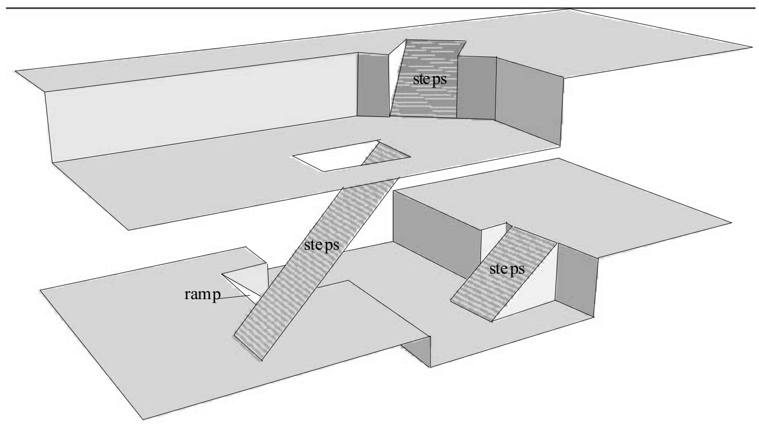

Fig. 3.4 A small example showing distinct surfaces (layers) which are topologically connected. The surfaces are composed of point, line and polygon primitives (not shown)

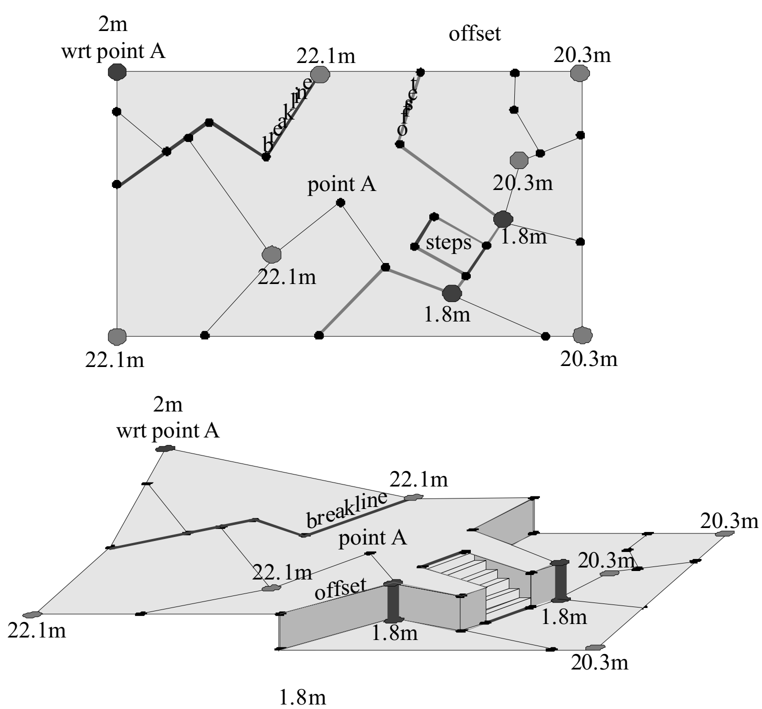

Fig. 3.5 Height and surface morphological constraints

primitives in the geometrical model and they can have a set of attributes associated. A small set of feature types have been defined, which have particular applicability to pedestrian access. These are 'spaces', 'barriers' (walls and fences), 'portals' (doors and windows) and 'teleports' (lifts). These have attributes which both parameterise their 3D geometries and have access implications (see following section).

3.11 Pedestrian navigation model

The pedestrian navigation model [20, 22] follows a similar approach to Meijers *et al.* [15], in that information on persistency, access-granting properties, direction of passage and structural information are described. However, they are attached to objects defined by the *semantic model* of 'barriers' (walls), 'portals' (doors and windows), 'teleports' (lifts) and 'spaces' (specific delineations of space), rather than to the boundaries of building sections of homogeneous access characteristics. An algorithm is then used to delineate space navigable to particular types of pedestrian, at the time and in the context in which access is attempted. These objects have persistency, access-granting, direction of passage and structural properties attached, some of which are time- and pedestrian-dependent. Persistency information is provided through lists of unique or recurring time periods (e.g. some barriers only exist at certain times of day). Access granting information is provided as lists of the times (unique or recurring) at which access is granted and (optionally) a specific or specific type of pedestrian. In this context, a pedestrian has a number of characteristics (e.g. age, gender) and may be in procession of one or more door keys or access cards. Direction of passage information and structural information can be applied to some of these objects. Barriers and openings are classified according to the ease of unauthorised access, e.g. how easily it can be passed with or without damage. Pedestrians have a maximum ease threshold of barriers for which they would be willing to breach. This might be context-dependent, for example if there is an emergency. Using this information, the model attempts to incorporate some of the microscale details of pedestrian access. As stated, a pedestrian has attributes, may have a collection of access cards of door keys has a threshold amount for gaining unauthorised access. Additionally, a pedestrian has a step-height he or she is able to negotiate, which would be zero or very small for a wheelchair user.

3.12 Implementation

A prototype implementation of the model design was implemented using ArcGIS for data preparation, editing and visualisation, with the data model and the 3D generating algorithm implemented in Java. This proof-of-concept model was used to generate the worked example in the next section. This example will be extended to full building models of Delft University in the RGI '3D Topography' project during 2007.

3.13 A worked example

Here we present a simple worked example using the model in order to illustrate some of the concepts of this paper. The images shown are annotated actual output from the prototype application. The scenario is a small fictitious example, of a very small area shown in Figure 6. It incorporates a section of road crossed by a bridge, a lower level accessed by a staircase and a ramp from either side of the road and a two storey building whose storeys are connected by a staircase. The main door of the building has a list of pedestrian- and time-dependent restrictions. Figure 7 shows the same area with the walls removed and from a slightly different viewpoint. The entirety of the space of the scenario (Figure 6) is accessible by a pedestrian who can negotiate steps.

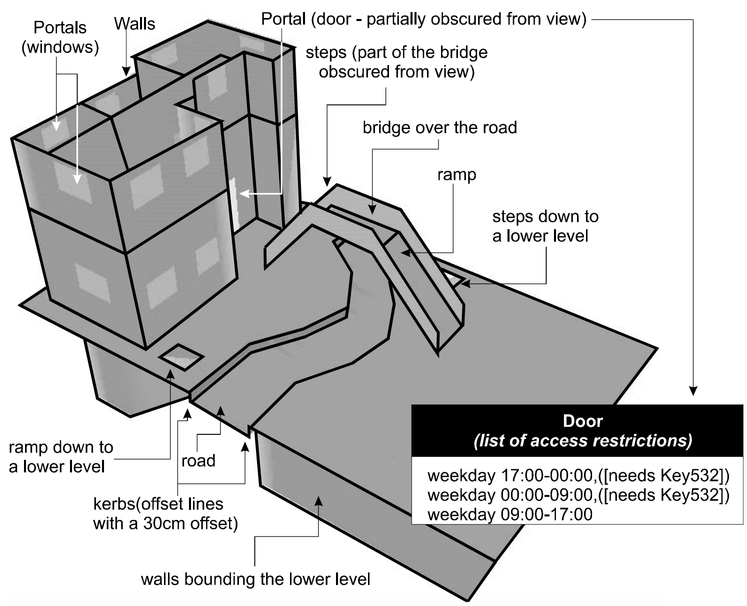

Fig. 3.6 An annotated image of the entire 3D scenario

The subsequent images (Figures 7, 8 and 9) show the areas of navigable spaces in the context described in the caption.

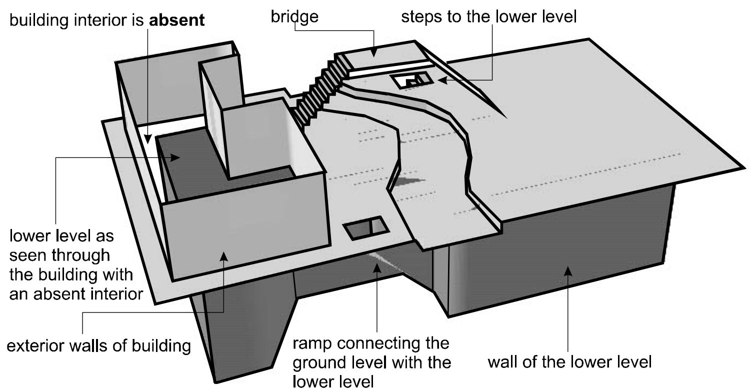

Fig. 3.7 The space accessible by a pedestrian without a key from outside the building, out of office hours (according to the access rules shown in Figure 6). Since access to the main door is not allowed, the interior of the building is absent, as is the upper storey, because no access has been gained to the internal staircase.

3.14 Evaluation and discussion

Although the example scenario is rather simplistic, it serves to illustrate the concepts in the model. It was produced by a prototype model in which navigable spaces by different pedestrians in different contexts can be delineated from a set of topologically-connected spaces with descriptions of objects which affect pedestrian access embedded and are properly attributed.

The semantic model and the attributes used for the navigation model are also simplistic but the approach is intended to allow the full complexity of navigable spaces in the built environment to be encompassed.

As part of the 3D Topgraphy project at Delft, it is our aim to apply this model to the challenge of representing the built environment of the university campus during 2007.

3.15 Conclusion

The enormous progress in two dimensional GIS over the last decade currently masks the rather less well-developed situation in three dimensional

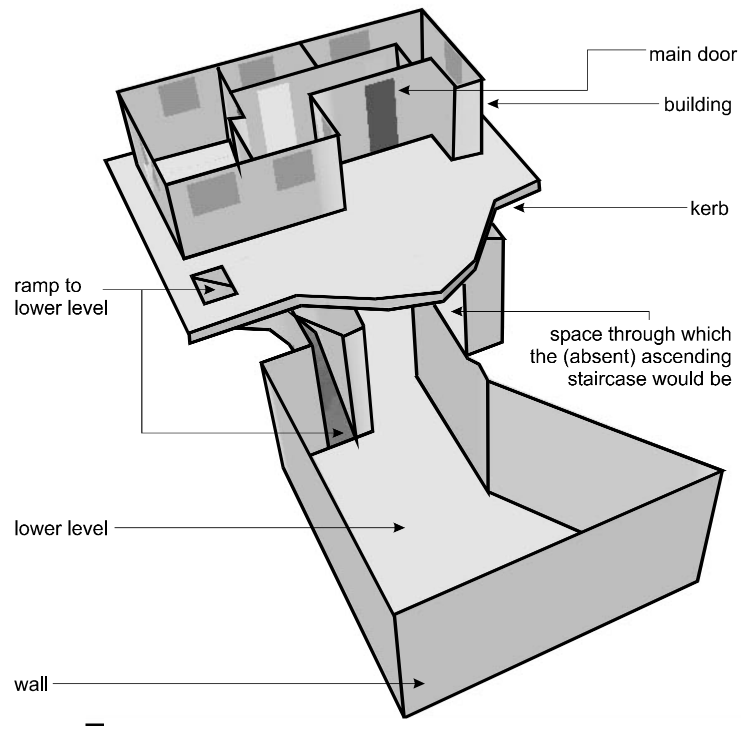

Fig. 3.8 This shows the space accessible to a pedestrian who starts just outside the building and cannot negotiate steps of any size. Note that all steps are absent; the road, the other side of the road, the bridge and the upper storey of the building are missing because they can only be accessed either by stairs or steps. All elements shown can be accessed without any steps.

GIS. There are a large number of application problems in three dimensions which have been solved in particular application domains. One general problem, for which no acceptable modelling solution appears to have been found, is the connection between buildings and the terrain. Without a solution to this challenge a wide range of applications where interaction has to cross the building-terrain divide are stalled.

References

[1] Altmaier, A. and T. Kolbe: Applications and Solutions for Interoperable 3D Geo-Visualization. Photogrammetric Week 2003, Stuttgart, Germany (2003)

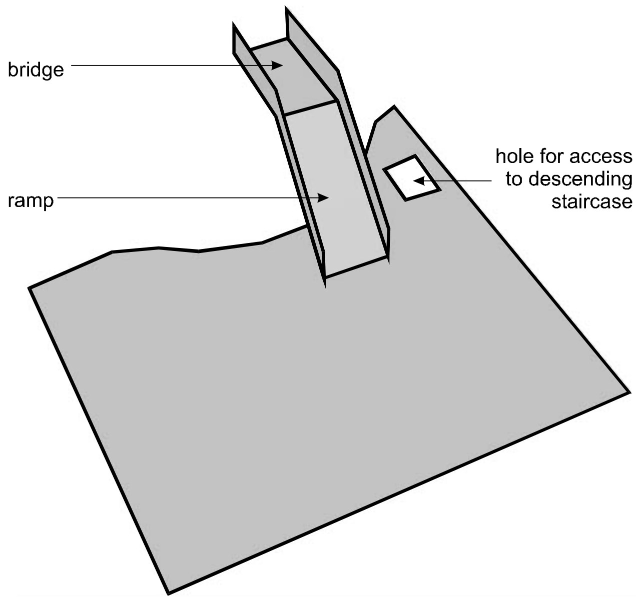

Fig. 3.9 This figure shows the space accessible to a pedestrian who starts on the opposite side of the road to that in Figure 9 and cannot negotiate steps of any size. Note that most of the bridge is accessible from this side of the road because this side is a ramp, but there is no access over the bridge. Also note that there is no lower level because access to this from this side of the road is by a staircase.

[2] Batty, M.: Model cities. UCL Centre for Advanced Spatial Analysis. Working Paper 113. Online at: `http://www.casa.ucl.ac.uk/working\_papers/paper113.pdf` (2007)

[3] Benner, J., Geiger, A., Leinemann, K.: Flexible generation of semantic 3D building models. Proceedings of the 1st International Workshop on Next Generation 3D City Models, Bonn, Germany (2005)

[4] Church, R. L. and J. Marston: Measuring Accessibility for People with a Disability. Geographical Analysis 35(1): 83–96 (2003)

[5] Döllner, J., H. Buchholz, Brodersen, F., Glander, T., Jütterschenke, S. and Klimetschek, A.: Smart Buildings – a concept for ad-hoc creation and refinement of 3D building models. Proceedings of the 1st International Workshop on Next Generation 3D City Models, Bonn, Germany (2005)

[6] Eastman, C. M.: Building product models: computer environments, supporting design and construction. Boca Raton, FL, USA, CRC Press (1999)

[7] Ellul, C. and Haklay, M.: Requirements for Topology in 3D GIS.. Transactions in GIS 10(2): 157–175 (2006)

[8] Gröger, G., Kolbe, T.H. and Czerwinski, A.: Candidate OpenGIS CityGML Implementation Specification (City Geography Markup Language). Open Geospatial Consortium/Special Interest Group 3D (SIG 3D): 120 (2006)
[9] Gwynne, S., E. R. Galea, et al.: A review of the Methodologies used in the Computer Simulation of Evacuation from the Built Environment. Building and Environment 34(6): 741–749 (1999)
[10] Khemlani, L.: A 'Federated' Approach to Building Information Modeling. CADENCE AEC Tech News 94 (2003)
[11] Kolbe, T., G. Groger and Plümer, L.: Towards Unified 3D-City-Models. ISPRS Commission IV Joint Workshop on Challenges in Geospatial Analysis, Integration and Visualization II, Stuttgart, Germany (2003)
[12] Kolbe, T. H., G. Gröger, et al.: CityGML – Interoperable Access to 3D City Models. Proceedings of the Int. Symposium on Geo-information for Disaster Management, Delft, The Netherlands, Springer Verlag (2005)
[13] Kwan, M. P. and J. Lee: Emergency response after 9/11: the potential of real-time 3D GIS for quick emergency response in micro-spatial environments.. Computers Environment and Urban Systems 29(2): 93–113 (2005)
[14] Lee, J.: A Spatial Access-Oriented Implementation of a 3-D GIS Topological Data Model for Urban Entities. Geoinformatica 8(3): 237–264 (2004)
[15] Meijers, M., Zlatanova, S. and Pfeifer, N.: 3D Geo-information Indoors: Structuring for Evacuation. Proceedings of the 1st International Workshop on Next Generation 3D City Models, Bonn, Germany. (2005)
[16] Okunuki, K., Church, R. and Marston, J.R.: A Study on a System for Guiding of the Optimal Route with a Hybrid Network and Grid Data Structure. Papers and Proceedings of the Geographic Information Systems Association, Japan (1999)
[17] Papamichael, K., Chauvet, H., La Porta, J., Dandridge, R.: Product Modeling for Computer-Aided Decision-Making. Automation in Construction 8 (1999)
[18] Pu, S. and S. Zlatanova: Evacuation Route Calculation of Inner Buildings. Geo-information for disaster management. P. van Oosterom, S. Zlatanova and E. M. Fendel. Heidelberg, Germany, Springer Verlag: 1143–1161. (2005)
[19] Sakkas, N. and J. Pérez: Elaborating metrics for the accessibility of buildings. Computers, Environment and Urban Systems 30(5) (2006)
[20] Slingsby, A. D.: Pedestrian accessibility in the built environment in the context of feature-based digital mapping. Proceedings of Computers in Urban Planning and Urban Management (CUPUM), London, UK. (2005)
[21] Slingsby, A. D.: Digital Mapping in Three Dimensional Space: Geometry, Features and Access. Centre for Advanced Spatial Analysis. PhD thesis (unpublished). London, UK, University College London (2006)

[22] Slingsby, A. D. and P. A. Longley: A Conceptual Framework for Describing Microscale Pedestrian Access in the Built Environment. Proceedings of GISRUK, Nottingham, UK (2006)

[23] Slingsby, A.D.: A layer-based data model as a basis for structuring 3D geometrical built-enviornment data with poorly-specified heights, in a GIS context. Proceedings of AGILE07, Aalborg, Denmark, May 2007. (2007)

[24] Stoter, J.: 3D cadastre. PhD Thesis, Delft University of Technology, The Netherlands (2004)

[25] Takase, Y., Yano, K., Nakaya, T., Isoda, Y., Kawasumi, T., Matsuoka, K., Tanaka, S., Kawahara, N., Inoue, M., Tsukamoto, A., Kirimura, T., Kawahara, D., Sho, N., Shimiya, K. and Sone, A.: Visualisation of historical city Kyoto by applying VR and Web3D-GIS technologies. CIPA International Workshop dedicated on e-Documentation and Standardisation in Cultural Heritage, Cyprus (2006)

[26] Zlatanova, S.: 3D GIS for Urban Development. ITC publication 69, ISBN 90-6164-178-0 (2006)

Chapter 4
Towards 3D Spatial Data Infrastructures (3D-SDI) based on open standards – experiences, results and future issues

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4.1 Introduction

The creation of Spatial Data Infrastructures (SDI) has been an important and actively studied topic in geoscience research for years. It is also regarded in politics and by decision makers as leveraging technology for reducing thr time and cost of geo services for internal usage as well as for public information services. In Europe, the new INSPIRE (Infrastructure for Spatial Information in Europe) directive 2007/2/EC provides general rules for implementating national spatial data infrastructures for environmental policies. SDIs must rely on open standards specified by the Open Geospatial Consortium (CS-W, WMS, WFS, WCS, WPS, OpenLS, etc.)

Based on the theoretical background of INSPIRE and several discussion drafts of the OGC, we have implemented an SDI for the city of Heidelberg that comprises an array of established OGC services and some new proposed technologies required to extend into the 3rd dimension. In this paper, we discuss the components that have been developed for a 3D SDI and some important aspects that must be addressed to make this kind of infrastructure work. For standard services, we could use existing open source solutions; others must be extended or developed from scratch, including new techniques for data preparation and integration. The components have been implemented for several projects with different goals, always with interoperability and reusability in mind.

The central part of the SDI is the OGC Web3D Service (W3DS), which delivers the actual 3D data. The W3DS specification is currently in draft status and is not yet adopted by the OGC. We present our own implementation of this service and some implications when considering different use cases. In our case it was important to use the W3DS not only for producing static

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scenes, but also to request data piecewise in order to stream it to the client; this implements a more dynamic visualization. This is due to the large data quantities, which are not comparable to the 2D bitmaps delivered by a WMS.

A possible extension to the WMS is the support of the Styled Layer Descriptor (SLD) profile for controlling the appearance of maps. It is advisable to separate the geometry or geographic raw data from the visualization rules. Proposals have been made to include further visualization elements directly in CityGML. We suggest using the SLD specification in combination with W3DS services. We describe how SLD can be extended to provide 3D symbolizations - e.g. for 3D points, linestrings, surfaces, and solids.

There must also be an adequate way to describe our 3D data in a catalogue service; we examined different alternatives. We also examined the integration of route services, for which the OGC OpenLS specification can be used, as we will show.

Finally, we discuss future research topics that arise from current trends such as Location Based Services or Service Oriented Architectures (SOA). We need to investigate how these concepts can be applied to mobile 3D navigation services, which have different requirements in terms of visualization and user guidance. In the long term, a higher level concept for defining chains of web services within an SOA could be applied that helps to orchestrate SDI services more flexibly. In particular, the Business Process Execution Language (BPEL) could be used to define scenarios realized through chaining the open GI services that constitute SDIs.

4.2 3D Data Management – an overview

Data management is at the heart of an SDI. A powerful database is necessary to manage and administer 3D data efficiently (Zlatanova & Prosperi 2005). Object-relational databases such as PostGIS or OracleSpatial have already been applied successfully to handling geographic information. A lot of work has been done in this respect; in this paper we summarize recent developments in standard-based data sources for 3D visualization services, such as the W3DS. In order to create a 3D data storage layer that can be used as a source for our W3DS implementation, we tested open and commercial database capabilities regarding geometry models, export formats, availability, etc. The following products were assessed:

iGeo3D is part of the degree-framework that allows users to manage 3D geodata through the web. It is completely based on OGC standards. The 3D database scheme ‘CityFeatureStore’ of the data storage module can be used for various database systems (Oracle, PostGreSQL/ PostGis). The degree-WFS offers write- and read access to the data and iGeoSecurity provides access protection. The CityGML format or multiple image formats can be used for exchanging the data.

The *City Model Administration open source toolkit (CAT3D)* was developed within the EU-project VEPS (Virtual Environmental Planning System) by the HfT Stuttgart. It can connect to different data sources and produce several output formats (VRML, KML, Shapefile). The architecture is modular so that additional data sources and formats can be supported by implementing the according modules.

A 3D extension by CPA Geoinformation for commercial *SupportGIS* offers ISO/OGC conform 3D data storage and supports databases such as Oracle, PostgreSQL, MySQL and Informix. Together with SupportGIS-3DViewer and SupportGIS-Web3D a 3D platform is provided with a CityGML central database structure.

Within the VisualMap project (FhG IGD/EML) a database called *ArchiBase* was developed which allows various different 3D geodata to be administered. The modelling tools can come from applications such as 3D Studio Max as well as from GIS. The scheme was realized for Oracle. The data can be managed via a graphical user interface, and exchange formats can be in VRML 2.0 and XML. Principles that evolved from this work can be found within CityServer3D.

CityServer3D (Haist & Coors 2005) is a multi-layered application consisting of a spatial database, a server and a client application. The database manages 3D geometries at multiple levels of detail along with the corresponding metadata. The server as the core component provides different interfaces for importing and exporting various geodata formats. The data is structured by a meta-model and stored in a database.

Currently, we use the well known PostGIS extension to PostgreSQL for 2D data and 3D points of the DEM, as well as VRML code snippets, but after evaluating the projects mentioned above, we will extend data management of our server to also support native 3D data types within the database as needed. The exchange of 3D city models through CityGML delivered by a WFS is separate; it is already covered by the above mentioned projects, such as iGeo3D, etc.

4.3 Towards a 3D Catalogue Service for 3D Metadata

Within an SDI it is important to record information about available datasets via metadata in order to make it possible to find relevant data. Three metadata standards seemed most relevant for spatial data: ISO 19115 along with its predecessors Dublin Core and CEN-TC287. Nonn et al. (2007) evaluated the suitability of the current metadata standards for 3D spatial data. The authors also investigated which enhancements or supplements might be needed by the most important metadata specification for spatial data, ISO 19115, so that it can be used to describe 3D landscape and city models. We tried to find the highest possible sufficiency for 3D spatial data, city- and landscape models. In particular, we used the present OGC CityGML discussion paper (Gröger et al. 2006) - especially regarding the question of how to allow a semantic description of structures within 3D city models.

As of today there is still no online object catalogue available for CityGML from which attribute values can be derived. If such a catalogue was available online, it would not be necessary to put this kind of information directly into the ISO 19115 standard; instead, the internet catalogue could be referenced. The feature type attributes contain an object type list, also linking the user to the specific parts of the online catalogue.

This work paves the way for future discussions on the needs of 3D-SDI, especially for 3D city models. Although current SDI developments focus on 2D spatial data, we think that in the long run a similar development is necessary for 3D data. Already a range of basic attributes in ISO 19115 apply to 3D data; even so, we found a need to add further specifications to the metadata catalogues. We have made first suggestions for ways to add these missing elements to the ISO 19115. We are aware that these suggestions are a first attempt and need further development. For first results, see Nonn et al. (2007).

4.4 Scene-based Visualization with the Web3D Service

Regarding the portrayal of 3D information, a Web3D Service (W3DS) was proposed to the OGC as a discussion draft (OGC 2005). The W3DS delivers 3D scenes of 3D city or landscape models over the web as VRML, X3D, GeoVRML, or similar formats. The parameters are similar to those of the WPVS (Web Perspective View Service), which adds to the well-known WMS interface parameters for camera position, view target, etc. We implemented a server that supports all these parameters, but also provides some noteworthy techniques applied to a W3DS service for the first time in a standard-conforming way. For example, in order to provide techniques that are already state of the art in computer graphics (such as dynamic concepts like continuous LODs for triangle meshes or streaming of geometry parts), we developed a sort of 'pseudo-streaming' using an intelligent client-application and pre-processed DEM-tiles with different resolutions and sizes. This allows faster delivery of scenes compared to typical implementations of the W3DS, which deliver only complete scenes in file documents, covering the entire requested scene. A similar scenario was introduced at Web3D 2002 (Schilling and Zipf 2002). Back then, there were no 3D OGC standards we could use for our scenario. This has changed; we incorporated these new standards into the project. The work presented here is embedded in a larger project that involves a several OGC Web Services (OWS), as well as several clients and the integration of various data sources.

As shown in figure 1, many requests from our Map3D-Client trigger a service chain involving separate OWS necessary to process the request. 2D maps are delivered by a Web Map Service (WMS) for overview maps of the region. 3D information is provided by our Web 3D Service (W3DS) implementation. The Web Feature Service (WFS) standard is or will be the basis for both of these services. The WFS is already integrated for the 2D map data used by the WMS and will also be used to provide the data necessary for creating 3D scenes.

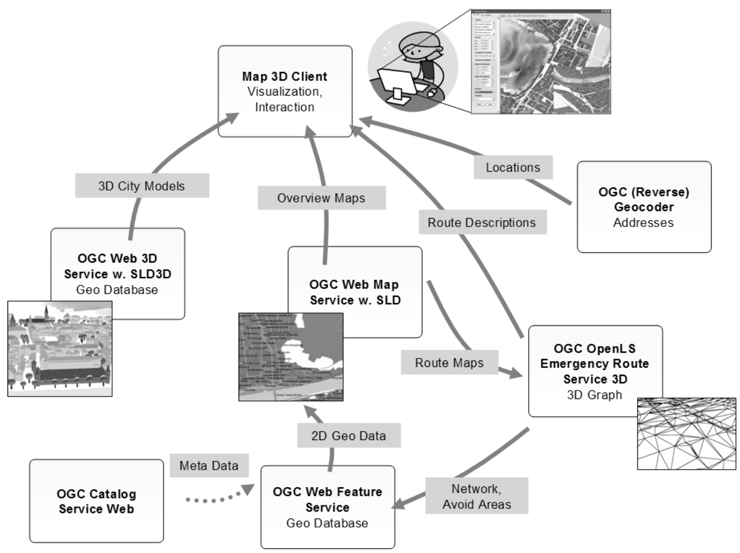

Fig. 4.1 Components and service chaining in our 3D-SDI (WPS to be added soon for pre-processing of terrain data)

We implemented the OpenLS Route Service Specification (as well as the OpenLS Utility Service (Geocoding and Reverse Geocoding)). The route calculation itself is done on a 2D network graph; however, the resulting route geometry is then replaced by 3D linestrings taken from the 3D network. This 3D network was pre-calculated by mapping the 2D linestrings onto the Digital Elevation Model (DEM) so that the route segments exactly follow the terrain including tunnels and bridges. This so-called Route Service 3D (RS3D) uses exactly the same interface as the already standardized OpenLS Route Service, without needing to extend anything. Due to the more accurate representation of route geometries from the 3D extension, we get a lot more route segments. Practical tests showed that we needed to reduce the geometries further using horizontal and vertical generalization to produce smooth visualizations and animations. A 2D overview map is also produced by our implementation of the OpenLS Presentation Service.

The OGC Catalog Service (CS-W) shown in figure 1 is based on the degree framework and delivers metadata of the actual spatial data. Before adding metadata to this service, we conducted an investigation to determine if the relevant metadata standards such as Dublin Core or ISO 19115 are appropriate for describing 3D spatial data such as 3D city models (Nonn et al. 2007). The purpose of the CS-W is to provide information through search functions such as where to find GI services and spatial data within the spatial data infrastructure or on the Web. We used these for 2D data in former projects, such as OK-GIS or geoXchange (Tschirner et al. 2005).

4.5 Streaming and different LODs of DEM using the W3DS

As mentioned earlier, we developed a ‘smart’ Java3D client that uses preprocessed DEM-tiles served by the W3DS to satisfy state-of-the-art computer graphics with respect to streaming. Further, it uses different LODs when changing the field of view of the viewer. This was done using open standards by OGC, as explained below:

A high-precision (5 meter) DEM, covering an nearly 150 square kilometres, was divided into several groups of smaller, rectangular DEM pieces with different accuracies and point-densities. Each DEM-tile group represents one Level-of-Detail (LOD). This means that those tiles covering wide areas describe the surface more approximately than smaller tiles with a high point density. Each DEM tile is replaced by four smaller tiles in the next higher LOD. This allows the client to retrieve DEM-tiles at different LODs using the W3DS. A dynamic DEM can be processed by requesting the needed tiles depending on the viewer’s position, the line of sight and the distance along the line of sight. All changes in the viewer’s field of view or position causes a new series of W3DS-GetScene requests delivering new DEM-tiles. These tiles are then added to the scenegraph. Memory is saved by only displaying the tiles in the view and by removing all tiles outside of the view on the fly. An example of the results is available as a video screen capture showing the effect on the DEM when navigating the scene in real time. The videos are available from http://www.gdi-3d.de.

4.6 Standard-based Configuration of 3D Visualization through extensions of the Styled Layer Descriptor

In conventional GIS, the raw data is typically separated from the visualisation properties. This provides the possibility of displaying the same data in multiple ways depending on the project use case or user preferences. So far, this separation is not yet established in 3D GIS data, since usually the 3D model is considered as a kind of visualization itself - including all appearance properties. This is the case for all common graphics formats like DXF, 3DS, VRML, and other proprietary CAD formats. In the GIS world we strive to describe only the geometry and the object classes in the raw datasets and to store attribute data and display properties in different files, as is the case with the most popular products.

For 2D web maps, Styled Layer Descriptor (SLD) documents exist, which define rules and symbols controlling the map appearance. The same should be applied to 3D maps, including city models. By using SLD it is also possible to integrate different data sources into a single rendering service like a WMS and to style all data consistently.

We propose an extension to the SLD specification in order to support 3D geometries and appearance properties. As of now, this approach is unique. However, there are considerations on extending CityGML by further visualization elements. If such an extension would also cover pure styling information this would undermine the desired separation of raw data and visualization rules. Therefore, we must be aware of existing OGC specifications and incorporate them into new standards, or simply extend existing ones. In this case, styling information for polygons, lines, and points in SLD is also partly useful in 3D. Therefore an SLD extension seems to be more promising. In the next sections we make some first suggestions for a SLD3D that incorporates standard SLD elements and some new elements only valid in 3D space. The SLD3D was implemented and tested in the 3D-SDI Heidelberg project (Neubauer 2007, Neubauer & Zipf 2007). The SLD files are currently used for configuring the W3DS server; however, in the future the client will be able to specify it as well in order to provide more flexibility of interaction.

Relevant aspects of this extension can be categorized as follows:

- Rotation of elements around all three axes
- Displacements and positions are extended by Z
- SolidSymbolizer for object volume description
- SurfaceSymbolizer for defining surfaces with triangular meshes (tin)
- Integration of external 3D objects into the scene
- Defining material properties
- Billboards for 2D graphics
- 3D legends
- Lines displayed cylindrically (e.g. for routes)

Current WMSs can provide the user with a choice of style options; the W3DS, on the other hand, can only provide style names and not a more detailed scene of what the portrayal will look like. The biggest drawback, however, is that the user has no way of defining his own styling rules. For a human or machine client to define these rules, there must be a styling language that the client and server can both understand. This work focuses on defining such a language, called 3D Symbology Encoding (3D SE). This language can be used to portray the output of Web 3D Services.

3D-Symbology-Encoding includes FeatureTypeStyle and CoverageStyle root elements taken from standard Symbology Encoding. These elements contain all styling, for example, filters and different kinds of symbolizers. As the specification states, Symbolizers are embedded in Rules, which have group conditions for styling features. A Symbolizer describes how a feature will appear on a map or in a 3D scene. The symbolizer also has graphical properties such as color and opacity.

The 3D-SE can be used flexibly by a number of services or applications that style georeferenced information in 3D. It can be seen as a declarative way to define the styling of 3D-geodata independent of service interface specifications, such as W3DS.

4.6.1 PolygonSymbolizer

The PolygonSymbolizer describes the standard 2D style of a polygon including *Fill* for the interiors and *Stroke* for the outline, as defined in SLD. Additionally the 3D-SLD extension describes 3D features like BillboardPlacement.

4.6.2 LineSymbolizer

A 2D line can be represented in 3D as a pipe feature, with a certain radius and colour. The standard attributes from SLD-specification also can be set (StrokeWidth, StrokeType, etc.).

4.6.3 BillboardPlacement

With the BillboardPlacement element, 2D objects (text, images, etc.) can be placed so that they always face the viewer. This is useful for icons, pixel graphics, signs, and other abstract graphics. BillboardPlacement contains 3 sub elements: AnchorPoint, Displacement, and Rotation. The syntax is:

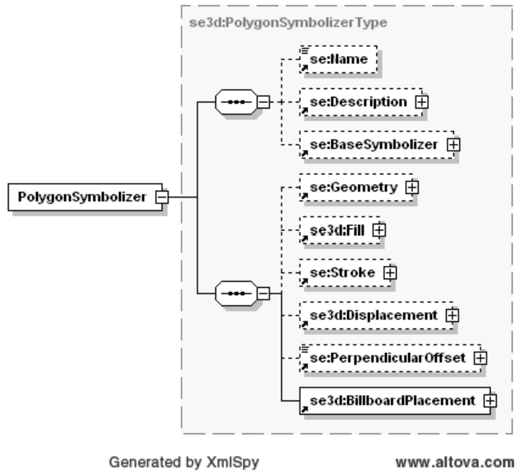

Fig. 4.2 XML schema for the SLD-3D PolygonSymbolizer

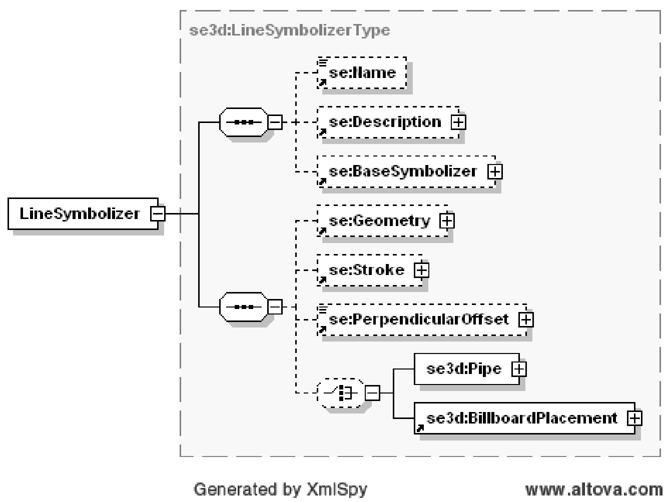

Fig. 4.3 XML schema of the SLD-3D LineSymbolizer

AnchorPoint

The 3D Symbology Encoding Anchor Point element is extended by AnchorPointZ. The coordinates are given as floating-point numbers like AnchorPointX and AnchorPointY. These elements each have values ranging from 0.0 to 1.0. The default point is X=0.5, Y=0.5, Z=0.5 which is at the middle height and length of the graphic/label text. Its syntax is:

Displacement

```
<xsd:element name="BillboardPlacement" type="se3d:BillboardPlacementType">
  <xsd:annotation>
</xsd:element>
<xsd:complexType name="BillboardPlacementType">
  <xsd:sequence>
    <xsd:element ref="se3d:AnchorPoint" minOccurs="0"/>
    <xsd:element ref="se3d:Displacement" minOccurs="0"/>
    <xsd:element ref="se:Rotation" minOccurs="0"/>
  </xsd:sequence>
</xsd:complexType>
```

Fig. 4.4 XSD schema of the SLD-3D BillboardPlacement

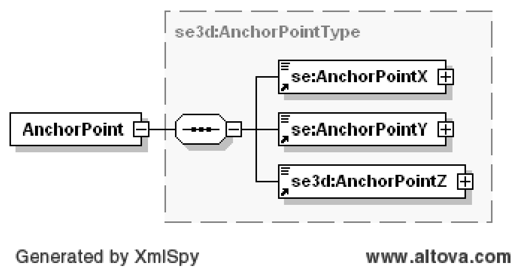

Fig. 4.5 XSD schema of the SLD-3D AnchorPoint

Displacement is extended by Z like AnchorPoint. The default displacement is X=0, Y=0, Z=0. The schema is visualized in figure 7.

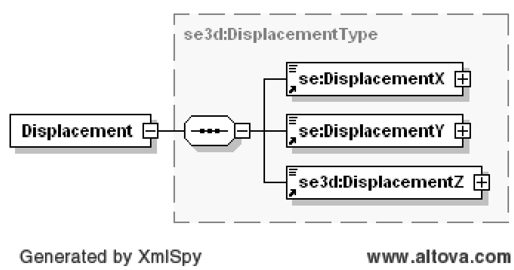

Fig. 4.6 XSD schema of the SLD-3D Displacement

If Displacement is used in conjunction with Size and/or Rotation, the graphic symbol can be scaled and/or rotated before it is displaced.