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.

Introduction

3D city models are increasingly considered as important resources for municipal planning and decision-making (Batty, 2007); examples of 3D City models include Virtual London (Batty, 2007) and Virtual Kyoto (Takase *et al.*, 2006). 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 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.

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 in-

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formation 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).

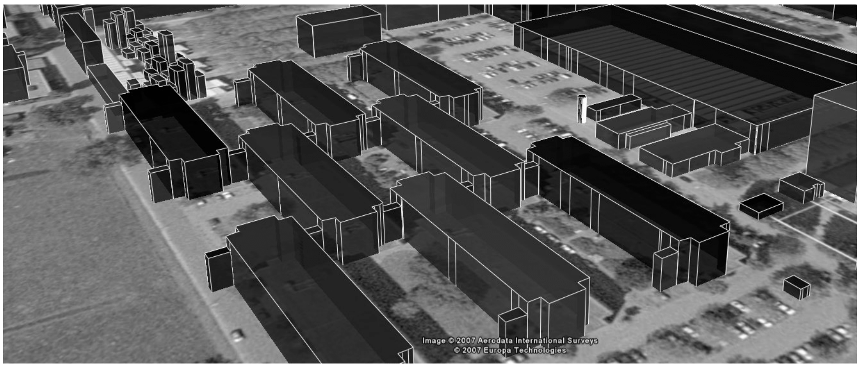

Figure 1. Extruded block model of part of the Technical University of Delft campus, rendered in Google Earth. *Source: Technical University of Delft.*

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 ArcScene 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. Zlatanova, 2000) for data validation, algorithms for 3D spatial analysis and potential application areas (e.g. Ellul and Haklay, 2006). 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 (Papamichael, 1999; Khemlani, 2003; Eastman, 1999). Similar approaches have been used for virtual cities; e.g. 'QUASY' (Benner et al, 2005) and 'Smart Buildings' (Döllner, 2005). CityGML[1] (Kolbe and Gröger, 2003; Kolbe *et al*, 2005; Groger *et al*, 2006) 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 ob-

[1] In this paper, we are using version 0.3.0 of the Candidate OpenGIS standard (Groger *et al*, 2006)

ject 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).

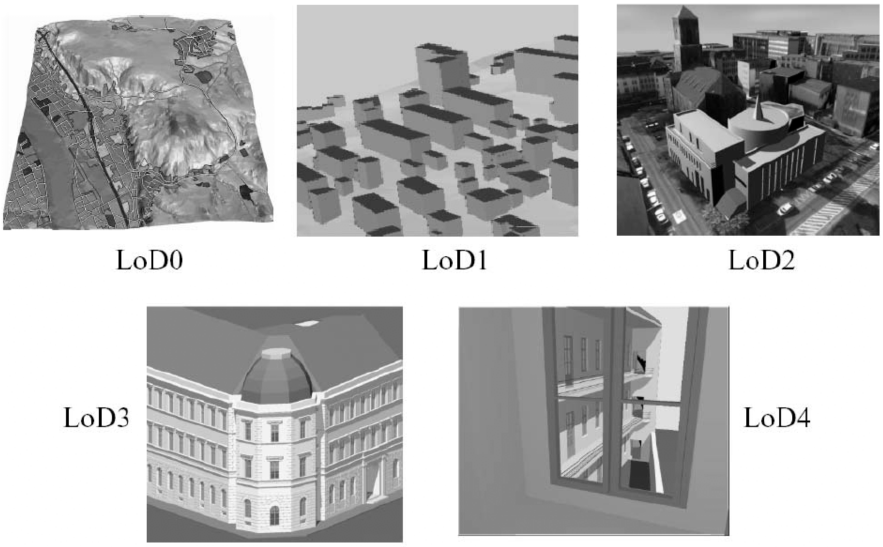

Figure 2. The five levels of detail defined in CityGML. *Source: Kolbe et al. (2005).*

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

- The formalised levels of detail allow parts of buildings to be modelled at the most appropriate levels of detail.
- Interior spaces in buildings can be modelled (where appropriate)
- The 3D city model is exchangeable and reusable.
- 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 (Altmaier and Kolbe, 2003) 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.

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

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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 include s(Pu and Zlatanova, 2005; Gwynne et al., 1999):

- keeping an spatial inventories of the nature and location of damage and hazardous equipment which may contribute to the aggravation of fires;
- knowing the capacity of escape routes;
- 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.

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.

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 *et al*'s (2005) 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* (Groger *et al.* 2006). 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].

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

Pedestrian access models

Most published research on pedestrian accessconcentrates either on aggregate measures of accessibly for different user groups (e.g. Church and Marston, 2003; Sakkas and Pérez, 2006), or simple network models such as those for transport modelling. Okunuki *et al.* (1999) 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 (2004) 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 (Kwan and Lee, 2005).

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

Meijers *et al.* (2005) 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 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.

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 (2004) 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.

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

Figure 3. CityGML's 'TerrainIntersectionCurve' (shown in black), a 3D polyline representing where the building meets the terrain. *Source: Groger et al. (2006).*

Model design and prototype

Our prototype model for representing navigable space in cities is based on Slingsby's (2006) 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 Slingsby, 2006).

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 (Slingsby, 2007). As can be seen in figure 4, the topological model must be able to cope with non-2D-manfold joins.

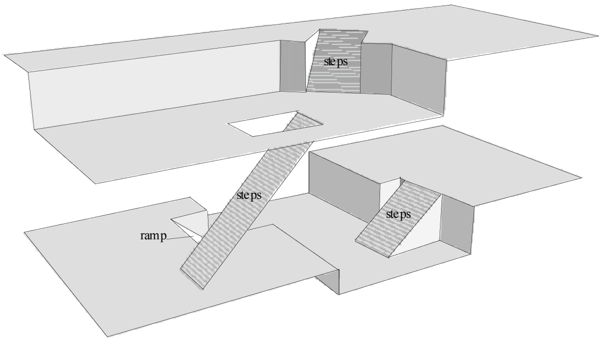

Figure 4. A small example showing distinct surfaces (layers) which are topologically connected. The surfaces are composed of point, line and polygon primitives (not shown).

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 (Slingsby, 2007).

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.

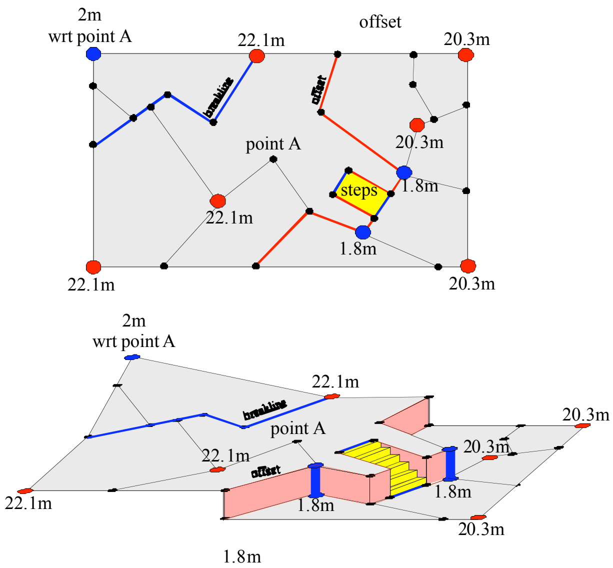

Figure 5: Height and surface morphological constraints.

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 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).

Pedestrian navigation model

The pedestrian navigation model (Slingsby, 2005; Slingsby and Longley, 2006) follows a similar approach to Meijers *et al.* (2005), 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.

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.

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.

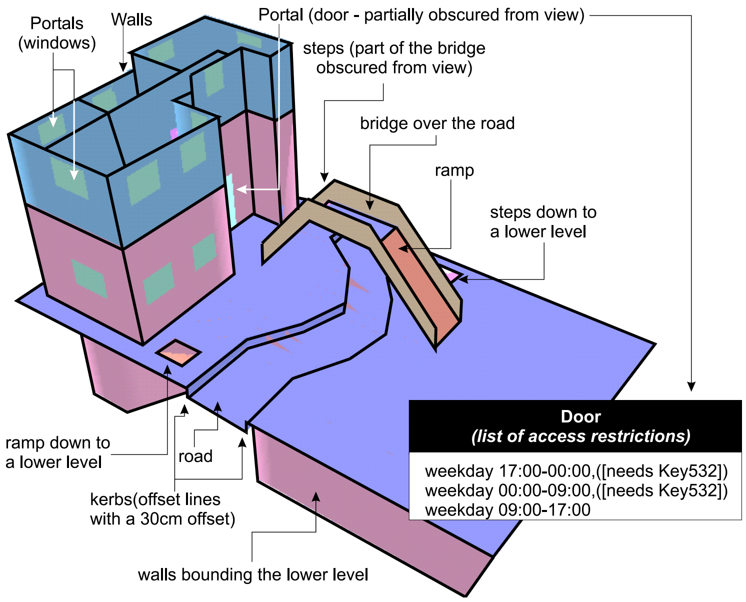

Figure 6. An annotated image of the entire 3D scenario.

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

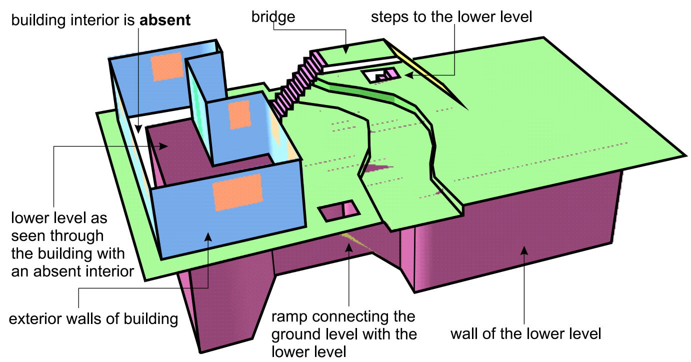

Figure 7. The space accessible by a pedestrian without a key from outside the building, out of office hours (according to the access rules shown in Figure 6). Since access to the main door is not allowed, the interior of the building is absent, as is the upper storey, because no access has been gained to the internal staircase.

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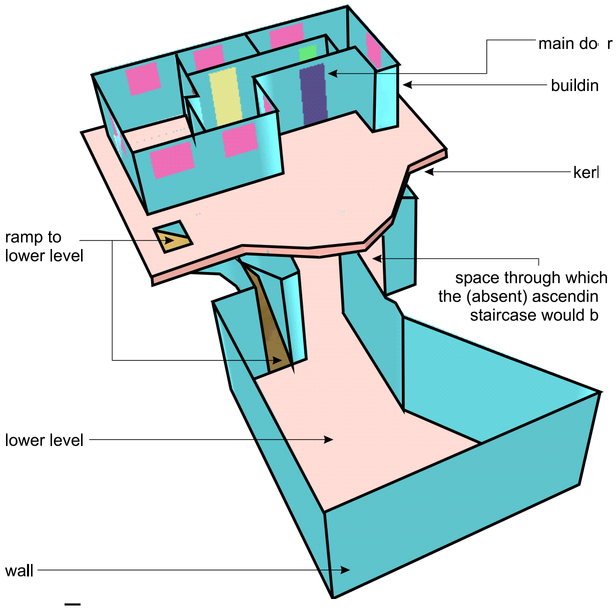

Figure 8. This shows the space accessible to a pedestrian who starts just outside the building and cannot negotiate steps of any size. Note that all steps are absent; the road, the other side of the road, the bridge and the upper storey of the building are missing because they can only be accessed either by stairs or steps. All elements shown can be accessed without any steps.

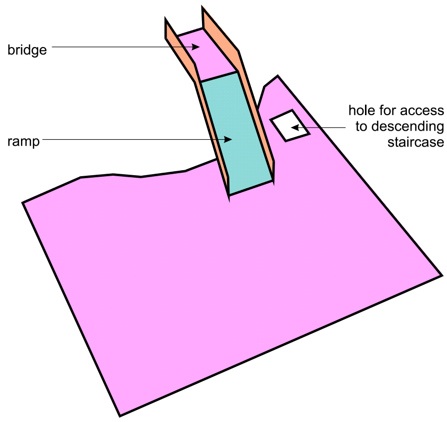

Figure 9.This figure shows the space accessible to a pedestrian who starts on the opposite side of the road to that in Figure 9 and cannot negotiate steps of any size. Note that most of the bridge is accessible from this side of the road because this side is a ramp, but there is no access over the bridge.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

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.

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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.

Conclusion

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

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