3D Topography Project
City University London: Final Report

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City University London was a participant of the 3D Topography Project that ran during 2007 and 2008. The overall aim of the project was to test and evaluate different approaches to 3D modelling using common datasets and so our main activity was to model the test datasets provided by the project and to evaluate the process. Our modelling approach[1] involves 'navigable space' both indoors and outdoors including pedestrian- and context-dependent restrictions to movement. The uniqueness of this approach compared to the others in this project and in the literature (which are geometry- and topology-based) resulted in a number of challenges that provides some interesting perspectives.

Our main aims were:

- To model the test datasets provided by the project, extended our model where appropriate and evaluate the process (section 1).
- To review the state of 3D GIS application and research in the Far East (section 2).
- To participate in the two 3D GeoInfo conferences that took place in the period of the project (section 3).
- To compare geological approaches to 3D modelling, using DGI EarthVision software (section 4).
- To use outputs of the project to inform funding proposals and to build collaborations (section 5).

1. Modelling Test Data

1.1. Modelling approach

Our data model's[1] main characteristics are:

- It is an extension of a 2.5D model in which:
    - Spaces are modelled in layers connected by pedestrian access routes
    - Each layer is a topologically-structured set of geometrical primitives (points, lines and polygons) in a 2D tessellation. Surface morphology is parameterised as breaks of slope, vertical discontinuities and spot heights recorded as attributes on appropriate geometrical primitives (Figure 1).
    - Each layer's surface is modelled on-demand (on-the-fly) as one or more TINs from the height information embedded in some of the geometrical primitives, such that slopes and vertical offsets (discontinuities) are represented (Figure 1).

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[1] Our model is based on that developed by Slingsby (2006) as part of his PhD at University College London. See bibliography at the end of this report for more details).

- Features or objects have their footprints represented as collections of geometrical primitives with parameterised 3D geometry. Feature types currently implemented are 'wall' (comprising lines and polygons), 'portal' (door; comprising lines or polygons), 'teleport' (lift; comprising polygons) and 'space' (comprising polygons). Microscale detail of pedestrian access can be represented.
- Both inside and outside spaces are modelled – no distinction is made in the geometrical model

We are targeting routing and gazetteer-type applications that need to be able to locate specific spaces within cities and pedestrian access between these spaces. Examples are cadastres that enable portions of space within cities such as shop units and flats and PDA or mobile phone-based pedestrian routing applications that assist with wayfinding.

1.2. Summary of model

The model is still a proof-of-concept prototype that is built in Java and outputs to 3D Shapefiles for visualisation, as summarised below.

1.2.1. Geometry

Geometry is modelled tessellations of the geometrical primitives of points, lines and polygons, organised into layers corresponding to the 2D footprints of spaces (i.e. the ground surface). Layers are connected where there is access. Surface morphology information is encoded within these as spot-heights (on points), relative heights (on points), offsets (vertical discontinuities; on lines) and surface characteristics (steps or ramps; on polygons), as shown in Figure 1. These can be considered as geometrical constraints that pin parts of the surface at positions in 3D space.

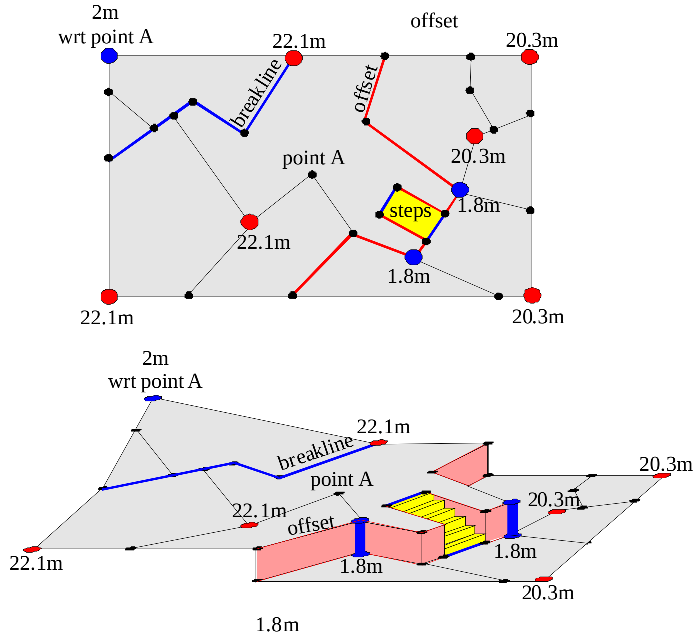


Figure 1. Specifying breaks of slope, offsets and heights (above) and how they are realised by the model (lower). *Source: Slingsby (2006).*

Once imported in the model, these surface morphological constraints are used to build TINs on-demand that interpolate surface geometry for each layer. These geometrical primitives are designed to represent space without reference to any real-world meaning.

In the prototype system, input data are prepared in ArcGIS (in the upper part of Figure 1), processed using VBA scripts and then imported into the model as a directory of Shapefiles. Data cleaning and topology-building is done in ArcGIS. The Java application stitches the layers together at the import stage and builds the required TINs whenever heights needed.

1.2.2. Features

Features are used here to refer to real-world meaning. The geometrical primitives do not represent real-world features, rather atomistic geometrical primitives used as bases for describing features. Geometrical primitives are indivisible by features. If a feature's extent needs to includes a fraction of a geometrical primitive, the primitive must be divided and all the features that reference the original primitive must be updated to use the two new primitives.

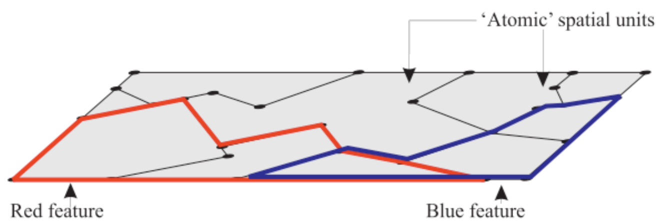


Figure 2. Illustration of how two overlapping features representing spaces are represented. *Source: Slingsby (2006).*

As stated above, the geometry of a feature is represented by its footprint (referencing one or more primitives) and some parameterisation to describe its extent in 3D (such as its height). Feature types currently implemented – reflecting our interest in pedestrian navigation and gazetteer-type applications – are 'wall' (comprising lines and polygons), 'portal' (door; comprising lines or polygons), 'teleport' (lift; comprising polygons) and 'space' (comprising polygons). In addition to 3D geometry parameterisation, other attributes can be attached to features. This is the basis of the pedestrian routing described next. For gazetteer-type applications, the ability to represent and locate units of space is important.

1.2.3. Pedestrian access

All features can have a bearing on whether access is allowed through any geometrical primitive that forms its geometrical extent. This access is dependent on the pedestrian and the time at which access is attempted. Pedestrians have a maximum step height that they can negotiate and may be in possession of access keys to doors. Door and wall features have a height and may have a list of permissions (including the need to have particular access keys or swipe cards) and they may effective between different times.

Space accessible to pedestrians is delineated iteratively according to the geometry, surface morphology and features attached to geometrical primitives. This is demonstrated later in this section.

1.3. Advantages and disadvantages of the model

The model was designed to:

- Be compatible with existing 2D vector mapping data
- Allow 3D data (height) to be added incrementally
- Contain information that would allow pedestrian- and context-dependent routing, seamlessly outside, inside buildings and between buildings.
- Allow different aggregations of space to be conceptualised

It was not designed to store full and topologically-correct 3D geometry. Rather it was designed to represent the structure and connectivity of spaces in cities, aiming to straddle the domains of outdoor GIS-type models and CAD/BIM models of individual buildings, facilitating GIS-type querying inside, outside and *between* buildings. The implementation is not designed for optimal querying, particularly in its prototype state. It is slow, due to the on-demand TIN generation – this would be better cached and updated whenever new data imported.

1.4. Test dataset 1 – from Technical University of Delft

The first test dataset was supplied as KML[2] and its rendering in Google Earth is shown in Figure 3. KML is an XML-based format, and in this case, each building was represented as a polygon of 3D coordinates defining the edge of the top of each building. The polygons' attribution was such that Google Earth extruded the polygons downwards to its terrain model.

Figure 3. Test dataset 1 specified in KML and rendered in Google Earth. *Source: Technical University of Delft.*

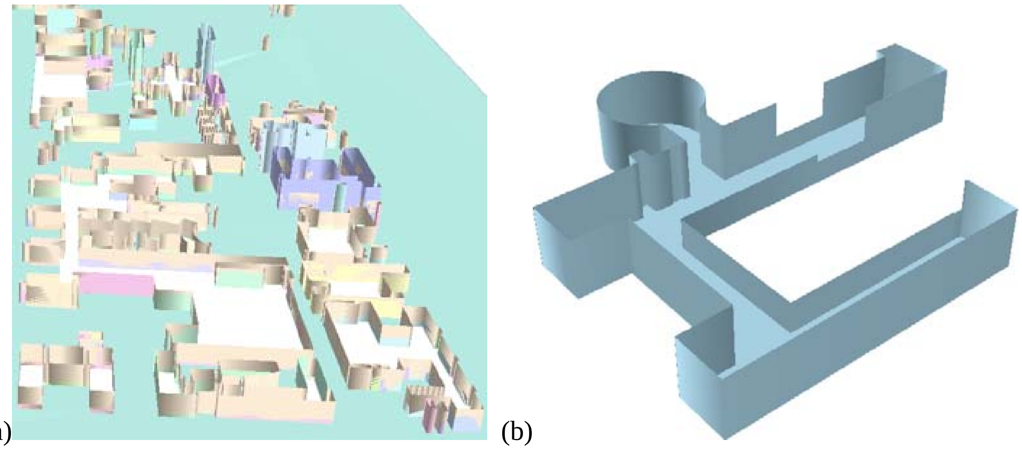
Since we use a 2.5D approach in our model, the geometry could be incorporated without much modification. We got the polygon data into ArcGIS and ran our scripts upon it to built the 2D topology that our model needed.

Slight complications were associated with the incorporation of height. To get the height of each building, we needed to subtract the polygon height from the terrain height that was within Google Earth. We were supplied with an unprocessed LiDAR model of the campus that included the buildings and trees, so it was difficult to automatically extract the terrain height at the building boundaries. Another complication was that in our model, the sides of buildings needed to be modelled as 'wall' features. The line primitives between the buildings

[2] http://code.google.com/apis/kml/documentation/kmlreference.html

and their environment were made as the basis of ‘wall’ features attributed with the height derived from the terrain model and the KML polygon heights. We also defined each individual building as a ‘space’ feature (Figure 4b). A number of spot heights for the terrain were obtained from the LiDAR model.

The result was ‘outside space’, with a completely enclosed space for each building. In terms of a model of navigable space, since no doorways were specified, outside space had no pedestrian access to any of the space inside buildings and vice versa.



(a) (b)

Figure 4. 3D Shapefile output from our model. *(a)* A query that requested all accessible space from a point that was not within a building. The result is all outside space, bounded by building walls with buildings as hollow voids, because they had no access. *(b)* A query for an individual building feature.

Once the data are imported into our model, we can do a number of queries that output the results as Shapefiles. Figure 4a shows part of the output of a query to return all accessible space (from a point outside any of the buildings). The resulting output shows all outside space and all the wall features that bound it but hollow buildings because the space within is inaccessible (completely surrounded by wall). Figure 4b shows a query to return one building feature (in this case, a polygon and the features of its boundary (a ‘wall’ feature).

This demonstrated the model’s ability to take data there are essentially 2D and incorporate selected heights from a terrain model. It also demonstrated that the model could be populated even though there was no pedestrian access information and no microscale surface morphology information existed. The algorithms that delineated accessible space still worked, though it was only affected by the presence of walls.

Figure 5. Comparision of the terrain model of a courtyard with its surrounding buildings and a photograph of the same courtyard.

Since our model is designed for both exterior and interior space, we were interested to investigate whether we could extract microscale terrain detail from the LiDAR data we were given. Inspection of the terrain model showed that the model was too noisy to be able to do this. In Figure 5, the noisiness of the terrain surface and the presence of trees, fences and cars show the difficulty in extract such microrelief. Hence, the prominent 'lump' centre right is a bike shed, while the darker area left centre against a building is a smooth apron to the left of the trees (which do not appear). It is feasible to collect some of this information from good-quality and high resolution vector mapping data (Slingsby, 2006) but this was not available to us for this area.

The key lesson learned from this series of experiments is that 3D modelling is very demanding of source data, and requires a huge amount of preparation time.

1.5. Test dataset 2 – from Technical University of Delft

The second dataset available was a CAD model (in DWG format) of an individual building, half of which contained all its storeys, lifts, staircases, doors and windows. This was approaching the detail that we sought (except context and pedestrian-dependent access permissions). However the full 3D nature of the dataset did not suit our model and we had difficulty dealing with it. The team at Delft University spent much effort producing a clean and topologically correct 3D model. The DWG geometries were arranged in ‘layers’ with helpful names that indicated their storey and what aspects of the storey they represented (Figure 6).

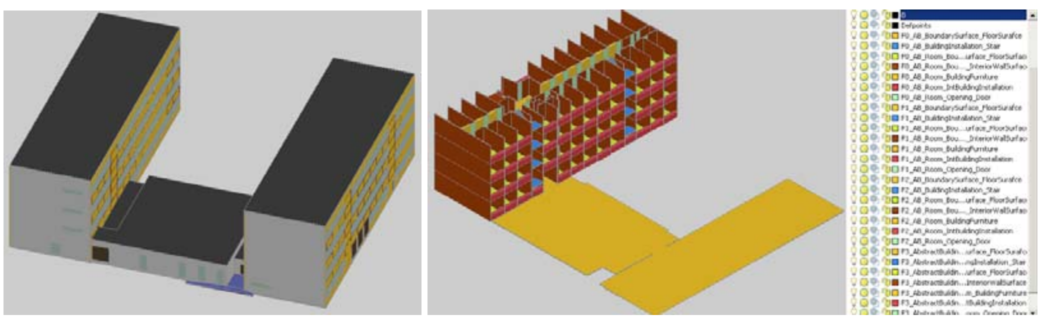


Figure 6. DWG file of the building, it’s 3D exterior view (left) and its internal structure, structured into ‘layers’ (right).

The DWG format is binary and although ArcGIS can read DWG, it cannot read DWG 3D geometries. We tried a number of software products including the AutoCAD and SketchUp, but were able to export the coordinates in text, whilst retaining the semantic information –and so the layer information was lost.

It is very unfortunate whenever digital information needs to be manually traced in order to convert into a different file format, but unfortunately we had to do this in this case. It should, of course, be technically possible to automate the output of coordinates in plain text whilst retaining the layer information. However, in our case, we displayed each layer in AutoCAD in a top-down view, exported as an image and then traced in ArcGIS to produce the input files required.

Figure 7 shows outputs of the model. Figure 7a shows that one wing of the building contains storeys connected by staircases and rooms enclosed by walls and the other wing is hollow. Figure 7b shows the view with the walls removed, showing the internal structure, Figure 7c shows the room detail and Figure 7d shows that the building is slightly raised and has a ramp leading up to the door. This is an offset edge (Figure 1).

The only difficulty we had with modelling this data was that we were not able to automatically interpret the DWG file. Otherwise, we were successfully able to represent the model as well as defining of ‘portal’ and ‘space’ features (individual rooms, in the latter case). Note that our model stores the connectivity between floor polygons and layers explicitly – the Figure 7 output is a result of a query that outputs all accessible space.

Our model is capable of richer geometries (microscale surface morphology) and pedestrian access information, which we demonstrate in the following sections.

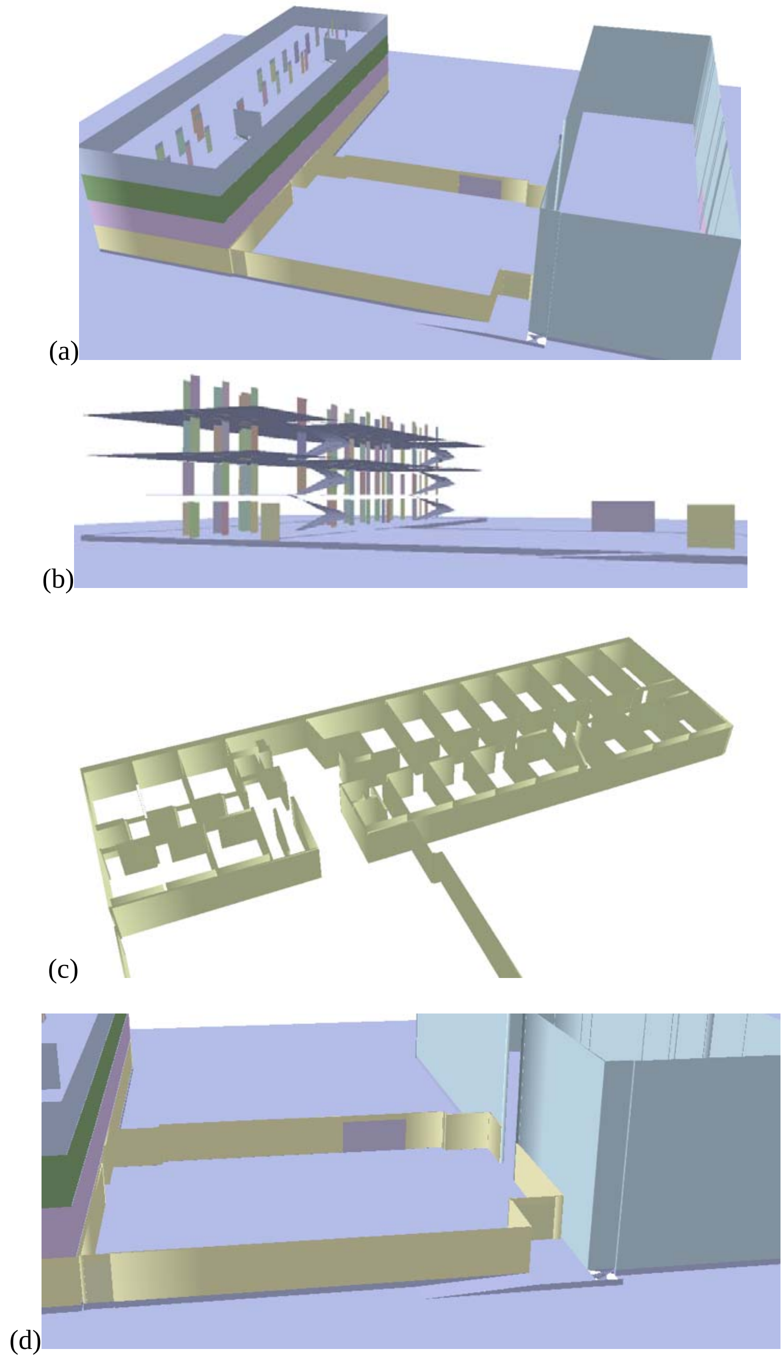


Figure 7. Outputs from model. (a) All accessible space (note that only one wing of the building has storey information. (b) All accessible space with the walls removed, showing

doors and staircases. (c) Showing ground floor only. (d) Showing the middle part of the building (only has one storey, with a ramp outside.

1.6. Test dataset 3 – (fictitional) example from 2006

Test dataset 3 is one of those used to develop the original model in 2006. It illustrates a simple scenario in which there is street with a kerb crossed by a bridge with steps on one side and a ramp on the other, adjacent to a two-storey building and with an underground area below. Figure 9 shows how some of these surface hindrances might affect access.

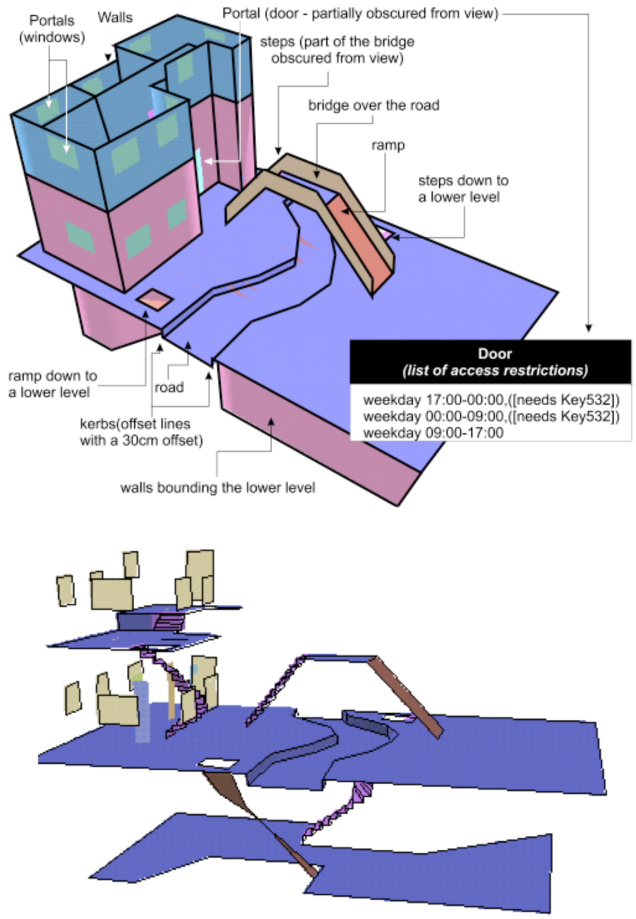


Figure 8: Annotated output of the dataset 3 scenario (above) and with the walls removed to reveal the 3D structure (below).

This was modelled in the same way as in the previous two examples and spaces accessible to different pedestrians could be queried. This example is used as an example of the type of modelling that our model was designed for.

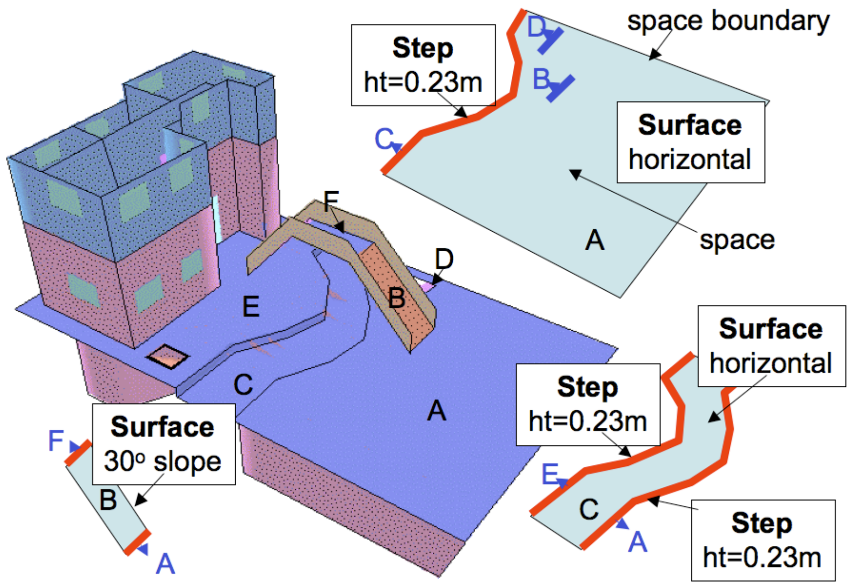


Figure 9. Potential hinderances to pedestrian movement caused by characteristics of surface morphology.

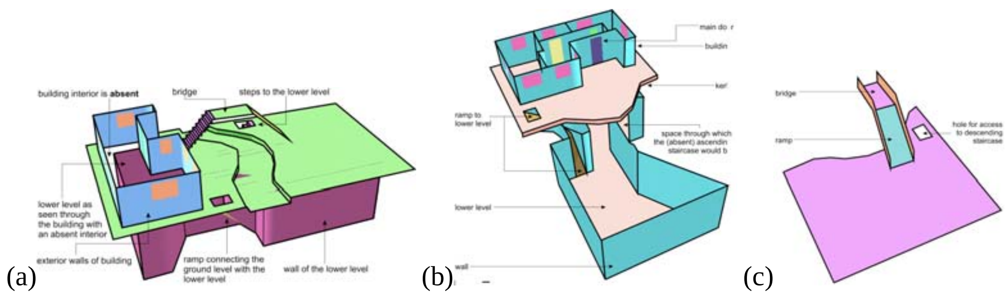


Figure 10. The spaces available to different types pedestrians. *(a)* Space accessible to someone without access to the building (note that it is hollow); *(b)* Space accessible to someone who starts at the far side of the road, has access to the building but cannot use steps (the underground space is served by a ramp, the bridge has steps on that side and the upper storey of the building is only accessible by steps. *(c)* Space accessible by someone who starts on this side of the road and cannot use steps.

1.7. Test dataset 4 – (fictional) example from 2008

The final test dataset we used was created for this project as a basis to test pedestrian routing. Our model is aimed at an application area between traditional GIS models of outside space and CAD models of building interiors. Thus, we wanted a test dataset containing outside space and more than one building to demonstrate this capability. Figure 11 shows 3D output of the accessible space and Figure 12 shows details of how the space was delineated.

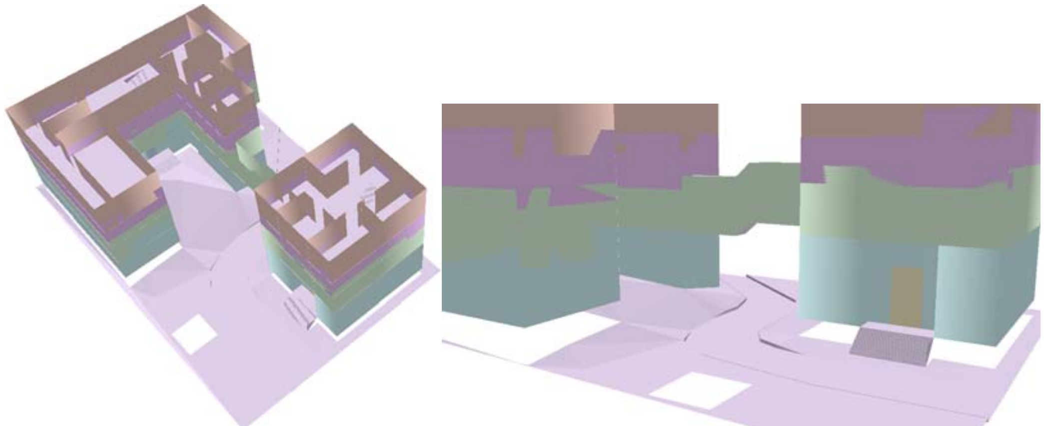


Figure 11. 3D output of example 4 from a (query of all accessible space, assuming access to buildings). Note the road with dropped kerbs, that there are two buildings higher than the terrain, reachable by steps, connected by split-level bridge and that the outside space has topography. (In this visual output, buildings appear to be hovering over the terrain).

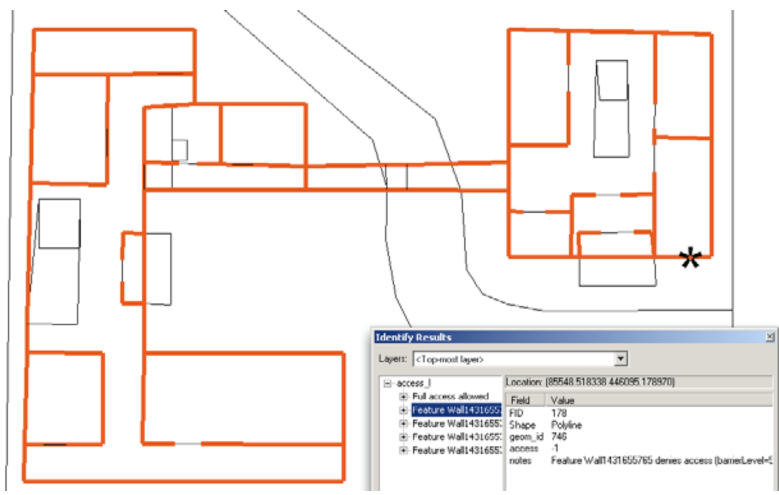


Figure 12. Algorithm output showing how the algorithm delineated accessible space. This map-view superimposes all building storeys. The thick red lines should where access was denied. The pop-up window the reason access was denied for the (superimposed) lines under the asterisk, which are wall features.

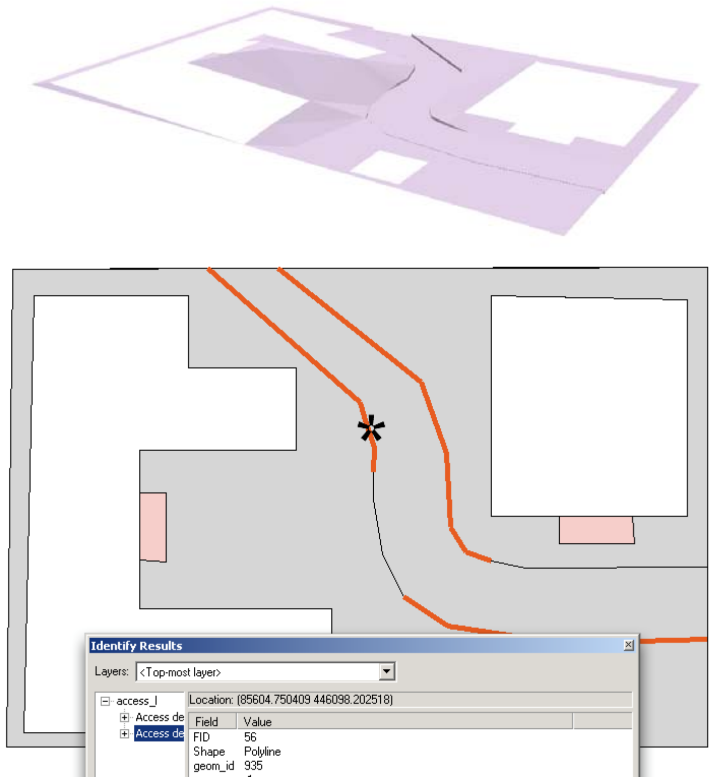


Figure 13. As Figure 12, but for a pedestrian who cannot negotiate steps. Note that no building interior is included (because of access by steps) and only the dropped portions of the kerbs allow access.

Using the same model, the space accessible to a pedestrian who is not able to use steps is delineated and shown in Figure 13. Note the effect of the kerb – this will affect the pedestrian's route. Space accessible to a pedestrian who can negotiate steps but is not allowed though the doors of all the rooms inside is should in Figure 14.

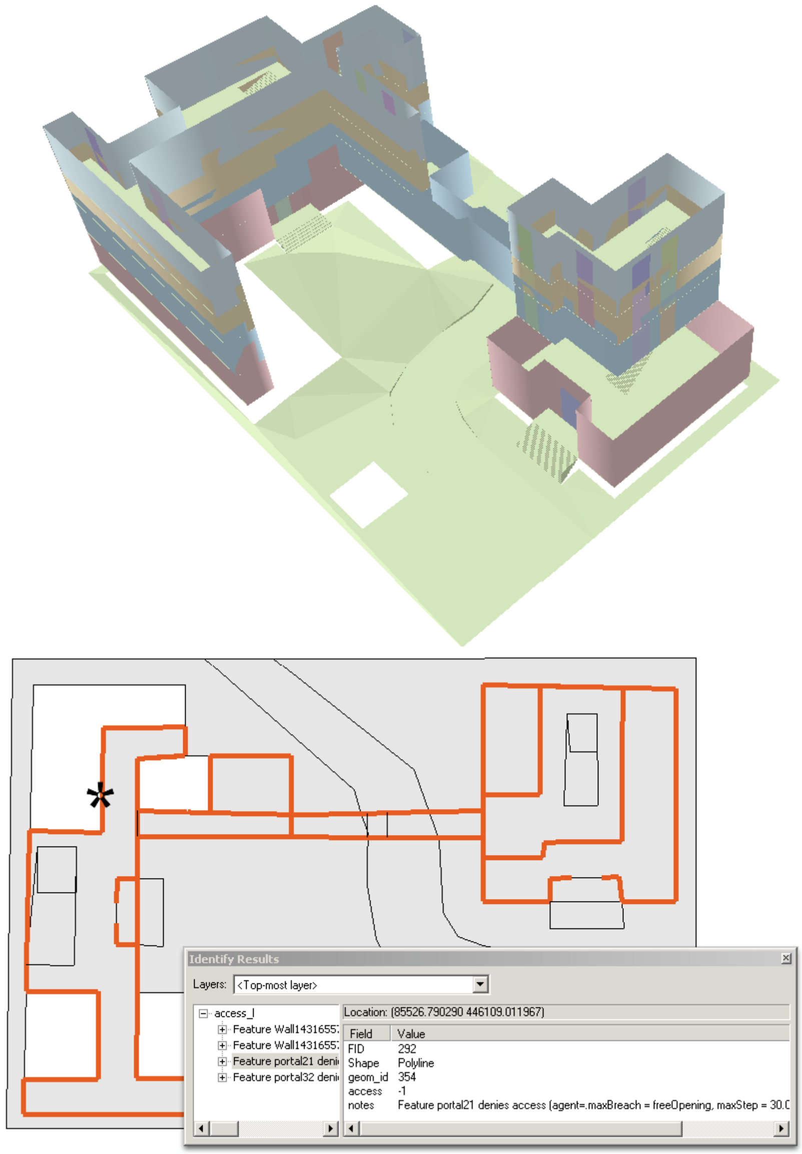


Figure 14. As Figure 12, but pedestrian has no access to any of the rooms, only the corridors.

The key lesson learned in this modelling work is the importance of floor plan interpretation and the value of semantic information about access.

1.8. Routing

We have not had time to implement any routing algorithms over this model, but we have done some exploratory work on the use of TINs to delineate routes, illustrated in Figure 15.

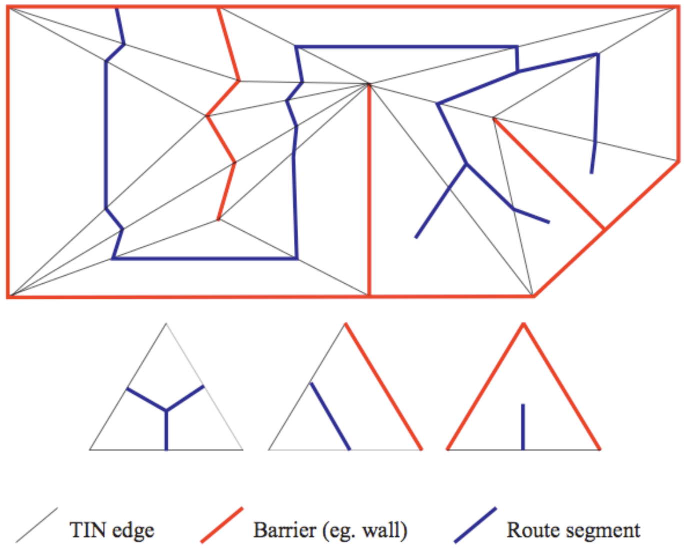


Figure 15. Experiments with using TINs for routing, where the red lines are obstacles (examples are walls, doors through which the pedestrian does not have access and the kerbs shown in Figure 13).

1.9. Conclusion

1.9.1. Data preparation and cleaning

Most topological 3D models require data that are topologically valid. By contrast, our model has the advantage of forming 3D topology in an ad hoc application –oriented way. The data preparation time and difficulty in cleaning data in this way increased the time cost of this approach. The project organisers at Delft University invested more time than expected to prepare these datasets and unable to prepare all the test datasets that were anticipated. Since good 3D city data is hard to obtain, we should establish a repository for cleaned and 3D topologically valid datasets. This has implications for data exchange formats (see below).

Although we did not need the 3D data to be topologically valid, we did require that each 2D floorplan was topologically valid (since we stored the data in a topologically-structured format). We achieved this through the use of ArcGIS and VBA scripts to prepare our data. For full 3D data, 3D topology validation is much more difficult, and something which perhaps should be considered to be a research priority in the 3D GIS research community.

1.9.2. 3D data exchange formats

Once the data were prepared, a data exchange format is required for its distribution. Even though 3D GIS has been an active research area for some time, data formats and data conversions are neither standard nor easy. Whilst our model was able to represent the two test datasets that were provided by the project, there were serious difficulties in using the 3D DWG format, which few free software tools are able to read or convert into a format that retained the non-geometrical information (attributes).

The use of KML for the first test dataset was easy to handle because it is open, ASCII-based and fully documented. The use of KML was possible because the data were 2D polygon-based, its reliance on Google Earth's DEM (which could not be exported) was problematic. In addition, the project partners whose models required valid 3D topography had to do a large amount of cleaning and consistency-checking.

With the second dataset, if the coordinates *and* the semantic could have been exported in an ASCII format, it may have been possible to build our floorplans form these, though not necessarily easily.

CityGML is an emerging XML-based standard that seems to show promise for exchanging semantically-rich 3D city models and is a format that we would like to try and work with. CityGML supports the representation of spaces within buildings at (optional) level of details and also supports the representation of some topology – but this is not required or enforced and is essentially a by-product of one of the geometrical modelling approaches it supports. The fact that it does not enforce topologically rigorous data has two implications. The first is that it should be relatively easy to transform data into CityGML. This may facilitate its widespread adoption; time will tell. However, the other implication is that the data will not be usable by the full 3D geometry models that require valid topology with the substantial difficulty of cleaning and validation of the type that caused so much difficulty in this project.

1.9.3. Data richness

Although the importance of semantics in GIS models is widely agreed, many 3D models emphasise geometrical aspects. As a result, most of the data exports available do not have much semantic information – this is what we found when trying to convert from a DWG file.

Our model was designed to allow the incremental addition of detail to 2D data. By the incremental addition of surface morphology data and surveyed heights into the model when they become available, it is intended that a good 3D model will eventually emerge. With the first test dataset, we demonstrated that we could do this. We tried to extract microscale surface morphology information from the terrain model, but found that this was not possible, due to its resolution, noise and the fine spatial resolution of the surface features that we tried to identify.

With the second test dataset, we demonstrated that we could represent multiple storeys, vertical offsets, ramps and steps. Beyond this, the test dataset was rather simple, for example all floor areas were flat. However as with the terrain model, it may be difficult to parameterise the surface in the way we require from generic 3D model input such as that produced by a laser-scanner.

Through the creation of test datasets, we demonstrated the other capabilities of our model. In particular, information on pedestrian access is at the level we require it is generally not available and we have not, as yet, managed to produce an implementation of pedestrian routing for a real example using real pedestrian access characteristics. We would like to see an extension to a format like CityGML that can encode this type of information.

1.9.4. Navigable space

We have demonstrated our model's representation of what we term 'navigable space'. We believe that models of this nature can support a range of applications related to location based services (data services depending on position in the environment), gazetteers and application of quantitative geography; the latter two where the identification and connectivity of spaces in the environment is required. However, obtaining all the data required to implement such application fully remains the largest obstacle to progress.

2. Review of 3D-GIS developments in the Far East

In addition to our practical tests with 3D data, we conducted a literature and web search for examples of 3D city models in order to benchmark examples of good practice around the world. In the course of this review we noted that many of implemented 3D models extant were in the Far East. As the 2007 'Location Based Services and TeleCartography' conference was being held in Hong Kong the City University 3D GIS team put together a tour of 3D GIS system developers in the Far East to explore work in this area and build international links for the project.

The programme for the tour was as follows:

5th November 2007 ESRI Japan, Tokyo
We met the Chiharu Masaki and his management team at ESRI Japan and were briefed on their system integration work with 3D data. We also corresponded with Yoko Tamura of the affiliated Pasco Corporation about the MapCube project:
http://www.pasco.co.jp/global/english/solutions/data_services/index.html

5th November 2007 Centre for SIS, U. of Tokyo
We met Profs Arikawa, Sezaki, Konomi and Shibasaki of CSIS who gave us a series of talks on the research at the centre including pedestrian navigation with 3D city models on mobiles.
http://www.csis.u-tokyo.ac.jp/english/index.html

5th November 2007 YRP Lab, U. of Tokyo
We met Prof. Sakamura of the YRP Lab who is researching the applications of RFID tags as digital infrastructure for a range of applications including pedestrian navigation, and who has developed a 3D city model viewer.
http://www.ubin.jp/english/index.html

6th November 2007 Hankuk University, Seoul, S.Korea
We met Prof YongJin Kwon of Hankuk University to discuss Korean applications of LBS and in-car navigation, which include 3D city models. We saw demonstrations of the semantic browsing approach to LBS being developed.

7th November 2007 Korea Adv Inst Sci & Tech - ICAD, Daejeon, S.Korea
We met Prof Soonhang Han who showed us the work done by Byounghyun Yoo "Image-based modelling of urban buildings" and published in Transactions of GIS in 2007.
http://icad.kaist.ac.kr/renewal/file/main/main.html

7th November 2007 Korea Adv Inst Sci & Tech- Ubiquitous Space Research Center of KIUSS, Daejeon, S.Korea
We met Seongju Chang Director of KIUSS to discuss the role of 3D city models in S. Korea's u-City research initiatives.

7th November 2007 Woodai Cals, Seoul, S.Korea
We met Mr Lee and Mr Kim of Woodai Cals Strategic Planning Center to see a demonstration of their EarthVisualizer software, as used in the comprehensive 3D city model of Seoul (called UPIS) made in collaboration with Seoul city government. Mr Lee subsequently attended the 3D Geo conference in Delft in December 2007.
http://www.wdcals.co.kr/eng/index.htm

8th November LBS & TeleCarto Conference, Hong Kong
We attended the LBS and Telecarto conference at which a number of papers were given about 3D city models and LBS.

http://www.lsgi.polyu.edu.hk/LBS2007/

9th November Chinese U. of Hong Kong
We visited Hui Lin's group at the Chinese University of Hong Kong who do work with Virtual Geographic Environments that enable users as avatars to explore and interact with models in 3D map-based environment. Examples of some of the innovative work include investigating the use of innovative natural interactions (e.g. gestures and speech) to interact with data and models. Exploring air quality models and pedestrian evacuation models in 3D city environments were two of the PhD projects that were in progress during the visit.

We made a video presentation of the various systems we saw on our visit and presented this at the 3Dgeo conference in Delft.

3. Participation in the two 3D GeoInfo conferences

During the project period, the second and third 'International Workshop on 3D Geo-Information (3DGeoInfo)' workshops were hosted in 2007 by the University of Delft and 2008 by the University of Seoul, respectively. We contributed papers to both.

3DGeoInfo07 was preceded by a useful Project meeting, at which the various partners demonstrated their work to date. The first test dataset had been made available and the each partner gave an account of their experiences with using the data. The issue of topological validity was an important theme in the meeting. There was also discussion about data formats, indoor models and integrating city-wide models with models of the natural environment. The conference itself was well attended and had a good selection of papers covering diverse aspects of 3D research. In addition to the paper sessions were themed discussion groups on these topics.

3DGeoInfo08 was less well attended and had no specific discussion groups organised, but was nevertheless a useful conference. It seems to us that there is increasing interest in indoor modelling and routing, based on the number of papers on this topic present at the meeting this year.

4. Comparing geological approaches to 3D modelling using DGI EarthVision software

As the project aims were to compare different 3D data structures we also considered the scope of 3D modelling systems in cognate areas. We were able to obtain access to one of the petroleum industry's most sophisticated 3D modeling packages earthvision 7.5 ('ev') from Dynamic Graphics and run it at City University.

ev is a true 3D modelling system in that it has a three axis referencing system, which allows representation of property at x, y, z whether in the earth, ocean or atmosphere. It has been used mostly for petroleum exploration, however, it is also suitable for environmental modelling, civil engineering models and space-time movement models. ev can represent surfaces, solids and planes that intersect other features arbitrarily ('fault' in geology), and can represent property variation within each structural element bounded by model edge, surface or plane. Complex models are assembled by adding in elements using a structure builder until the model is complete. This is a sophisticated approach allowing models of great complexity, but it makes modifications of the model very expensive.

However, the ev system can be used for space-time movement models such as the one shown in figure 16, which can be displayed over maps in 2D or 3D. This may be a valuable application of software developed for geology in the planning and urban modelling domain.

It is recommended that the more mature domains of 3D geological and medical modelling are further explored for 3D city modelling software and data structures.

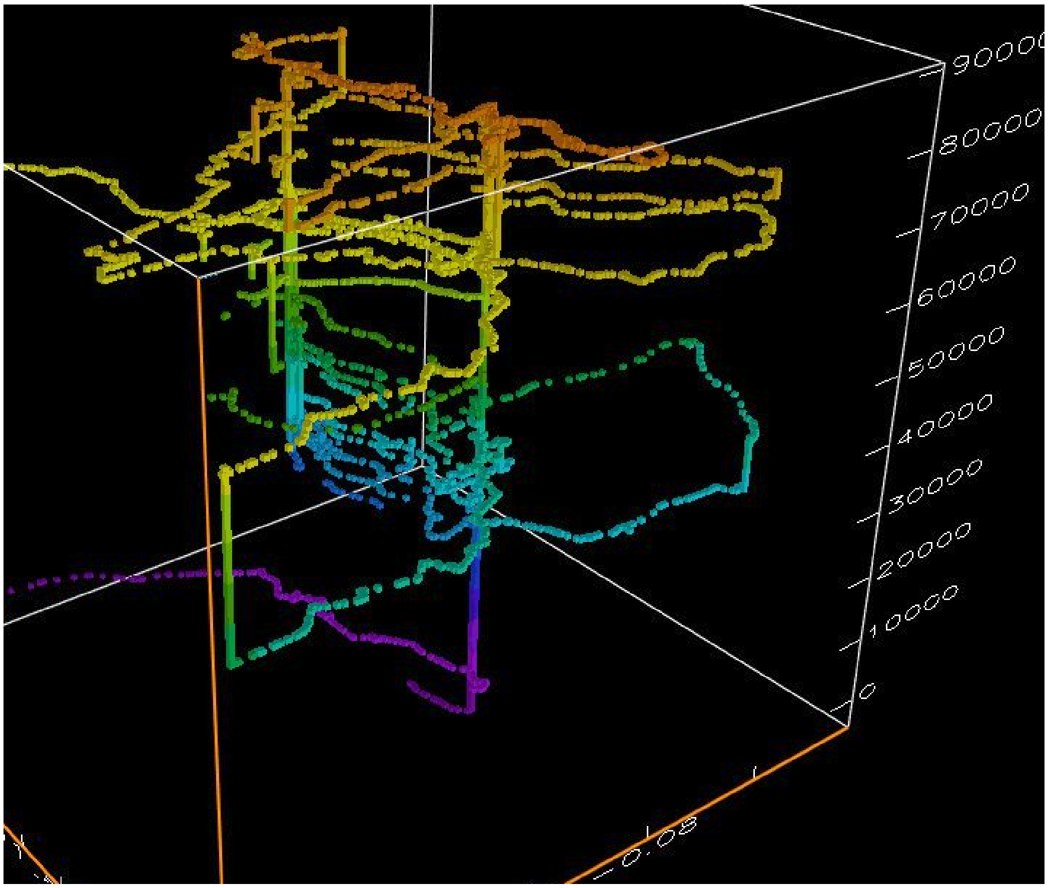


Figure 16. Space-time movement model for an individual moving around London: the x and y axes represent geographic space and the z axis represents time in seconds after midnight, which are coloured for ease of reference in 3D

5. Funding proposals and further work

This project has demonstrated to a number of us of the importance of 3D topology for validation and for applications. Chris Gold has suggested an informal working group through ISPRS Working Group on 3D and Mobile GIS under Commission II, in which we discuss and try to come to a consensus.

City University is engaged in preparatory work towards a 3D GIS research proposal to the UK Engineering and Physical Sciences Research Council with Chris Gold of University of Glamorgan. We will support any European actions in this area.

6. Conclusions

In conclusion, the funding under this project has been invaluable in supporting the:

- reviewing of 3D modelling methodologies and systems
- travel to see other advanced 3D modelling systems
- development of comparable 3D models using common datasets from Delft
- participation in the 3Dgeo conference series

The emergent research issues from our participation in the project are the importance of:

- 3D topology
- Data exchange formats for 3D data
- Repository of topologically valid 3D models needed

We thank the RGI Programme for its support and look forward to further co-operation in future.

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