A SIMPLE DATA STRUCTURE FOR 3D GIS MODELLING

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Abstract

Building models are utilized in many applications. For example, in Goole Earth buildings are represented as simple polyhedra for visualization of big areas like cities; complex models including a building interior are essential for analysis like simulation of rescue operations. But separate buildings may be not very useful without information about their exterior (e.g. a surrounding terrain or a transportation network) and interior (e.g. internal building structure including rooms, corridors, doors, etc.). Combining all elements into one model where the elements are connected makes further analysis possible.

The CityGML exchange format is becoming more and more utilized by many researchers and organisations to represent city models. Despite a standard or exchange format used for model storage a spatial data has to be represented somehow in a computer memory. With the new data structure, the dual half-edge (DHE), which is related to the quad-edge, half-edge, and radial-edge data structures, the geometry and topology can be represented in one consisted model. In a simple case a model is represented as a cell complex where the cells are linked together by dual connections. The only entities used to build the model are edges and vertices. They are connected using pointers and form a graph. Thanks to the Poincaré duality implemented in this solution faces and cells are represented by dual edges and dual vertices respectively.

The DHE was tested on building models imported from the CityGML format, and reconstructed from paper plans using a CAD system to create a preliminary geometrical model. Standard graph traversal algorithms can be used in spatial analysis of the model. Escape routes from a building were calculated using the Dijkstra algorithm (the shortest path calculation from a room to the closest exit).

Keywords: *3D modelling, data structures, topology, building management*

1. INTRODUCTION

Kwan and Lee (2005) proposed a use of 3D models to improve simulation efficiency; they allow for a more accurate phenomenon or object representation. But usually they are bigger and more detailed, thus demand more efficient algorithms and structures for analysis. Fortunately, complex simulations not possible a few years ago are viable thanks to technological developments which provide more powerful and faster computers.

In GIS building models represented as a simple block are usually positioned geometrically on the ground surface without topological connections between the building and the ground which prohibits advanced analysis such as flow over the ground surface and around buildings and through tunnels. Also CAD structures do not fit the topological model assumed in GIS.

Probably IFC (Industry Foundation Classes) (ISO/PAS 16739, 2005) and CityGML (OGC, 2012) standards are the most discussed in the literature. They both allow for storing information about a building structure. However from the GIS point of view the CityGML is more practical – transportation network, vegetation, water bodies etc. may be also included in a model. Thus there is an effort put into translation from IFC to the CityGML format (Isikdag and Zlatanova, 2009). CityGML is gaining great interest from many researchers and organisations and is successfully utilized but the topology representation is very basic and limited.

A different data structure is required to allow for full 3D modelling with the geometry and topology included. In a case of building interiors multiple volumes are necessary to represent rooms, corridors, etc. They can be represented as cell complexes. It was shown that 3D objects can be effectively adopted as mathematical models with 3D cell complexes (Dobkin and Laszlo, 1987; Lee and Lee, 2001; Masuda, 1993).

2. THE DUAL HALF-EDGE (DHE) DATA STRUCTURE

The DHE (Boguslawski and Gold, 2011) is a new data structure based on the augmented quad-edge (AQE) (Ledoux, 2006; Ledoux and Gold, 2007) which uses the quad-edge (QE) data structure (Guibas and Stolfi, 1985) to represent individual cells. The QE operators are limited to navigation within a single cell, and adjacent cells remain unconnected. Navigation between the cells was solved by using the dual graph to link pairs of adjacent cells. Ledoux and Gold (2007) showed that the AQE and navigational operators are suitable for 3D Voronoi/Delaunay structures however, the construction operators were complex and arbitrary 3D models were not supported. The DHE is a modification of the AQE and is related to other data structures: facet-edge (Dobkin and Laszlo, 1987), radial-edge (Weiler, 1988) and half-edge (Mäntylä, 1988).

The DHE was developed to build 3D object models, especially building interior models which can be used in emergency management systems. Models are composed of cell complexes where all cells are connected by an adjacent face, for example a building with rooms represented as cells. In addition to cells representing an object, there is also an external cell which encloses the rest of cells in the complex. It can be considered as ‘the rest of the world’ – its volume is infinite. This external cell prevents the topological inconsistency at the boundary of the model where cells do not have an adjacent cell to connect to. Additionally navigation in the complex can be implemented without testing if a boundary of a model is approached.

Duality is an important idea, which lies behind the DHE. 3D Poincaré duality rules (Munkres, 1984) are defined in a following way: for a space of dimension d and an element of dimension $k<=d$ a dual element exists of dimension $d–k$. Thus in 3D a vertex has a dual cell, a face has a dual penetrating edge, etc. (see Figure 1). This reduces the number of entities in the representation to two: edges and vertices. For example, a cell is represented as a single dual vertex – a special class to represent a cell is not required: properties of a cell (e.g. ID, volume) can be assigned to its dual vertex; the same applies to a face – properties of a face can be assigned to its dual, penetrating edge.

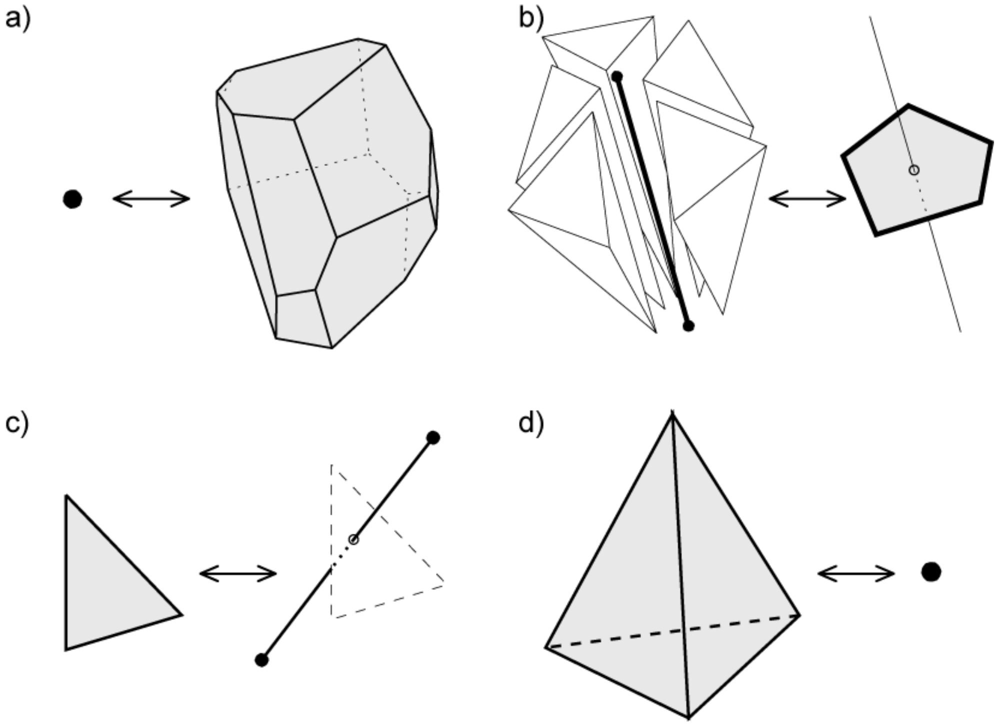

Figure 1: Poincaré duality. (Ledoux and Gold, 2007)

DHE models consist of two structures: in the primal and in the dual space; they are represented as graphs with complete symmetry between them – without a special flag it is not possible to find which graph is navigated at the moment; entities, connections and navigation in either graph is organized in the same way. For the sake of clarity the primal is considered as the geometry of a model, while the dual represents the topology (connections between cells).

In the example presented in Figure 2 two adjacent cells are linked by a common face. The dual edge representing the face links two dual vertices. Technically, the dual edge is a bundle of dual edges – the number of dual edges is the same as the number of edges forming a face. Because navigation around the bundle is possible (a radial cycle) the bundle can be considered as a single edge.

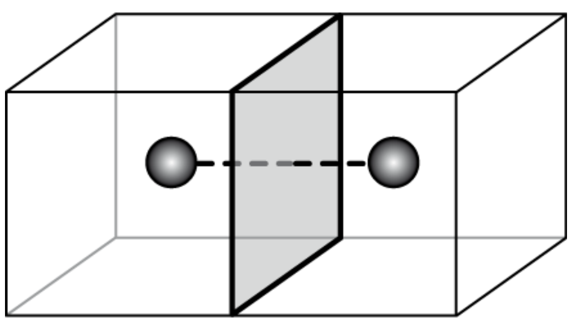

Figure 2: A dual edge (dashed line) represents a shared primal face (grey) and links two adjacent cells.

A single edge is the smallest possible element which can be considered as a consistent model – however, each edge consists of two linked half-edges; each one is associated with the dual half-edge. An atomic element, the dual half-edge, is represented using ten pointers to store references to vertices and topological information: V, S, NV, NF, and D in each space – five in the primal and five in the dual, where: V is a reference to a vertex; S – a second half of the edge; NV and NF – the next half-edge around a shared vertex and shared face respectively (the next in anticlockwise direction looking from the outside of a cell); D – the dual part.

A vertex, which does not store any topological information, represents a point in 3D space. A vertex with unique coordinates is stored only once and a reference to this vertex is used where required.

A set of construction operators, associated with the DHE, allows not only for complexes with cells linked by a shared face, but also by shared edge, and vertex. One of the subsets, Euler operators (see Figure 3), conforms to CAD systems. The construction process is as simple as adding edges one by one to obtain a polyhedron. It is also possible to define a sequence of Euler operators necessary to create a new cell or cell complex. The same sequence performed in the reverse order using reverse operators can be used to implement the ‘Undo’ operation.

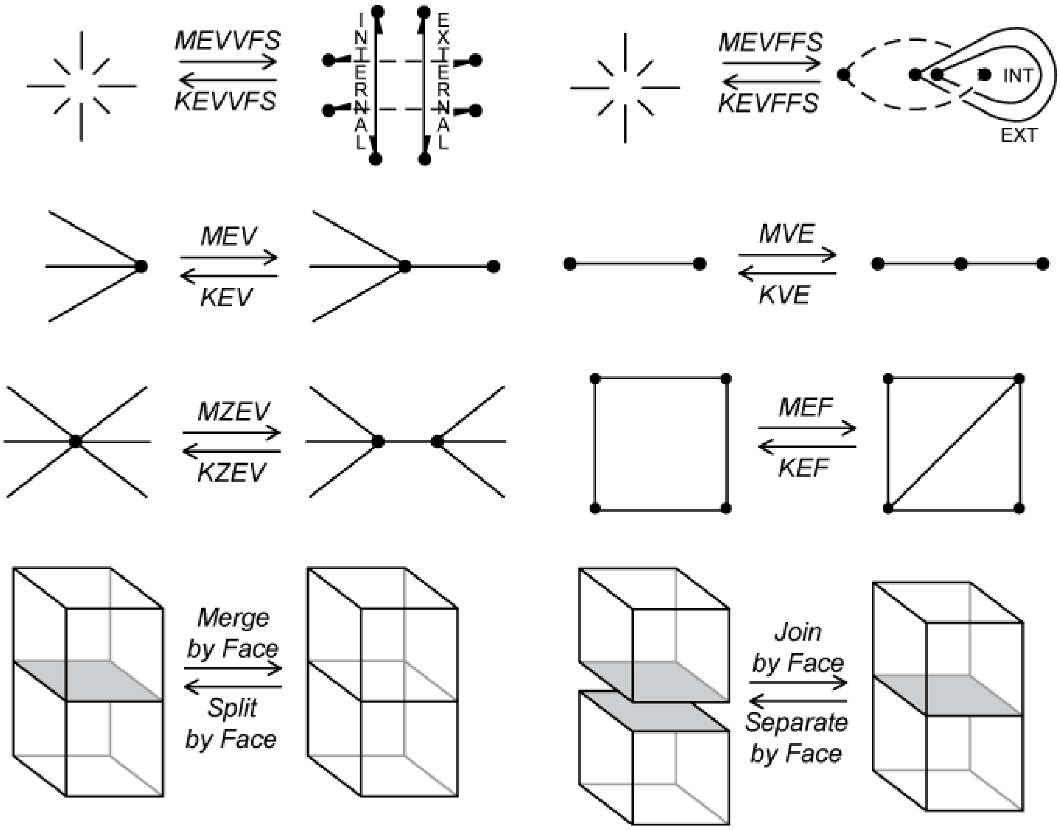

Figure 3: Euler operators and extended Euler operators (the dual and external part is shown only in a case of MEVVFS and MEVFFS).

An important advantage is that the dual graph of connections is constructed automatically during the construction of the primal, the geometry. All changes of a model are done locally therefore it is not required to update all the dual connections individually which would be time consuming.

3. CITYGML MODELS

The DHE data structure described in the previous section may be used to reconstruct CityGML models. The idea of model representation proposed in CityGML format (OGC, 2012) fits to the DHE – basically, models are represented as solids with defined faces, edges, and vertices. Thus, they can be easily converted and modelled with the DHE. A big advantage of the DHE is that topological connections between adjacent rooms may be automatically detected and stored in the model. However, it may be necessary to modify some cells before the connection. For example, adjacent cells may have faces of different shapes or sizes; in this case new edges are added where required and then cells can be connected.

It should be noted that only adjacency relationship can be detected; no overlapping detection and validation methods are currently provided. This fact does not downgrade the value of the data structure which is very general and suitable mechanisms (e.g. validation) may be developed depending on the implemented application.

An example presented in Figure 4 shows a model of a house reconstructed from the CityGML format (the original dataset is available from www.citygml.org). The model is represented in the highest level of detail – the interior with rooms, walls, and furniture is present. Data quality is very good thus, no validation is required. However topological relations are not present in the original data set; they are reconstructed automatically while the geometry of the model is reconstructed and the adjacency relationships between elements are detected.

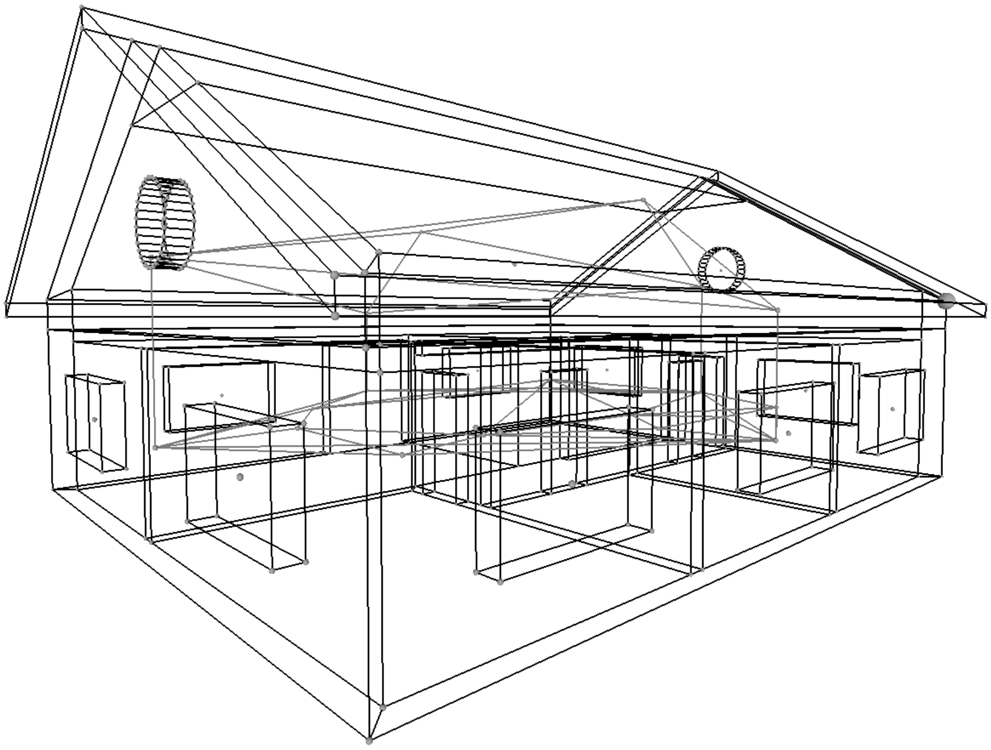

Figure 4: A model of a house reconstructed from CityGML. (Source: www.citygml.org)

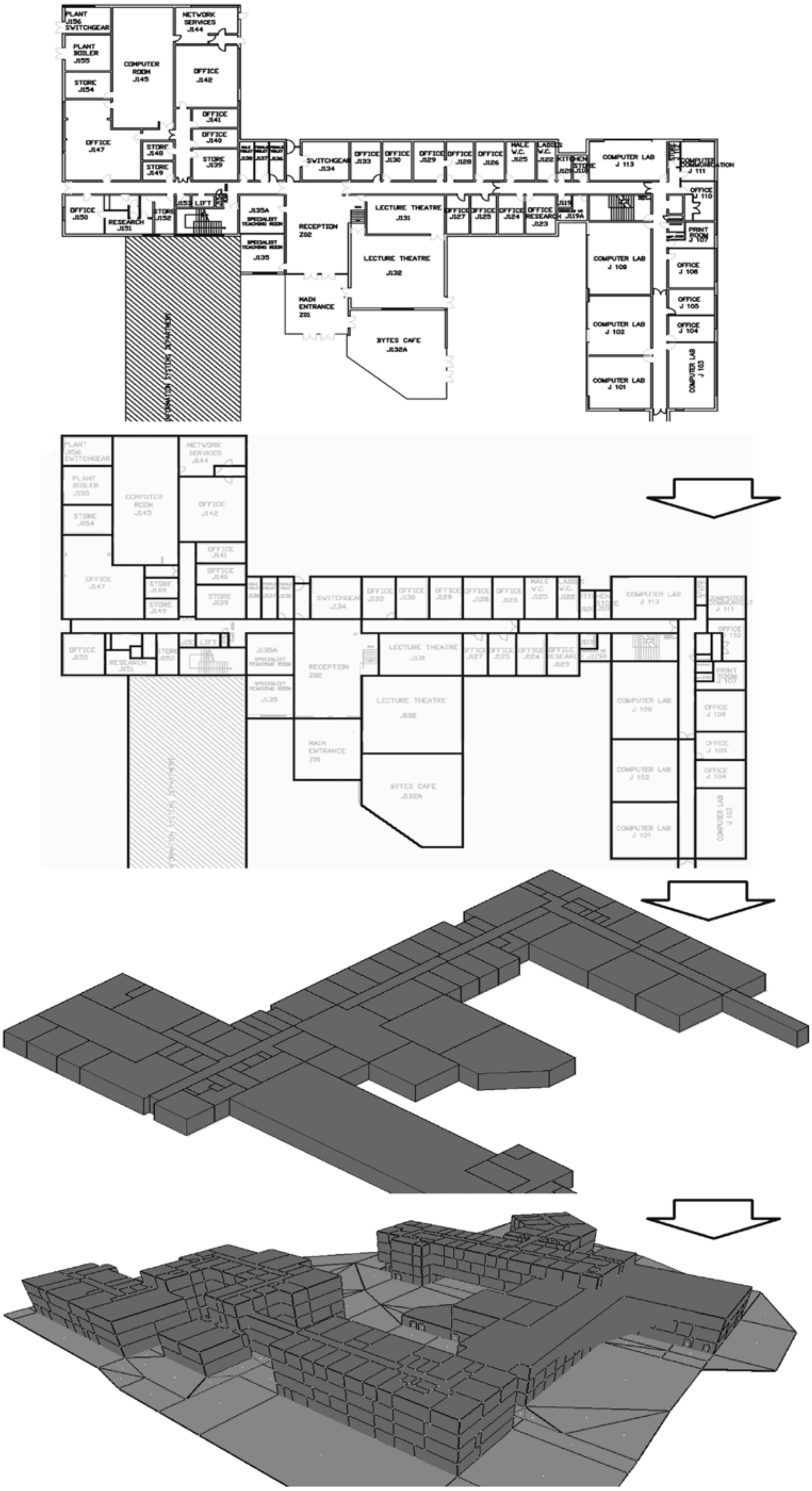

Figure 5: A 3D model reconstructed from paper plans.

4. MODELS RECONSTRUCTED FROM PAPER PLANS

Another source of models may be paper or architectural plans. The reconstruction process is shown in Figure 5. First paper plans are scanned and used as a texture background layer in a CAD system, e.g. AutoCAD. In the next step all rooms, corridors, and doors are outlined (vectorised) and represented as polygons – this is done for all levels in the building. Then outlined objects are extruded to the height of a single floor**:** in this way that there is no gap between neighbouring levels. The model can be enriched with the external terrain. At this stage the model is represented as a set of separate cells which can be used for visualisation but not for analysis. To use the model in analysis, like escape route calculation or looking for the shortest path between rooms, the topological relations between elements must be reconstructed.

All these connections are set during the construction process using the DHE and Euler Operators – to check the adjacency between elements geometric intersection testing routines were used. The primal and the dual graphs are simultaneously updated.

5. ANALYSIS

The model presented in the previous section was created with the intention to use it in emergency systems for finding escape routes from a building. In this case only cell adjacency by a shared face is taken into consideration. To avoid navigation through solid walls the connections between rooms are associated with weights – an infinite value means no access, any other (positive) value is computed from the geometric distance between the dual nodes representing adjacent cells. In the presented example (see Figure 6) navigation between two rooms is available only if there are doors in between – only these connections have a positive weight, the rest have an infinite value. The door is represented as a flat cell (zero volume); in the dual the node representing this cell is connected with two dual nodes representing adjacent rooms.

A different rule is used in a case of the terrain – navigation between all cells representing the terrain is allowed.

In a real life emergency assembly points are usually located outside buildings. Thus the surrounding terrain included in the model is essential for emergency simulations. It is not enough to geometrically adjust a building to the terrain model. They must be topologically connected into one consistent model. Otherwise analysis is not possible or the efficiency is impaired.

To analyse DHE models graph traversal algorithms can be used. For example, the Dijkstra algorithm was used to find escape routes from a building – they can be computed for each room in the building; one of them is presented in Figure 6: the shortest path (grey cells) from the preselected room (black cell in the distance) to the closest exit (black cell on the front).

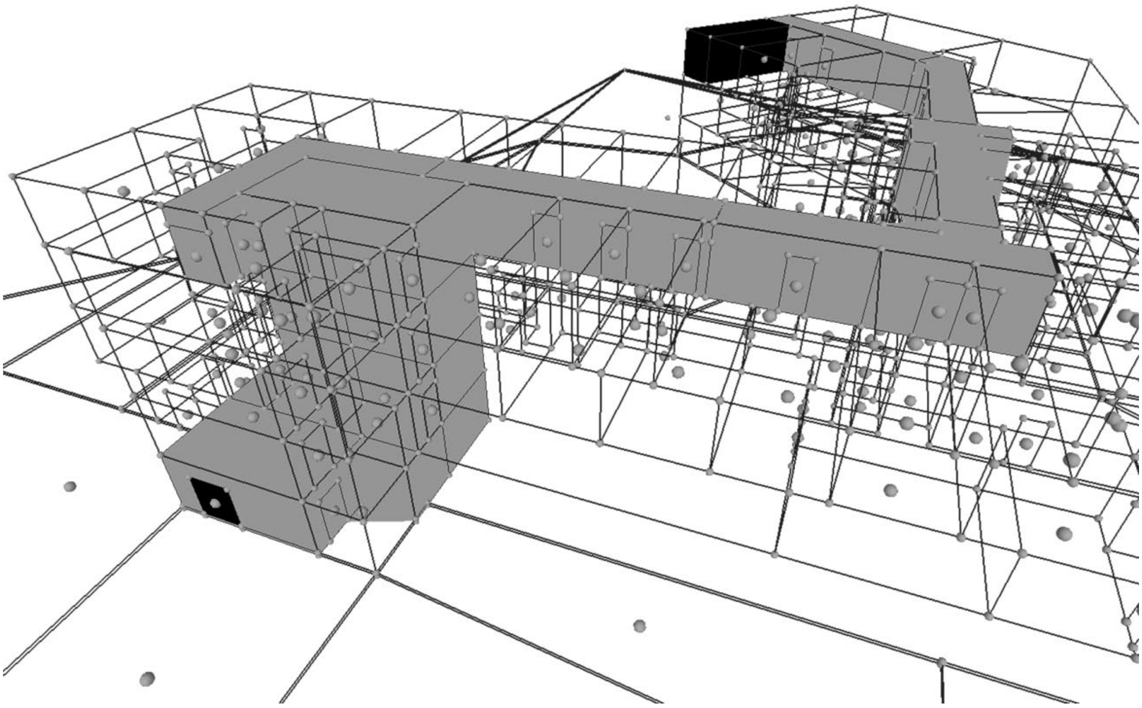

Figure 6: The shortest path between a preselected room and the closest exit.

6. CONCLUSIONS

The DHE is a general data structure which can be used for 3D spatial modelling. Models are constructed using edges and vertices; other entities, like faces and cells (volumes), are represented by dual edges and vertices – this significantly simplifies the data structure.

Building modelling is only one of many possible applications. Different building representations also depends on application: walls between rooms can be modelled as thick cells (e.g. the CityGML example), or can be not considered – adjacent rooms are linked directly (e.g. the building model reconstructed from paper plans). The DHE may be also used in models based on cell complexes, e.g. models used in the FEM (Finite Element Method) are represented as cell complexes.

Because topological relations are reconstructed in DHE models, they can be used for GIS analysis. These relations increase the storage cost but they are crucial to answer spatial queries which is important for real-time simulations, e.g. emergency management systems used in disaster centres. Changes can be quickly introduced into the model as real events take place – construction operators modify the geometry of the model simultaneously with the topology, and all the changes are made locally.

7. ACKNOWLEDGEMENTS

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