A 3D data model and topological analyses for emergency response in urban areas

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ABSTRACT: 3D geospatial information has always been a challenge due to a variety of data models, resolutions and details, ways of representation (b-reps, voxel, SCG), etc. After 9/11 the interest in 3D models (buildings or undergrounds) for emergency responses is progressively increasing. Such models are mostly available from the design phase (as CAD models). Design CAD models are in most of the cases too detailed for computing, for example evacuation routes. Therefore, this chapter is motivated by the need of a new data model to represent and to analyze 3D geospatial data in emergency management systems for field workers and decision makers. This chapter reviews 3D data models developed for geometric or topological representations of 3D objects and proposes a 3D Data Model for emergency response to represent urban built environments in multi-levels. The proposed data model is a composite model integrating: 1) 3D geometric model to measure and represent 3D spatial objects geometrically only, 2) 3D topological model to represent only the topological relationships among the 3D objects using a network-based model, and 3) 3D city model to visualize the 3D objects in multi-views.

1 INTRODUCTION

Human-induced disasters such as fires and the terrorist attacks on September 11th, 2001 (WTC, New York), March 11th, 2004 (Madrid) or July 7th, 2005 (London) usually occur on the micro-space of multi-level structures (such as buildings) in urban areas. Such disasters not only affect multi-level structures in urban areas, but also impact upon their immediate environment at the street level in ways that considerably reduce the speed of emergency response. The complex internal structures of built environments and the traffic bottlenecks at the street level also make speedy escape or rescue particularly difficult in any emergency situations (Kwan & Lee 2005). Reducing rescue time can have a significant impact on evacuation in disaster environments. Geospatial researchers have learned that the availability, management and presentation of geospatial information play a critical role in disaster management, especially in 3D urban space such as large public buildings, shopping centers, underground metro (subways) and garages. However, most current GIS-based emergency management systems for earthquake, floods and other disasters have been developed using 2D GIS with 3D visualization systems. The systems have limitations in representing the micro-scale urban areas in 3D space, such as the complex internal structure of buildings, as well as in analyzing human movements during emergency situations in micro-scale environments.

With the goal being to achieve a real-time emergency response system for evacuations in 3D GIS, this chapter focuses on developing a 3D data model to represent urban built-environments including the interior structures of buildings and on 3D spatial analysis functions used for emergency responses such as 3D navigation and 3D buffering.

Section 2 of this chapter reviews 3D data models developed for geometric or topological representations of 3D objects, and Section 3 proposes an 3D Data Model for emergency response, which is a composite model integrating three data models: 1) 3D geometric model to measure and represent 3D spatial objects geometrically only, 2) 3D topological model to represent only the topological relationships among the 3D objects using the network-based topological model, and 3) 3D city model to visualize the 3D objects in micro-view. The following section describes the algorithms of 3D spatial analysis functionalities. In the fifth section, the output from implementing the emergency response system is discussed. And, the final section discusses several significant substantive insights derived from this study.

2 REQUIREMENTS OF EMERGENCY RESPONSE SYSTEM

In general, emergency management is described in terms of how societies respond to disasters. These responses are a 4-stage cycle of emergency response phases: mitigation, preparedness, response and recovery (Cutter 2003). The mitigation phase is related to activities leading to a reduction of occurring emergency situations, and the second phase is the active preparation for any following unexpected events. Response is an acute phase after an emergency, while recovery is a phase after the acute emergency including all arrangements to remove arisen detriments and long-term supply of irreversible detriments (Zlatanova & Holweg 2004). Geospatial technologies have been used throughout all phases of the emergency response cycle, although more in some phases than others. Especially, systems to support decision makers in the phases of mitigation, preparedness and recovery are in use, but the number of systems for technical support in the response phase is quite limited (Zlatanova & Holweg 2004), which requires time-critical response. The emergency response system, one of the time-critical applications (TCA), is related to decisions that have to be made by a human decision maker in emergency situations. The geospatial technology supports the decision maker in getting several rescue strategies derived from the highest quality and quantity of spatial data. The GIS based decision support system in areas of TCA requires appropriate data management and efficient data discovery and integration to facilitate the decision makers whenever they need to make a decision in real-time.

In order to respond to emergencies in real-time, Kwan & Lee (2005) proposed GIS-based Intelligent Emergency Response System (GIERS) and evaluated the potential benefit of a 3D GIS for improving the speed of emergency response. The experiment demonstrates that response delay within multi-level structures due to the indoor route uncertainty can be much longer than delays incurred in ground transportation in terms of the street network uncertainty. The results express that extending conventional 2D GIS to 3D GIS representing the internal structures of high-rise buildings can significantly improve the overall speed of rescue operations. Such an output motivates geospatial scientists to develop an intelligent emergency evacuation system of complex buildings using 3D GIS (Meijers et al. 2005) integrated with Intelligent Transportation System (ITS) technologies, called an Intelligent Building Evacuation (IBE) System.

In terms of TCA, the 3D GIS-based emergency response system has to fulfill requirements similar to 2D GIS but and some specific for the 3D domain (Cutter 2003, Zlatanova and Holweg 2004):

- Dynamic and multi-dimensional representation of physical and human processes – the system incorporates important geospatial data about the emergency situations, represented by combined indoor (3D models) and outdoor (more traditional geospatial data) data models, which also deal with dynamically changing and uncertain disaster environments such as current availability of exits, stairs and the characteristics of the evacuees (age, gender, disability).
- Spatial data acquisition and integration – data updated with newly collected data from the field can be very critical for both a) monitoring the disaster events and b) giving instructions to the involved people. From a database point of view, this process requires 3D position utility to determine the event locations, and strict consistency rules for integration with existing models and immediatly propagating the information to all the users;
- Interoperability for data integration and semantic/data discovery – the integration of multiple systems and databases become a critical issue to develop the emergency re-

sponse system, in order to access data from multiple data sources. In this respect, integration of CAD (3D indoor models) and 3D GIS (3D outdoor models) is becoming of critical importance

- 3D spatial analysis – incorporate dynamic geospatial data about the emergency situation, as well as have spatial-temporal analytical and modeling capabilities to facilitate better planning and decision making on emergency responses, for example, 3D topological analytical methods (3D buffering, overlap, intersect, etc.) and 3D shortest route analysis functions.
- Mobile and wireless communication – the ability to provide updated information (3D graphics, images, etc) to rescue units, decision makers and citizens fast, almost in real-time, through communication technologies to transfer on-site information. 3D presentations (and especially vector interactive models) may result in large data files and require wide bands and special treatments (e.g. appropriate selections of data and generalizations)
- 3D visualization – data presentation on handheld and desktop, wired and wireless equipments.

The emergency response system this chapter discusses is a spatial decision support system that facilitates coordination and implementation of emergency response operations such as pedestrian evacuation and rescue within micro-scale urban indoor space. One important similarity of these multi-level structures is that they involve compartmentalized zones or areas connected by complex transport routes such as corridors. In addition, different levels of these structures are connected by a limited number of vertical conduits such as elevators and stairways. Many GIS-based analytical techniques can be applied for directing quick evacuation or rescue in these micro-spatial environments if their internal structure can be represented using a navigable 3D GIS data model (Lee 2001). Further, as the horizontal and vertical conduits within multi-level structures are ultimately connected to the ground transportation system, much would be gained in emergency response through establishing a real-time 3D GIS that links together the traffic systems within these structures with the ground transportation system.

To base an evacuation model on spatial analysis and modeling, a navigable data model of the building interior(s) and a dynamical geospatial database are needed. Determining the safest and most efficient way to evacuate a building can be dealt with as a transportation problem. This includes a navigable 3D GIS, a dynamic geospatial database, data positioning in real-time, analytical models to simulate possible trajectories of change and to formulate alternative decision scenarios, and a distributed information architecture.

3 REVIEWS ON 3D DATA MODELS

3D geospatial information has always been challenged due to a variety of data models, resolution and details, and ways of geometric and topological representations. Since 9/11 there has been special interest in 3D models to represent internal structures of micro-scale environments (built-in urban areas). Such models are mostly available from the design phase (as CAD models). Although design CAD models are, in most cases, too detailed for computing evacuation routes, for effective disaster management several different models have to be used. This section will review currently developed 3D data models, which are 3D geometric models, 3D topological and graph models, 3D city models and 3D CAD models.

3.1 *3D Geometric Models*

Practically most of the work on geometry model has been completed by the Open Geospatial Consortium Inc. (OGC, formerly the Open GIS Consortium). It is the membership of organizations developing standards for describing the real world phenomena and therefore most related to GIS. Although the initial work of the OGC has mostly been concentrated on traditional 2D GIS issues, the focus has progressed to the next stage. The OGC’s current abstract model incorporates many of the geometry types as required in CAD and Architecture Engineering Construction (AEC) industry. ISO has also independently from OGC developed ISO/TC 211 19107

Spatial Schema (Hering 2001). Currently the OGC Topic 1, Feature Geometry (of the Abstract Specifications) is identical with ISO/TC 211 19107.

The specifications aim at complete description of real phenomena. A ‘feature’ in OGC terms is an abstraction of a real world phenomenon, which is associated with a location relative to the Earth. In general, the feature can be described by vector or raster representations. Geometric and topological primitives (i.e. simple features and complex features in OGC terms) are used to construct geographic features and represent their relationships. Raster data is based on a complete tessellation of the space, in which each unit gets an attribute value. The ISO 19107 Spatial Schema standard deals only with vector data.

Actually the Spatial Schema treats the two models: geometry and topology. Each real world phenomena can be described by a geometric object (GM_Object) and/or a topological object (TP_Object). The Geometrical model provides the means for the quantitative description (coordinates and mathematical functions) regarding dimension, position, size, shape, and orientation. The geometry is the aspect of geographical information that depends on the geodetic reference system (particularly relevant for 2D GIS). Topology, in contracts, deals with the spatial relationships of geometric features within continuous mappings.

The geometry of spatial features is described by the basic class GM_Object, which is a combination of a geometry and a coordinate reference system. The geometry object can be a GM_Primitive, GM_Complex and GM_Aggregare. The GM_primitive is an abstract class derived from Geometric primitive (Figure 1). As it can be realized the Abstract Specifications provide a concept for representation of 3D objects as well as specific primitives such as free-form shapes (Bézier, B-spline, Cubic-spline, and Polynomial spline), spheres, ellipse, cone and triangulated surfaces.

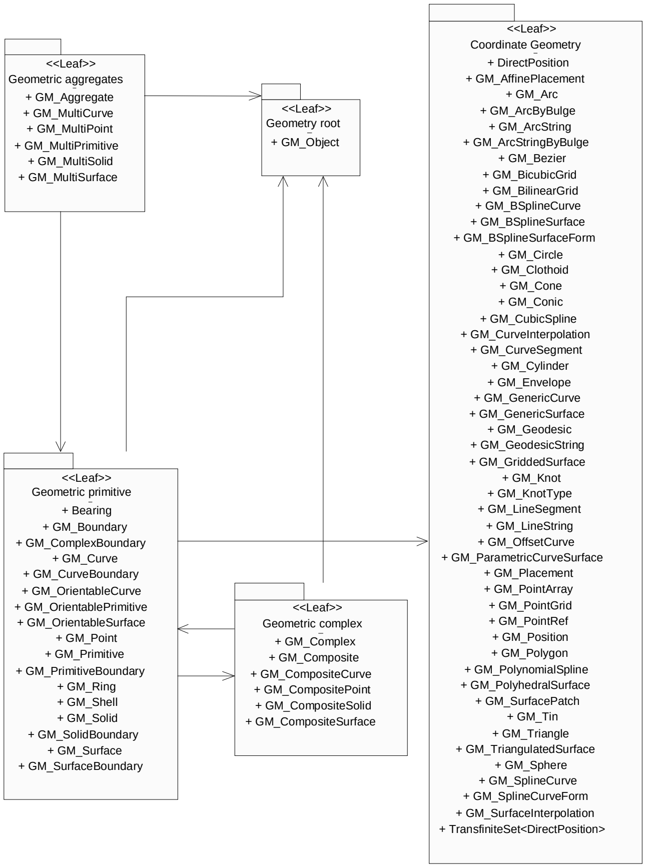

Figure 1: Geometry package: Class content and internal dependencies (ISO/TC211 19107)

It should be realised that the Abstract specifications provide only conceptual guidance in preparing Implementation specifications (Reed 2006). The way these can be implemented at different platforms (based on CORBA, OLE/COM and SQL) is described in three different Simple Feature Implementation Specifications (OGC, 2005). The set of primitives in the Implementation specifications is rather limited to the support of only 2D primitives, i.e. point, line and polygon (Figure 2). A real simple 3D object (tetrahedron, polyhedron, sphere, cone, etc.) is still to be included.

This chapter will further consider only the Simple Feature Implementation Specification for SQL (SFS), which provides guidance for implementing spatial data types in Database Management System (DBMS). In the last couple of years almost all mainstream DBMS (Oracle, Ingres, Informix, PostGIS, MySQL) offer support for spatial data types. Most of the DBMS are compliant with the model as described in SFS, but variations exist even in the supported data types. For example, Informix supports three basic spatial data types: point, line and polygon; Ingres supports one more type: circle; Oracle Spatial has points, lines, polygons and circles, as well as arc strings and compound polygons. It should be notices that all DBMS (except Informix) maintain, the 2D objects with their 3D coordinates. However, the spatial functions supplied with the data types are predominantly only 2D (the third coordinate is omitted from the computations), although some exceptions exist. For example, PostGIS has a number of true three-dimensional functions, e.g. length, and MinMax bounding box

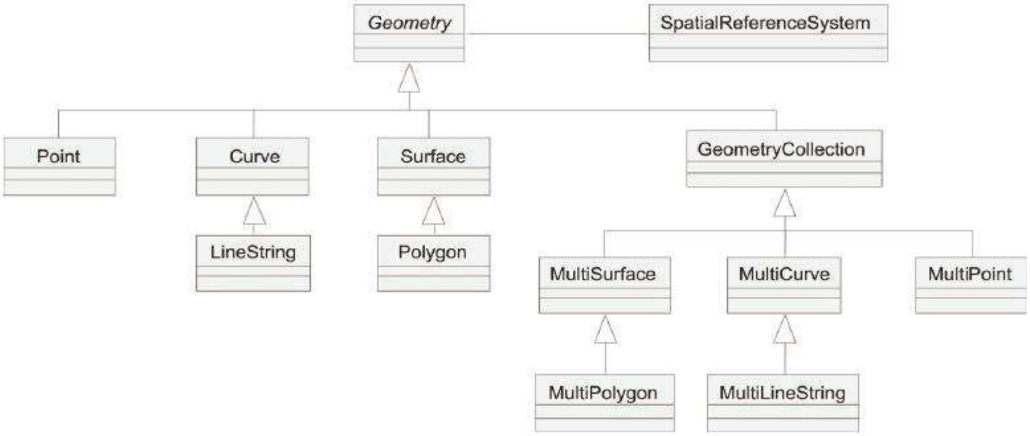

Figure 2: Simple Feature Specifications for SQL (SFS)

As mentioned above the data types currently in are 2D but they can be given with their 3D/4D coordinates. Practically this means that 3D data can be managed in DBMS (and eventually analysed). Using 3D polygons, 3D objects can be represented as polyhedrons in two ways: as a list of data type *polygons* or as data type *multipolygon/collection* (Stoter and Zlatanova 2003).Using the first approach, one or two more columns have to be introduced in the relational table, to be able to specify that a polygon belongs to a particular 3D objects. One 3D object is represented by several rows in the geometry table. In the second case, a 3D object is described in one row, since all the information about the polygon is decoded in the Oracle Spatial geometry type. Although the number of records is reduced, the redundancy of coordinates cannot be avoided. Each triple coordinates is repeated at least three times in the list of coordinates. An apparent advantage of the 3D multipolygon approach is the one-to-one correspondence between a record and a 3D feature. Furthermore the 3D multipolygon (compare to list of polygons) is recognized as one object by front-end (GIS/CAD) applications (Figure 3). SQL examples illustrating the creation and query of these tables can be found in Zlatanova and Storer 2006.

Spatial DBMS can play a significant role in emergency response in near future as a general data store for both operational data (*in situ*) and existing 2D/3D/4D data. Presently, 3D features stored in DBMS can easily be combined with other features described by natively supported or user-defined data types and visualized in a 3D environment (Figure 4). Research and prototype developments have already reported new data types for a 3D polyhedron (Arens et al 2005) and freeform surfaces (Pu et al 2006, Figure 5) as recommended by the Abstract Specification. Hopefully, the Implementation specification for SQL will be soon extended with more geometry types. It should be noticed geometric models are very convenient for rapid 3D visualisation and performing metric operations (compute area, volume, find object within given area, etc.). Most of the DBMS support several spatial indexing schemas, which further contributes to the better performance compared to topological models (Zlatanova & Stoter 2006). Presently most of the DBMS (with one exception Oracle Spatial) maintain only the geometrical model, but the most common topological operations as defined by the 9-intersection model (Egenhofer & Herring, 1990) are also supported. Consequently numerous spatial analyses can be preformed as well. However, it should be realised that DBMS will never be able to support all the spatial analyses that an emergency response system may need. As discussed elsewhere (e.g. Zlatanova & Stoter, 2006) DBMS would support generic functions and operations and the complex variety of spatial analyses has to be performed at a front-end application.

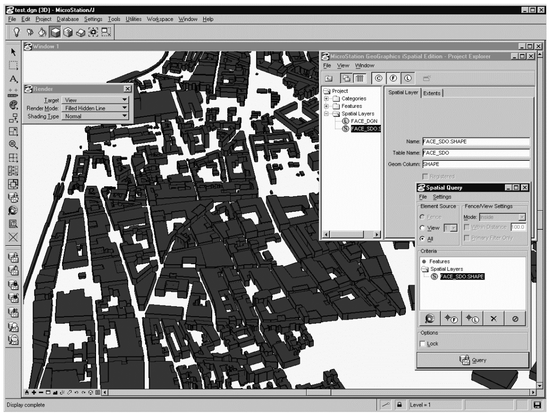

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Figure 3: 3D buildings stored in DBMs and visualized in Bentley software

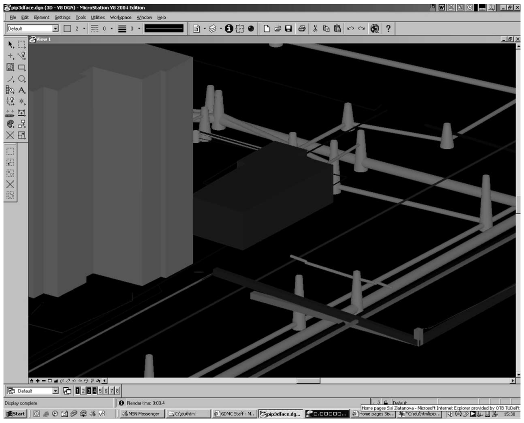


Figure 3: 3D pipes integrated with buildings

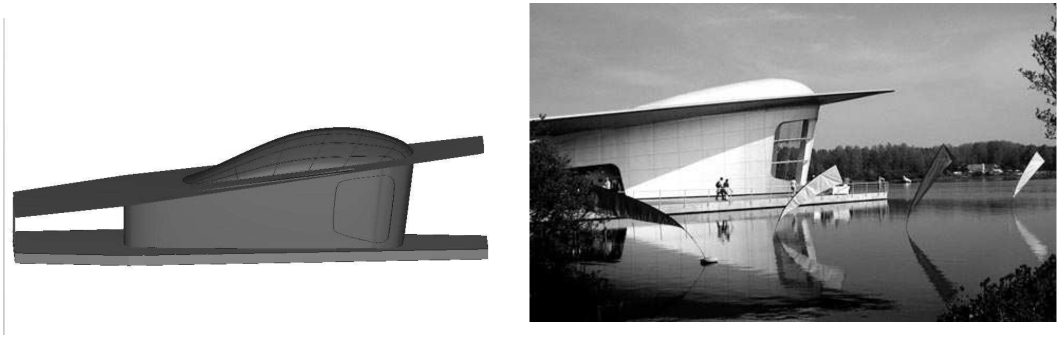


Figure 4: A building modeled with NURBS (CAD model and real photo)

3.2 *3D Topological and Graph Models*

The topological model is closely related to the representation of spatial relationships among objects in geographic phenomena. Over the last fifteen years, topological models for n-dimensional objects have been developed by a number of researchers (Rikkers et al. 1994, Pigot 1992, Pigot & Hazelton 1992). However, the 3D topological models have not been implemented in the commercial 3D GIS systems (Zlatanova et al. 2002) even though models have been implemented in CAD systems such as SHAPES by XOX Inc. or GeomagicStudio by Raindrop Geomagic Inc. Likewise the geometrical model, OGC Abstract Specifications discuss

3D topological primitives, but Implementation Specifications for a topological model are not available yet.

3D entity-based data models for geospatial representation are based on the concepts used in 2D vector GISs. A number of systems have been developed to implement 3D data structures based on boundary representations (Raper 2000). B-rep has a hierarchical data structure in which an object surface is composed of four elements of predefined primitives: point, edge, face and volume (Hoffmann, 1989; Li 1994). Since the 3D B-reps are extensions of representations of planar configurations in 2D B-reps, each volume in B-reps for 3D geographic entities is represented by its bounding surface (Worboys 1995). Examples of the developed data models based upon 3D B-reps are the system of 'simplicial complexes' described by Carlson (1987), the structured vector fields described by Burns (1988), 3D formal data structure (FDS) developed by Molenaar (1990) and the 'GOCAD' system developed by Mallet (1990). Tetrahedral Network (TEN) introduced by Pilouk (1996) improves 3D FDS to allow modeling of objects with indeterminate boundaries such as geological entities and pollution clouds. Zlatanova (2000) designed Simplified Spatial Model (SSS) to serve web-oriented applications with many visualization queries by simplifying 3D FDS, and Coors (2003) developed Urban Data Model (UDM), representing the geometry of a body or a surface by planar convex faces. In these models, topological relations are represented by a geometric representation of the cells and their neighborhoods defined in terms of their boundary and co-boundary cells based upon boundary representations (Corbett 1979, Pigot 1995).

Compared to the geometrical models, the topological models perform relatively bad (Zlanatova et al. 2004). First, many spatial queries are based on pure geometric properties. For example a query 'give all the features within given area' is completed on the 3D coordinates of objects. But the 3D coordinates in the topological models are stored in the node table, which requires traversal of three or two more tables (edge, face and body). In contracts, in the geometric models, 3D coordinates are organized with the features, generally in a single table. Second, the geometric model is integrated within the commercially developed DBMS allowing for efficiently, while topological models are mostly organized (with exception of Radius Topology and Oracle Spatial 10g) in user-defined objects and tables. Lastly, DBMS maintain spatial indexing, which is not applicable for topological models. Since the tables contain only references to id's of the objects, only a general indexing is possible. As concluded in Penning 2004, a spatial index (R-three) built on a MinMax bounding box of a face, speeds up significantly the insert operation of Oracle Topology 10g. The topological models have their advantages in avoiding redundant storage, maintaining data consistency, and performing specific topological operations such as overlap, intersections, etc. (Penninga 2004). However some of the 3D topological data models have problems maintaining efficiently local neighbourhoods, especially when the real geometry of the feature is not of importance.

In order to deal with this problem, graph models have been developed (Chalmet et al.1982, Hoppe & Tardos 1995, Lu et al. 2003, Smith 1991, Lee 2001). Instead of representing the topological relationships between topological primitives (node, arc, face and body), the graph models present the topological relationships among 3D objects by drawing a dual graph interpreting the 'meet' relation between 3D and 3D objects as defined by the 9-intesection model (Egenhofer & Herring 1992). To plan and design an evacuation network within a building, the interior of a building is modelled as node-edge graph (Chalmet et al.1982, Hoppe & Tardos 1995, Lu et al. 2003, Smith 1991), which is a logical network model. Similar to the node-edge graphs which use duality to represent space-activity interactions, the Combinatorial Data Model (CDM) was developed to represent more than just adjacency and connectivity relationships ($G = (V(G), E(G)$ and $H = (V(H), E(H)$, respectively), among 3D spatial objects in built environments (Lee 2001, Lee & Kwan 2005). In the CDM model, the graph H is a subgraph of the graph G because $V(H) \subseteq V(G)$ and $E(H) \subseteq E(G)$. The CDM is defined as a set of nodes (3D entities in primal space) with a set of edges (spatial relationships between 3D entities in primal space) that represent the topological relationships among entities in built environments. Both the node-edge graph and the CDM are logical network data models representing topological relations of the 3D entities (Lee 2001, Lee & Kwan 2005). As a logical data model, CDM is a pure graph representing the adjacency, connectivity and hierarchical relationships among the internal units (e.g. rooms and corridors) of a building. In order to implement network-based analysis such as shortest path algorithms in the CDM (and node-edge graphs), the logical network model needs to be complemented by a 3D geometric network model that accurately represents these geometric properties (e.g. distance or size), called Geometric Network Model (GNM). For the transformation, a node in the CDM (graph *H*) representing a corridor within the building is considered as a consolidated ‘Master_Node’. The Master_Node is a sub-graph representing a connectivity relationship among the compartmentalized zones of the corridor generated to represent the relationships between a room and a hallway as one-to-one relations (one-to-many relations in the CDM). In other words, the node in the CDM (graph *H*) is converted into a linear feature in the GNM, which is a sub-graph representing a two-dimensional shape such as a hallway.

The importance of graph models is recognized by DBMS as well. For example, Oracle Spatial 10g offers support of graph organized in two to four relational tables NODE, LINK, PathNODE and PathLINK. Additionally, it is possible to assign the real geometry to each node or link. For example if a room is associated as a node, the 3D polyhedron (or box) can be also stored together with the node. Such a structure might be quite powerful for calculations and visualization of 3D evacuation routes. Path table and path link table are optional for storage of pre-calculated paths (routes). High-level languages PL/SQL or Java API are available for building and analyzing the network.

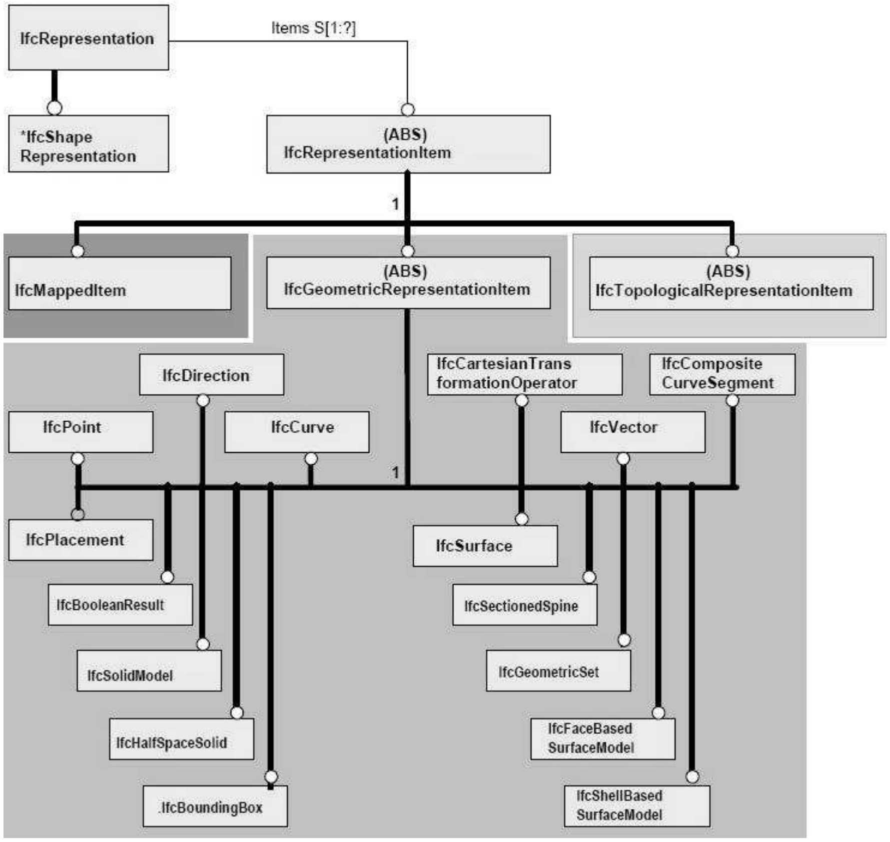


Figure 5 Shape representations included in IFC

3.3 *3D City Models*

3D City Models become a very important issue due to the increasing demand for a realistic presentation of the real world in GIS. The 3D model data are potentially of great importance to the understanding of urban structure and the mechanism of urban growth through visualizing urban and built environments. There are many applications of 3D Urban Models now available. They are based on linking visualization systems (such as CAD or net-based Virtual Reality

(VR) (Faust 1995)) to data stored within a GIS. UCLA researchers have pioneered the delivery of geographic information into a 3D modeling environment (Liggett & Jepson 1995). To date, not only research centers, such as the Center for Advanced Spatial Analysis (CASA) at University College London (Smith 1998, Shiode 2001, Longley & Batty 2003) and the GIS Technology Section at Delft University of Technology (Oosterom et al. 2002), but also consulting companies, such as the Environmental Simulation Center (www.urbansimulation.com), Urban Data Solution (www.u-data.com), CommunityViz (www.communityviz.com), Miller-Hare (www.millerhare.com) have developed 3D Urban Models to support planning applications. Batty et al. (2001) listed web addresses for visualization projects in cities with a population greater than one million.

In order to represent urban objects in the systems, some applications use photo-realistic CAD-type models with Level of Details LOD technologies (Liggett & Jepson 1995, Koninger & Bartel 1998, Sugihara et al. 2000, Shiode 2001) or ESRI 3D shapefile formats (ESRI 1998, Multigen-Paradigm 2003), the others implement 3D topological data models based on B-rep (Tempfli 1998, Holtier et al. 2000, Stoter & Zlatanova 2003, Stoter & Oosterom 2002). Depending on the degree of urban environments, which is the amount of geometric content within the model, 3D visualization models deal with buildings as a simple prismatic form created by extruding the building footprint (a 2D polygon) (Jepson et al. 2001), while Urban Simulation Systems deal with buildings as a compound 3D form generated by stacking extruded floor polygons (Holtier et al. 2000). CityGML, a multi-purpose and multi-scale representation for the storage of and interoperable access to 3D city models, covers the geometrical, topological and semantic aspects of 3D city models (Kolbe et al. 2005). All systems are tied to aggregated attribute information on housing code, fire code, zoning code, and environmental code violation, as well as tax delinquencies based on a 3D floor or building object, instead of attribute information on 3D individual objects in the building. In addition, most systems don't implement suitable data models to represent topological relationships among 3D spatial objects within a building and to be used for various spatial queries to analyze spatial relations of the objects in urban environments.

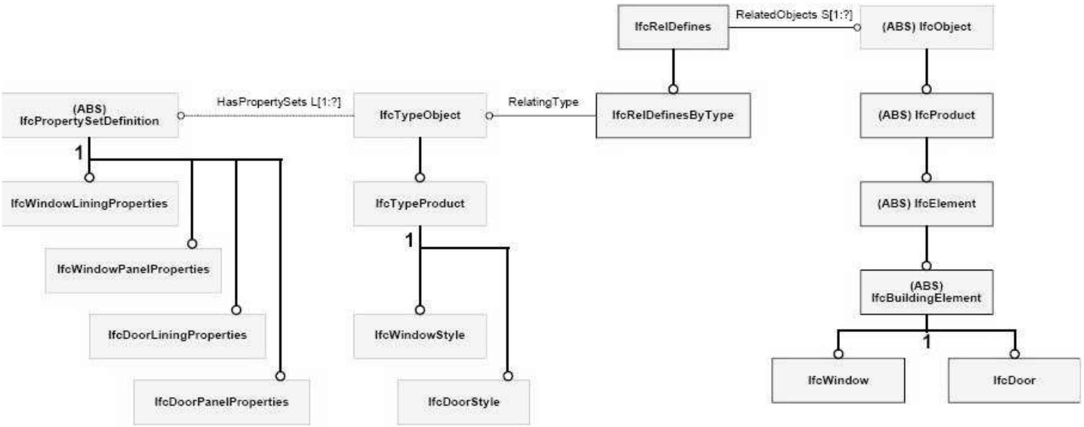


Figure 6: Doors and windows in IFC

3.4 *3D CAD Models*

CAD was primarily developed for engineers responsible for designing and building 'things'. CAD was able to deal with large-scale, detailed models, without maintenance of attributes and lacking support of geodetic reference systems. The complexity of design tasks to be solved contributed to the development of a huge variety of shapes and supporting tools, which resulted in numerous data exchange problems. Attempts for standardizations are carried out within several organizations but for the scope of this chapter, we will focus on the efforts of International Alliance for Interoperability (IAI),(www.iai-international.org) on standardization of buildings. IAI is a membership of organizations aiming at improvement of productivity and efficiency in the construction in all the three design aspects, i.e. organization, process and technology. From

1999-2006 IAI developed the specifications for Industry Foundation Classes (IFC) available as ISO 16739 standard, which covers the entire process of building design. The IFC are based on STEP, yet another more general framework for representation and exchange of CAD product data, described within ISO 10303.

The variety of shapes described by IFC is much larger compared to GIS and truly three-dimensional: curves, geometry sets (consisting of points curves and surfaces as 2D and 3D elements), Surface models (which include facetted face sets and shells, always 3D), Solid Models (B-reps, Constructive Solid Geometry, Swept models), etc. (Figure 6). Some of the B-reps used in CAD systems are very similar to the geometrical or topological models widely implemented in GIS. In contract to GIS, CAD systems maintain topological models only per 3D object, i.e. spatial relationships between two distinct objects can be found only by geometrical computations. Moreover IFC has a complex thematic hierarchy, i.e. contains entities for walls (inc. curtain walls), windows and doors (Figure 7), roofs and slabs, openings, coverings and louvers, projections +/- and shading, railings, ramps and stairs. IFC contains relationships for placing items in openings, assembling and connecting elements, covering one element with another, proximity of elements (Figure 8), associating classification, documents, approvals and rules. Since the development of this standard number of tools for viewing and creating IFC are available (), but since the complexity of IFC

Much of this information can readily be used for integration with 3D GIS and 3D city models. Apparently many of the details intended included in IFC are not needed for 3D GIS models. Therefore, similar to research in 3D City models, appropriate LOD are also investigated in AEC domain. Wix et al 2005 report first results of integrating GIS and AEC models using GML to IFC representations. The LOD adopted by the researchers are very similar to the ones proposed within CityGML. As the developments toward 3D GIS and AEC/CAD integration progress, the interest of GIS specialists in IFC will also increase.

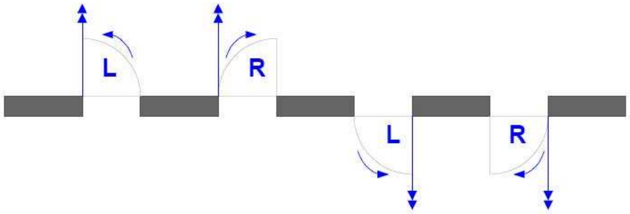


Figure 7 Doors openings in IFC

4 THREE COMPONENTS OF A 3D DATA MODEL FOR EMERGENCY RESPONSES

In reviewing the advantages and disadvantages of the different models in the previous section, it is a difficult task to select an appropriate data structure designed for the characteristics of the applications, for example, objects of interest, resolution, required spatial analysis, etc. (Zlatanova et al. 2004). A model designed for 3D spatial analysis may not exhibit good performance on 3D visualization and navigation. In other words, different data models might be suitable for the execution of specific tasks but not others. In order to maximize efficiency and effectiveness in the provision of operations, Oosterom et al. (2002) proposed multiple topological models maintained in one database by describing the objects, rules and constraints of each model in a metadata table. Metric and position operations such as area or volume computations are realised on the geometric model, while spatial relationship operations such as ‘meet’ and ‘overlap’ are performed on the topological model.

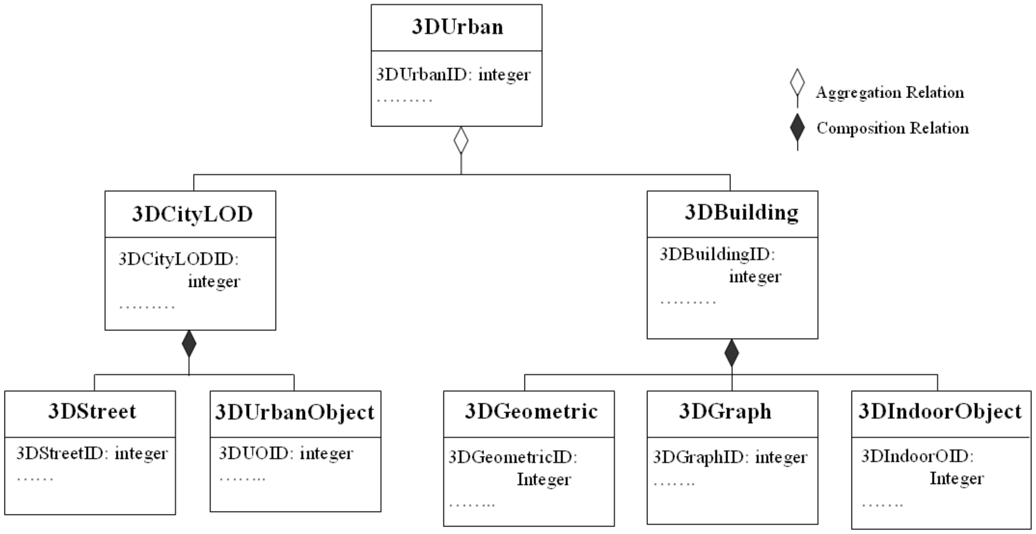


Figure 8: UMLObject Diagram: Object Relationships of the 3D Data Model

As mentioned before, the emergency response system is a spatial decision support system that facilitates coordination and implementation of emergency response operations such as pedestrian evacuation and rescue within micro-scale urban indoor space not only providing dynamic, specific and accurate evacuation guidance based on indoor geospatial information, but the system visualizes the information to communicate with users in macro-level (an impacted region) and in micro-level (disaster site inside buildings). In order to represent spatial objects in urban areas for ER, this chapter proposes a 3D data model, which is a hybrid data model consisting of the three models: a 3D geometric model, a 3D graph model and a 3D city model. The 3D geometric model is used for 3D geometric representation of solid features consisting of a number of 3D polygonal faces defining an enclosed boundary, while the 3D graph model is proposed to represent the topological relationships among the 3D solid features. The 3D city model can be used for visualizing the information in a 3D real view.

Based on the methods of object-orientation, object-object relationships of the model are represented using an UML (Unified Modeling Language) object diagram (Zeiler 1999). Figure 9 shows the classes of the model. A 3DCityLOD and a 3DBuilding classes are associated with a 3DUrban class through an aggregation relationship that models the case where the 3DCityLOD and 3DBuilding classes are part of a 3DUrban class. The aggregation relationship is indicated by a hollow diamond headed arrow pointing from the part to the whole, and the cardinality of aggregation is indicated in the diagram. The 3DCityLOD associates with a 3DStreet and a 3DUrbanObject classes through composition relationships. The composition is a strong form of aggregation in which objects from the 3DCityLOD class control the lifetime of objects from the ‘part’ classes. The 3DBuilding class associates with a 3DGeometric, a 3DGraph, and a 3DIndoorObject classes through composition relationships. The 3DGeometrc represents the geometric dimension of the 3D spatial objects (such as rooms or spatial units) on a partly symbolic and simplified 3D representation in a model view (Lin & Zhu 2006), and the 3DGraph represents the connectivity relationships among the 3D spatial objects based on a geometric network representation. The reference of a 3D object in the 3DGeometric to its corresponding objects in the 3DGraph and a 3DIndoorObject should be maintained in the system. The 3DStreet is the network of ground transportation, which represents the connectivity relationships among the urban objects in a model view. The 3DIndoorObject and the 3DUrbanObject are for a virtual representation of the urban environment that enables people to explore and interact with the geospatial information about the emergency situations in the worldview giving a photorealistic 3D display.

4.1 *3D Geometric Representation for Spatial Objects in Micro-scale Urban Areas*

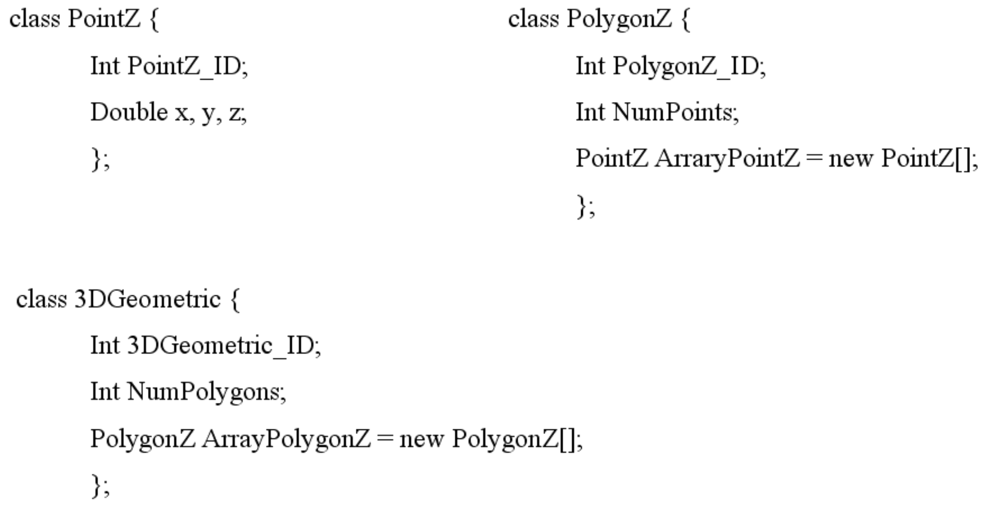
As discussed in Section 3.1, a spatial object can be represented by geometry types, which are basically an ordered sequence of vertices that are connected by straight-line segments or circle arcs. The supported primitive or composed types are points and point clusters, lines, compound lines, n-point polygons, compound polygons, and circles. 3D objects can be represented using either the simple geometry type ‘polygon’ (with 3D coordiantes) or the geometry type ‘collection’ (or ‘multipolygon’).

This chapter proposes the 3D geometric model based on the first approach. The basic components of the model are points, polygons, and solids. To formalize the solid objects consisting of a number of polygonal faces defining an enclosed boundary, the schema of the objects is shown in Figure 10. The primal classes of the 3D geometric model are PointZ, PolygonZ, and 3DGeometric. The PointZ consists of an identifier and position data in 3D (x,y,z-coordinates), and the PolygonZ consists of a set of Points *pt* and other attributes including an identifier, and total number of points. The PolygonZ is considered a single ring, which is a closed, non-self-intersecting loop. The 3DGeometric consists of an identifier and a list of all polygons constructing a 3D solid object representing a spatial unit (such as a room of a building) of the urban objects.

4.2 *3D Topological Representation among the Spatial Objects*

In order to represent topological relationships among 3D spatial objects in built environments (such as buildings), the 3D Geometric Network Data Model (Lee 2004a) is developed to abstract and represent the connectivity spatial relationships of the internal structure of buildings. It is derived through 3D Poincaré Duality using a graph-theoretic framework and a hierarchical representation schema, and a Straight-Medial Axis Transformation (S-MAT) modelling (Lee 2001 & 2004a). The 3D Poincaré Duality is utilized to abstract the topological relations among a set of 3D objects and to transform ‘3D to 2D relations’ in primal space to ‘0D to 1D relations’ in dual space. It represents connectivity relations among objects in 3D space as a dual graph, $H = (V(H), E(H)$. In order to represent the geometric properties (such as distances between nodes in the graph) of the dual graph, the S-MAT is utilized to identify linear features from a simple polygon (a hallway in this case). Each node representing subunits of a building retrieved from the graph $H = (V(H), E(H)$ is projected and connected to the medial axis to generate the graph $G = (V(G), E(G)$. The graph G is the geometric network model used to describe the connectivity relationships among 3D objects within a building. Because the 3D GNM was developed to represent connectivity relationships among the 3D objects based on a graph model, the network model can be used for emergency response systems, in order to pathfinding, allocation and tracing analyses in 3D micro-spatial environments. Such applications require a 3D network-based data model to represent the internal structures of urban-built environments and environmental factors to model pedestrian-based indoor movement, such as traffic flows, damage status, toxicity status, bottleneck locations, etc.

This section describes the detailed construction method for generating the 3D topological model for 3D objects within a building (3DGraph class) based upon the work of Lee (2006). The adjacency relationships among spatial units are the combinations of the adjacency relations in the horizontal directions and the adjacency relations in vertical directions, because of the nature of the 3D geographic entities in built-environments (Lee & Kwan 2005). Therefore, the adjacency relationships are defined by two individual procedures. The adjacency relations of 3D units in horizontal directions are derived from the topological relationships between polygons (such as floor plans). The adjacency relations in floor j of the building i can be described as the graph $Gh_{ij} = (V(Gh_{ij}), E(Gh_{ij}))$, while $j = 1$ to n in case of n story building. The adjacency relations of 3D units in vertical directions are defined by the layer-overlay functions implemented in 2D GIS. The adjacency relationships between the floor j and floor $j-1$ of the building can be described as the graph $Gv_j = (V(Gv_j), E(Gv_j))$, while $j = 1$ to n-1. The defined graphs can be combined using a UNION operation. The combined graph can describe all incidence of the topological model because the defined graphs are equivalence classes.



```
class PointZ {                          class PolygonZ {
        Int PointZ_ID;                          Int PolygonZ_ID;
        Double x, y, z;                         Int NumPoints;
        };                                      PointZ ArraryPointZ = new PointZ[];
                                                };

class 3DGeometric {
        Int 3DGeometric_ID;
        Int NumPolygons;
        PolygonZ ArrayPolygonZ = new PolygonZ[];
        };
```

Figure 9: 3D Geometric: 3D Geometry model

In order to define the adjacency relations of 3D units in horizontal directions, the hallways are transformed into linear features based on the Straight-MAT algorithm (Lee 2004a), which are a sub-network consolidated into a hallway node in the dual graph generated by the 3D Poincaré Duality. Each node representing spatial units in floor j of a building is projected and connected into the medial axis and into other nodes based on their adjacency relations. The graph $Gh_{ij} = (V(Gh_{ij}), E(Gh_{ij}))$, representing the geometric network for a floor j of a building i (Figure 12b), is combined with graph $Gv_j = (V(Gv_j), E(Gv_j))$ to produce the graph $G_i = (V(G_i), E(G_i))$ (Figure 11b), which is the topological model (adjacency)of a building i. The graph G_i is the combination of the dash and solid thick lines presented in the Figure 11b.

The connectivity relationships among 3D spatial units are defined as a subset of the adjacency relationships (Lee & Kwan 2005), as seen in Figure 11. From the property, it is known that the graph $G_i = (V(G_i), E(G_i))$, which represents adjacency relationships, is a supergraph of the graph $H_i = (V(H_i), E(H_i))$, which represents connectivity relationships among spatial units in floors of a building i, because $V(H_i) \subseteq V(G_i)$ and $E(H_i) \subseteq E(G_i)$. In this case, because $V(G_i) = V(H_i)$, graph H_i is called a spanning subgraph of graph G_i. The graph H_i representing the connectivity relationships can be generated from the graph G_i by removing edges, which are representing only adjacency relationships among the 3D spatial units (Lee & Kwan 2005). The graph H_i is presented by the solid thick lines in Figure 11b.

The 3DGraph, $G_i = (V(G_i), E(G_i))$, needs to be integrated with the network of the ground transportation system (3DStreet class), $S = (V(S), E(S))$, in order to implement multimodal transportation network analyses in urban environments using the topological models of the study area (3DUrban), $UG = (V(UG), E(UG))$. The first step of the integration is to define the connectivity relations between the building's networks (3DGraph) and the street network (3DStreet). The connectivity relations are abstracted to 'Transfer_edges', where Transfer_edges $(E(C)) = \{(n_i, n_j) / n_i \in V(G_i) \cap n_j \in V(S)\}$. The node n_i represents entrance halls of the buildings, and node n_j is defined by projection $p(n_i, E(S))$ (Lee 2004a) of node n_i onto edge $E(S)$ of the street network S. The output is represented by a transferring network, $C = (V(C), E(C))$. As the final step, the 3DUrban's network $UG = (V(UG), E(UG))$ is constructed by combining the 3DGraph ($G_i = (E(G_i), E(G_i))$) with the 3DStreet ($S = (V(S), E(S))$) and the transferring network ($C = (V(C), E(C))$), because each network graph pertains to an equivalent class. The combined network, $UG = (V(UG), E(UG))$, describes a network representation of the internal structure of a building as well as among buildings within the urban area and the street network, in order to model pedestrian movements in the multimodal transportation network.

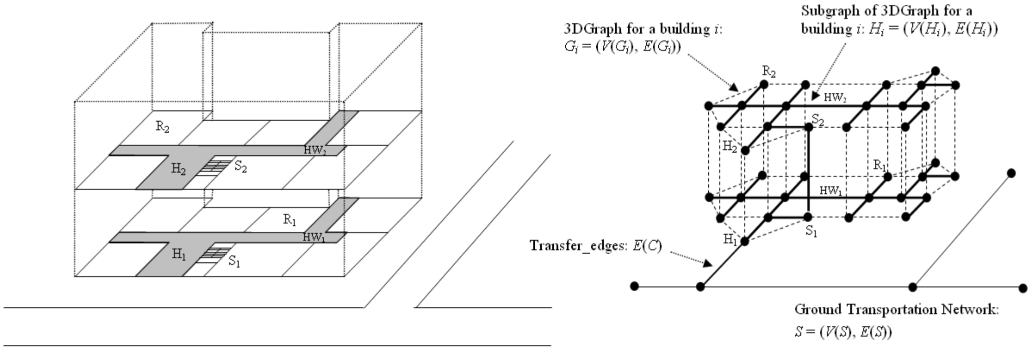


Figure 10: An Example Building and 3DGraphic Model

4.3 *3D Visualization using City Models*

In order to provide important information for different aspects of disaster management, 3D city models enable multi-purpose and multi-scale 3D visualization to present emergency situation information to users (rescuees and rescuers) (Kolbe et al. 2005). Although 3D visualization has to be very close to the real view, it is practically impossible to represent all the details but too few details may create unrealistic views. In contrast, high graphic density does disturb the user’s understanding of the message. In order to resolve the problems, most city models support different LOD, which may arise from independent data collection processes and are used for efficient visualization and efficient data analysis. In one city model data set, the same object may be represented in different LOD simultaneously, enabling the analysis and visualization of the same object with regard to different degrees of resolution.

The 3DUrban object shown in Figure 9 represents the geometrical, topological and semantic aspects of a complex 3D city model. The spatial objects represented in the model are not only buildings, but also other spatial objects such as man-made urban furniture, vegetation objects, water bodies, and transportation facilities like streets and railways. The 3DCityLOD are intended mainly for the buildings. The coarse level LOD0 is essentially a two and half dimensional Digital Elevation Model (DEM), over which an aerial image or a map may be draped. The detail LOD1 comprises detailed vegetation and transportation objects, as well as urban street furniture such as trees, light poles, traffic signals, and so on, which are represented by the 3DCityLOD objects. Buildings in LOD0 are represented by 3DGeometric, which is the block model, representing spatial properties of buildings without any roof structures or texture. LOD1 denotes architectural models with detailed wall and roof structures, balconies, bays and projections, as well as interior structures like rooms, interior doors, stairs, and furniture. The 3DIndoorObject represents the semantic properties of buildings in the detail level. The 3DCityLOD and 3DIndoorObject objects have relations to objects in other databases or data sets (Kolbe et al. 2005). For example, a building in 3DBuilding class is derived from an architectural model or 3D CAD model. The reference of a 3D object to its corresponding object in an external data set is essential. Such a reference denotes the external information system and the unique identifier of the object in this system.

5 3D TOPOLOGICAL ANALYSES FOR EMERGENCY RESPONSES

To define and develop spatial data manipulating and analytical methods to implement the planning/decision process, the emergency response system requires several important functionalities including a 3D location positioning, a network connectivity analysis, a traffic flow analysis, 3D topological analysis (3D buffer, overlay, intersect, etc.) and an indoor navigation (Dane & Rizos 1998, Miller & Shaw 2001). The 3D location positioning obtained by location-aware devices is used to identify location information of disaster sites, occupants, traffic congestion areas, and isolated zones within buildings. The network connectivity analysis is used to define isolated networks or areas, which do not have any exit node connecting to destination nodes because of being blocked by traffic congestion or disaster. The next function is an evacuation model to estimate dynamic capacities and flow rates of hallways and stairwells to update occupancy movements and traffic flow impedances in the database. The other function is to identify building evacuation bottlenecks, which are congestion locations in the network during an evacuation event. The final is an indoor navigation function to identify feasible and safe routes within a multi-level structure and to provide navigation guidance for rescue personnel. Because of the limited scope of this study, this chapter is focusing on developing or introducing two functionalities: a 3D buffer function and a 3D optimal route algorithm for internal structures of built environments.

5.1 *3D Shortest Route Method*

In order to support emergency guidance operations such as pedestrian evacuation and rescue within urban indoor spaces, the emergency response system needs to identify 1) the location of emergency crews and disaster events and conditions within the multi-level structure and 2) optimal routes from an affected area to safe locations outside that area. First of all, this section introduces the developed location positioning techniques, and then proposes a 3D Shortest Path algorithm, the modified Dijkstra shortest path algorithm in a 3D GIS.

5.1.1 *3D Geo-location*

In the past few years, new information technology has greatly enhanced the collection of activity data. The Global Positioning System (GPS) provides location information. In addition, these locational devices are equipped with mobile GIS software (such as ArcPad) and can generate on-screen geo-referenced maps to support ufsers' operations on-site (e.g., providing navigational guidance). However, there are limitations in using GPS within a multi-level structure due to a degradation or loss of signal in certain areas of a building. Positioning techniques have been extensively investigated in Location Based Services (LBS) applications, including better localization inside buildings. Network-based or hybrid positioning technology used by most LBS providers to achieve a positional fix faster and easier than conventional GPS-based technology. Nevertheless, the problems of loss-of-fix in LBS-derived locational data still remain (Kwan & Lee 2005). Various indoor positioning technologies are described an analysed in Kolodziej and Hjelm, 2006. Dürr and Rothermel (Dürr & Rothermel 2003) proposed a fine-grained Geocast location model to determine client positions within a building based on geometric and symbolic addressing.

The global positioning techniques such as Global Navigation Satellite Systems (GNSS) to collect 3D locations have improved the quality and quantity of these data and reduced their cost. GPS receivers are currently integrated in cellular phones and PDAs, (Samet 2001). GPS devices are able to offer the easiest method and a quite accurate way of 3D positioning of the user, but only outside buildings.

The positioning within mobile networks using only the information related to the base network transmitter is a very effective method, but it is very inaccurate and practically not applicable (Zlatanova & Verbree 2003). The only advantage, compared to GPS positioning, is the possibility of working inside buildings. None of the currently experimented techniques based on mobile networks are able to obtain accuracy more than 50 meters.

Due to weak GPS signals and the limited accuracy of radio network solutions, neither technique is appropriate for indoor positioning. Wireless LANs (WLANs) are used to track mobile users in closed spaces such as buildings and tunnels (Prasithsangaree et al. 2001). The system for location positioning using WLANs runs on a standalone server and gives the x,y-position and the floor of the mobile unit. The positioning accuracy achieved by the system is up to 1 meter. Despite providing accurate positioning for indoors, however, the WLANs have problems with implementation because they require a reference database for an average signal measurements at fixed points throughout a building (Pahlavan & Li 2002, Zlatanova & Verbree 2003).

For the 3D positioning, a 3D Indoor Geo-Coding technique (Lee 2004b) has been developed to identify the location of disaster events and conditions within the multi-level structure based on the descriptive location information for the real-time emergency response decision making system. The location information like ‘there is a chemical explosion at 416 McEniry at the University of North Carolina at Charlotte’ obtained from 911 calls or emergency crews with wireless communication devices is transmitted back to the emergency response system in real-time. The 3D Indoor Geo-coding method translates the descriptive location information into geographic positions within the building, the x, y, z coordinates based on a given reference data set.

5.1.2 *3D Shortest Path Algorithm*

One challenging task of 3D GIS is to support spatial analysis among different types of real 3D objects, such as a shortest path analysis in 3D space. Scott (1994) implemented a shortest path algorithm for an un-indexed three-dimensional voxel space using a cumulative distance cost approach. This approach produces a set of voxels, such that each voxel contains an attribute about the cost of traveling to that voxel from a specified start point, if there is uniform friction of movement throughout the representation. The three-dimensional shortest path algorithm moves through the ‘cost volume’ along the steepest cost slope from target to origin using a 3 by 3 by 3 search kernel (Raper 2000). For B-rep approaches, Kirkby et al. (1997) implemented a modified version of the Dijkstra shortest path algorithm in a 3D GIS, in which the gradient over a 2.5D surface was added into the computation. In this section, a spatial access algorithm in a 3D GIS is introduced in terms of the Dijkstra algorithm.

The network representation of the topological relationships among spatial objects in a study area is described as the graph $N = (V(N), E(N))$. Given this representation, one of the well-known algorithms for finding shortest paths in graphs is applied to the tasks of spatial access in the 3DUrbanObject, because the algorithms use logical networks containing the connectivity of the network without position. In other words, optimal path searching algorithms can be applied to the network problem in 3D space, such as spatial searching problems in the 3DUrbanObject. Dijkstra algorithm (Dijkstra 1959) (priority-first search) is implemented for this purpose. Since Dijkstra algorithm solves the single source shortest-paths problem on a weighted, directed graph $G = (V, E)$, it identifies the source from which the shortest path to all other vertices is to be found (Cormen et al. 1985, Liu 1996). The algorithm needs to be modified in order to implement spatial queries such as the shortest path from a source node to a destination node in the NRS.

Let $G = (V, E)$ be a graph with vertex set $V[G]$; w be an adjacency matrix giving the distances in $V[G]$; vertex s be a source in G; and vertex t be a destination in G. The algorithm maintains a set S of vertices whose final shortest path weights from the source s have already been determined. A priority queue Q contains all vertices in $V – S$, keyed by their d values (total distance values or traffic impedances) (Cormen et al. 1985). The edge set $EP[G]$ is the shortest path between the source vertex s and the destination vertex t in graph G. The traffic impedances (d values) are based on the environment and human factors, which are dynamic factors affecting on determining optimal evacuation route under emergency situations (Pu & Zlatanova 2005). The environmental factors include damage status, toxicity status, power status and traffic capacities on halls, hallways and stairs of the affected area. Human factors affecting people’s speed of movement are population density, age and gender, level of disability, terrain effects, and so on. Based on the factors, the traffic impedance will be calculated for the study area.

The 3D shortest path algorithm (3DShortestPath (N, s, t, *AdjList*)) is as follows (Lee 2006). Initialize(G, s) initializes two attributes for each node v, $v \in V[G]$: the travel cost $d[v]$ to ∞ and the predecessor $p[v]$ to NIL, and it initializes $d[s]$ to 0. The function ExtractMin(Q) returns and removes a node u from the priority queue Q which $d[u]$ is currently minimal. While ADJ(*AdjList*, u) returns a set containing the neighbor nodes of u, $u \in V(G)$, and TrafficCost(u, v) returns a traffic cost between a node u and a node v, Traverse(v, $S(N)$) returns that vertex u, $u \in S(N)$, for which $p[v]$ is the vertex u. RearrangeQ(Q) re-organizes the priority queue Q based on the shortest travel cost from a source s to each node.

```
Procedure 3DShortestPath (3DUrbanObject N, Node s, Node t, LinkedList AdjList) {
  CALL Initialize(G, s)
    $S(N) \leftarrow \emptyset$
    $Q \leftarrow V(N)$
```

```
WHILE $Q \neq \varnothing$
        Do $u \leftarrow$ CALL ExtractMin($Q$)
        IF ($u = t$) THEN
                EXIT WHILE
        ELSE
                $S(N) \leftarrow S(N) \cup \{u\}$
        END IF
        FOR each vertex $v \in$ ADJ($AdjList$, $u$)
            IF $d[v] > d[u]$ + TrafficCost($AdjList[u, v]$) THEN
                    $d[v] \leftarrow d[u]$ + TrafficCost($AdjList[u, v]$)
                    $p[v] \leftarrow u$
                    CALL RearrangeQ($Q$)
            END IF
        END FOR
END WHILE
WHILE p[$v$] $\neq$ NIL
        $u \leftarrow$ CALL Traverse($v$, $S(N)$)
        $e = (v, u)$
        $EP(N) \leftarrow EP(N) \cup \{e\}$
        $v \leftarrow u$
END WHILE
}
```

5.2 *3D Buffer Function*

In order to identify what is near features or within a given distance, the buffer operation could be used in GIS. Suppose tourists are looking for a hotel nearby an airport. The first step for this operation can be to create a buffer object from a feature (such as an airport), and then hotels will be identified within the buffer object using an overlay operation. In 2D, the buffer object is a polygon, while the buffer object is a 3D solid object in 3D. The 3D searching operation should deal with complex geometric computational problems involved with defining topological relationships (inclusion relationships) between the 3D buffer object and well-formed 3D objects representing a micro-scale urban area (such as spatial units in a building).

In order to alleviate the problem, this chapter proposes a new approach to identifying spatial units within a specified distance. Based on the topological models of the study area (3DUrban), $UG = (V(UG), E(UG))$, the new approach utilizes an algorithm to find a minimum spanning tree (MST) in a connected and undirected graph (Kruskal 1956). A MST, one type of valued graph, is a specific network that satisfies three criteria (Chou 1997). First, the tree connects all nodes in the network with a minimal number of links. Second, the root of every tree is located at one of the nodes in the network. Thirdly, the distance between each node and the root of the tree is minimized. A minimal tree rooted at any node can be constructed for the network. Because the topological model of 3DUrban, $UG = (V(UG), E(UG))$, is a network representation having geometric properties (lengths and directions), one of the well-known algorithms for finding minimum spanning trees in graphs is applied to the tasks of 3D spatial buffer, one of topological analyses in 3D space. In other word, the algorithm can generate a minimum spanning tree from a node n_i of the UG network, and then the network segments within a specific distance (buffer's distance) from the node n_i can be identified from the MST, whose each node contains the total distance (or cost) from the rooted node n_i. From the identified network segment, the set of nodes can be determined. The nodes in the UG network represent the spatial units within the specific distance from the node, the 3D buffer object. The Prim's algorithm (1957) is implemented for this purpose. Since the Prim's algorithm identifies the minimum spanning tree from a source node to all other nodes, the algorithm needs to be modified in order to implement spatial queries such as a 3D buffer from a rooted node to other nodes within a specific distance, a buffer distance.

The following procedure explains how the nodes within a given distance from the rooted node are identified. The input data are a weighted graph $UG = (V(UG), E(UG))$ for each edge e,

$e \in E[UG]$ having a distance value d_e for the edge. Others are the buffer distance, *b-dis*, and the rooted node *r*. The output file is a *N*[ ], a set of nodes.

- Step 1: to pick a node *r* as a starting node from the graph *UG*.
- Step 2: to initialize two attributes for each node *v*, $v \in V[UG]$: the distance from the rooted node *r*, $d[v]$ to ∞ and the predecessor node, $p[v]$ to NIL, as well, it initializes $d[r]$ to 0. The *N*[ ] is *N*[ ] + *r*. Based on $d[v]$, a min-priority queue for all the nodes is generated.
- Step 3: to extract a node *u* from the min-priority queue.
- Step 4: to find the edge $e = (u, v)$, of minimum cost (for distance) extending from node *u*. Set $d[v] = d[u] + d_e$, and $p[v] = u$, if $d[v] > d[u]$. If $d[v] <$ *b-dis*, add a node *v* to the *N*[ ]. Update the min-priority queue based on the $d[v]$.
- Step 5: to repeat step four for all the edges extending from the node *u*.
- Step 6: to repeat step three until $d[v] >$ *b-dis*. The nodes in the *N*[ ] are the list of nodes within the buffer distance, *b-dis* from the node *r*.

6 EXPERIMENTAL IMPLEMENTATIONS OF THE TOPOLOGICAL DATA MODEL

In order to evaluate the potential benefits of the 3D network-based topological data model for providing better services for emergency responses, we undertake an experimental implementation of 3D topological analyses based on the 3DUrban's network $UG = (V(UG), E(UG))$ representing topological relationships among 3D spatial objects in micro-scale built-environments. The implementations are demonstrated based on two topological analyses, 3D optimal route analysis (Kwan & Lee 2005) and 3D buffer analysis (Lee & Kwan 2005).

6.1 *3D Optimal Route Analysis*

We describe the implementation of the 3D optimal route analysis based upon the work of Kwan & Lee (2005). The study area for this experimental case is an area in downtown Columbus, Ohio (USA), located east of Scioto River. We asfsume that a 250-pound highly explosive bomb exploded on the 42nd floor of Franklin County Municipal Building (labeled 'Disaster Site' in Figure 12), and that the shock also caused minor damage on some other floors as well as part of the stairways inside the building. Figure 12 shows the shortest routes under normal traffic conditions (in red) between the disaster building and the fire station located at 405 Oak Street. Suppose that traffic is blocked at two locations on South High Street and Mound Street (indicated by two red dots in Figure 12) nearby the disaster building. Because of these unexpected traffic blocks, the usual shortest path from the fire station to the disaster building is no longer the optimal route. Instead the route in blue in Figure 12 becomes the new shortest path (in terms of travel time). If emergency responders do not have prior knowledge about this new optimal route, they will try to access the disaster site following the usual shortest path (red route). They will then, in this scenario, need to reroute twice because of the two unexpected traffic blocks. The additional delay between the new optimal route and the hypothetical detour route represents the effect of road network uncertainty on emergency response time.

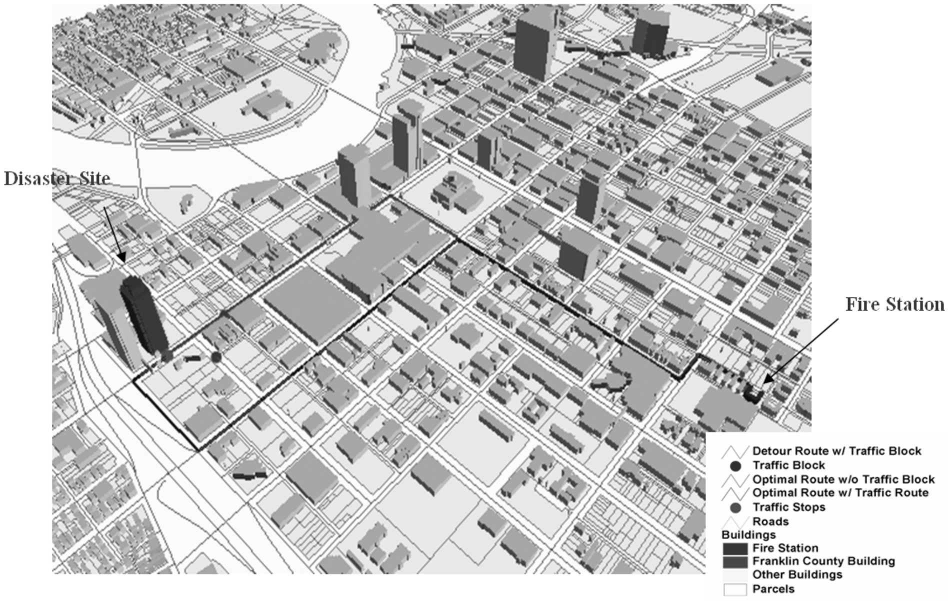


Figure 11 The shortest path between a fire station and a disaster building (from Kwan and Lee, 2005)

After arriving at the disaster building at Entrance A (Figure 13), emergency responders discover that this entrance is blocked by debris and cannot be used to reach the destination room (disaster site) on the 42nd floor (Figure 13). They then walk to another side of the building in order to use Entrance B (Figure 13). These responders are, however, blocked at the 28th floor as they attempt to walk up to the 42nd floor using the stairway. They then walk down to the ground level and use another stairway to go up again (Figure 14). They are blocked on the 28th floor again and have to walk down a couple of floors and walk through some corridors to go up using another stairway (Figure 14). The additional delay between the optimal route (green line) and the hypothetical detour route (red dotted line in Figure 14) represents the effect of entry point uncertainty and route uncertainty in the building on emergency response time.

In order to simulate this scenario, three travel speeds are assigned to the 3D network developed for the study: (a) 25 miles per hour for the road network; (b) 75 feet per minute for walking horizontally outside or inside the building; and (c) 40 feet per minute for going up or down vertically using the stairways inside the building. The total travel time it takes to reach the destination node *c* without using the system is 39.83 minutes, while it is only 24.19 minutes when the optimal route found by the system is used. This means that emergency responders can reach the destination node 15.64 minutes earlier than when such a system is not used. In the experiment, optimal routing performed using an integrated 3D network saves more than one-third of the travel time otherwise needed for reaching the disaster site. Further, the results suggest that optimal routing using only the ground transport network as in conventional 2D GIS leads to a mere 2.18 minutes saving in travel time. This means that a 3D network that integrates the street network with the building's network brings an additional saving of 13.46 minutes. This amounts to 86% of the total travel time saved due to the use of the optimal route found by using the 3D network. This experiment demonstrates that the travel time needed to reach a disaster site inside a multi-level structure can be much longer than the time needed to travel from a source node (a fire station) to the disaster building. It shows that extending conventional 2D GIS to include the internal structures of high-rise buildings can significantly improve the overall speed of rescue operations.

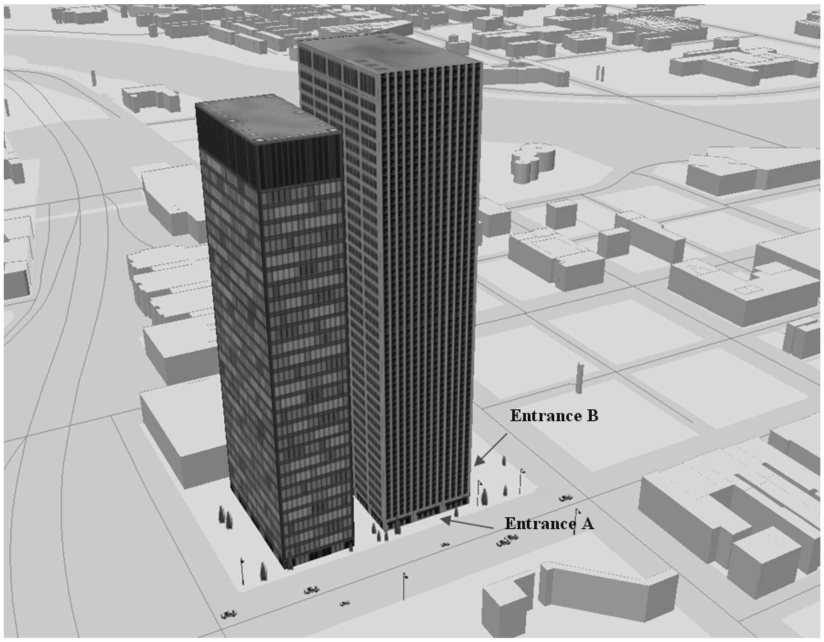


Figure 12: Two possible entrances of the disaster building

6.2 *3D Buffering Analysis - Spatial Query based on an adjacency relationship*

The implementation of the 3D buffer analysis is described based upon the work of Lee & Kwan (2005) in this section. Analysis of the urban phenomena requires those relationships to describe how the individual spatial objects interact. The topological structure can be used efficiently in a query to find neighbors – Which other 3D spatial objects are located on top or under a certain 3D object? This neighbor information can be used in environmentally oriented analyses including noise, air pollution, and emergency situations in urban environments.

This example presents spatial queries based on topological relationships among the 3D object, $G_i = (V(G_i), E(G_i))$, to access the adjacency information among rooms within a building *i*. A click on a node in the Viewer area of 3D NRS Implementation Module runs a VB code, which delivers a Query-Result window showing a Node-ID. The Node-ID is associated with the room number. After selecting a node, the user needs to click the 'Find Adjacency Objects' button to send a request to the system. The query results are displayed in the Viewer area (Figure 15b). Figure 15b shows the result of a spatial query to retrieve adjacent rooms to TE210. Based on the sub-graph (thick lines) representing the query result, we can define that the TE210 Conference Room is adjacent to seven rooms, which are TE212 Auditorium, TE208 Computer Lab, TE209 & TE211 Research Labs, TE201 Hallway, TE110 Classroom, and TE310 Classroom. These rooms are sharing a vertical or horizontal wall with the TE210. Based on the topological information, the same result is displayed in the 3D Viewer using ArcScene of ESRI Inc. in Figure 15a. The solid object of TE210 is colored in dark green, and the solid objects of adjacent rooms to TE210 are colored in light green).

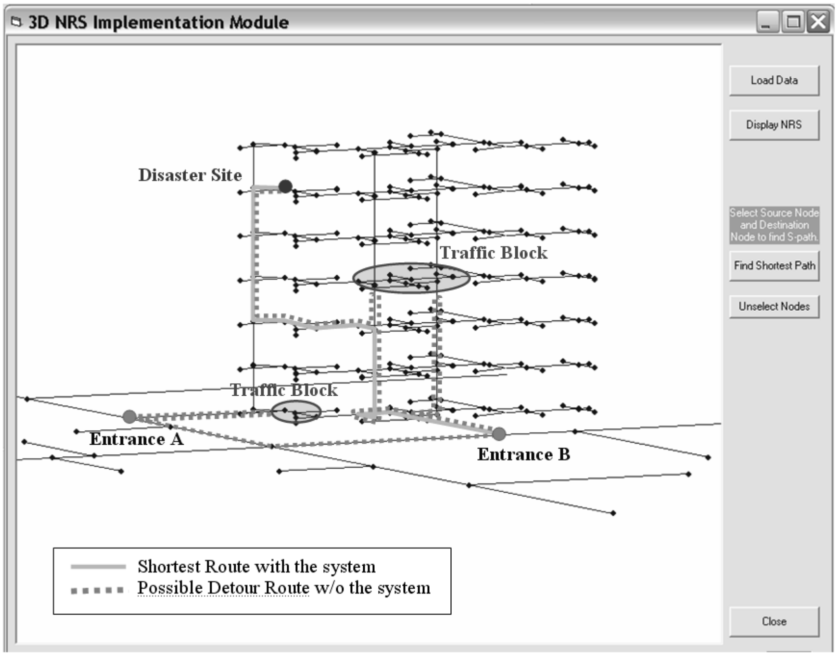
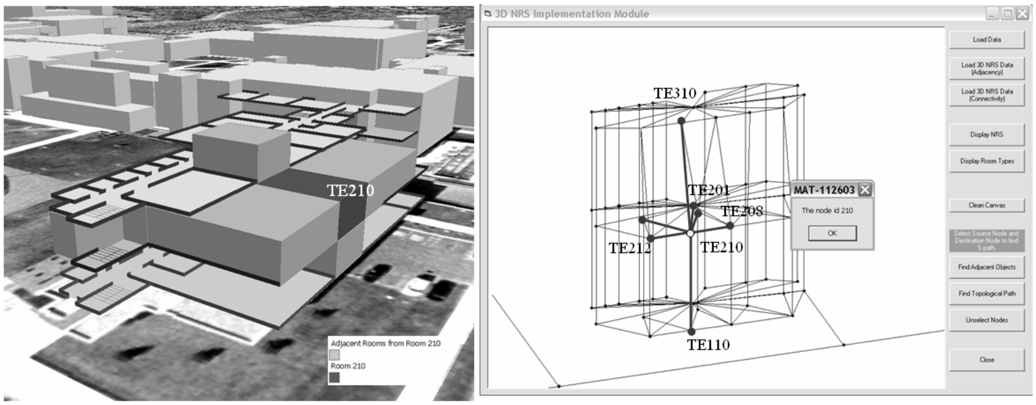


Figure 13: The shortest path between two entrances (A and B) and a disaster site on the 42nd floor of the building] (from Kwan & Lee, 2005)



(a) (b)

Figure 14:Adjacency relationships from TE210 (from Lee&Kwam, 2005)

7 CONCLUSSIONS

3D geospatial information has always faced challenges due to a variety of data models and no common data models. After 9/11 the interest of 3D models representing micro-spatial entities (buildings or undergrounds) in emergency responses has been progressively increasing. Although such models are mostly available from the design phase (as CAD models), design CAD models are in most cases, too detailed for computing evacuation routes. Therefore, this chapter proposed a data model to represent and to analyze 3D geospatial data in emergency management systems for field workers and decision makers. However, CAD models and their standard representations (e.g. IFC) have to be further studied with respect to easy elimination of unnecessary details and automatically generation of simple multi-level structures, which can be used for emergency evacuations.

This chapter described the algorithms of 3D spatial data manipulating and analytical methods to implement the planning/decision making process, which are 3D topological analysis (3D buffering) and an indoor navigation function to identify feasible and safe routes within a multi-level structure and to provide navigation guidance for rescue personnel. Also, this chapter presented the experimental implementations of 3D topological analyses, which are spatial queries based on adjacency relationships among the 3D spatial units, and 3D shortest route for evacuation from a building.

While focusing on formulating a conceptual framework of a 3D data model for ER this chapter ignores several important elements in developing a real-time emergency response system. First, successful implementation and use of the ER system depends on the availability of accurate real-time information about the emergency situation from various sources and analytical functions. The system needs to integrate with temporal databases to manage dynamic geospatial entities, which are dynamic capacities and flow rates of hallways and stairwells, in order to identify the optimal route from the source node to the destination node and the building evacuation bottlenecks within the network in real-time emergency situations. The proposed 3D Shortest Path algorithm needs to be improved in order to treat traffic cost or impedance variables as a function of all routes to predict the amount of flow per time period on the 3D network.

Additionally, several important functionalities for ER should be developed, including a 3D location positioning, a network connectivity analysis, and other topological analyses to define isolated networks or areas, which do not have any exit node connecting to destination nodes because of being blocked by traffic congestions or disaster. Lastly, the ER system should explore geo-referenced virtual environments in 3D Virtual Reality (VR) systems (Liu & Zhu 2006). Evacuation instructions sent from the emergency center to rescuers via wireless communication networks will be displayed on mobile devices with the 3D VR system. The virtual reality IBE system will be a major step in providing 3D location-based services to indoor urban areas.

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