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Emergency response after 9/11: the potential of real-time 3D GIS for quick emergency response in micro-spatial environments

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Abstract

Terrorist attacks at the World Trade Center (WTC) in New York City and the Pentagon on September 11, 2001, not only affected multi-level structures in urban areas but also impacted upon their immediate environment at the street level in ways that considerably reduced the speed of emergency response. In this paper, we examine the potential of using real-time 3D GIS for the development and implementation of GIS-based intelligent emergency response systems (GIERS) that aim at facilitating quick emergency response to terrorist attacks on multi-level structures (e.g. multi-story office buildings). We outline a system architecture and a network data model that integrates the ground transportation system with the internal conduits within multi-level structures into a navigable 3D GIS. We examine important implementation issues of GIERS, especially the need for wireless and mobile deployment. Important decision support functionalities of GIERS are also explored with particular reference to the application of network-based shortest path algorithms. Finally, we present the results of an experimental implementation of an integrated 3D network data model using a GIS database of Franklin County, Ohio (USA). Our study shows that response delay within multi-level structures can be much longer than delays incurred on the ground transportation system, and GIERS have the potential for considerably reducing these delays.

Keywords: Emergency response; Intelligent GIS; 3D GIS; Spatial decision support systems; Micro-spatial environments

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1. Introduction

Terrorist attacks at the World Trade Center (WTC) in New York City and the Pentagon in Washington, DC, on September 11, 2001, resulted in serious structural damage or collapse of buildings. Like other similar disasters (e.g. the bombing of the Alfred P. Murrah Federal Building in Oklahoma City on April 19, 1995), these events not only affected multi-level structures in urban areas but also impacted upon their immediate environment at the street level in ways that considerably reduced the speed of emergency response. The complex internal structure of these buildings and the restricted number of access points at the street level also render speedy escape and rescue particularly difficult in any emergency situation. When disasters occur in this kind of complex multi-level structures, a short period of time (e.g. 5 min) may mean significant change in the disaster environment within which trapped people have to escape and rescue personnel have to operate.

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 navigable 3D GIS data models (Lee, 2001a, 2001b). 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.

While it may be difficult to avoid enormous casualties in a major structural collapse, establishing an intelligent real-time 3D GIS that facilitates speedy escape and quick rescue in emergency situations may have the potential for considerably reducing casualties. In light of the fact that about 80 floors of both WTC towers were largely unaffected for at least 50 min after the plane strikes on September 11, accurate information derived from an operational real-time GIS-based intelligent emergency response system and disseminated quickly to people inside the buildings and emergency personnel might have ameliorated the effects of the disaster.

In this paper, we examine the potential of using real-time 3D GIS for the development and implementation of GIS-based intelligent emergency response systems (GIERS) that aim at facilitating quick emergency response to terrorist attacks on multi-level structures (e.g. multi-story office buildings). We outline a system architecture and a network data model that integrates the ground transportation system with the internal conduits within multi-level structures into a navigable 3D GIS. We examine important implementation issues of GIERS, especially the need for wireless and mobile deployment. Important decision support functionalities of GIERS are also explored with particular reference to the application of network-based shortest path algorithms. Finally, we present the results of an experimental implementation of an integrated 3D network data model using GIS data of an area in downtown Columbus, Ohio (USA). We evaluate the benefit of using such a 3D network and conclude that GIERS built upon an integrated real-time 3D GIS have considerable potential for improving the speed of emergency response after terrorist attacks on multi-level structures in urban areas.

2. Emergency management information systems

An emergency management information system (EMIS) is a decision support system that integrates all phases of emergency management and response (Galloway, 2003; Tzemos & Burnett, 1995). It supports the emergency manager in planning and training for responding to emergencies in the pre-emergency phase, and in coordinating and implementing evacuation and/or rescue operations during the emergency response phase. Emergency planners use such systems to display and analyze the spatial relationships among possible event locations, shelters and other emergency management facilities and resources, transportation routes, and population at risk. An EMIS also allows the animated visualization of the temporal progression of both the hazard situation and the evacuation of the affected population from a disaster site. Response time and real-time data are important elements for an effective EMIS, which enables emergency operators to accurately evaluate and quickly implement emergency response plans so as to reduce the risk to the affected population.

Since most existing EMIS are designed and developed for handling emergencies in 2D environments, there are serious limitations when applying these systems to disasters that affect multi-level structures (e.g. multi-story buildings and subway stations). In order to respond to emergencies that occur in 3D micro-spatial environments, it is necessary to know which rooms and floors are affected, the current occupancy pattern, and which routes inside the structure are feasible and safe for reaching them. In addition, multi-level structures may also have several basement layers, with underground subway, gas, water and electricity lines that considerably increase the risk and complicate the tasks of emergency response (Cahan & Ball, 2002). An intelligent emergency response system, under the overarching framework of EMIS, therefore needs to incorporate 3D GIS capabilities and functionalities for representing the 3D structure of micro-spatial environments (e.g. internal structure of buildings) and conducting GIS-based analyses to provide real-time navigation guidance both for reaching the disaster site and for negotiating within a multi-level structure under emergency situations. In the rest of the paper, we focus mainly on the response phase of emergency management. The next section describes a system architecture and outlines some essential components and functionalities of a GIS-based intelligent emergency response system (GIERS).

3. System architecture of GIERS

A GIS-based intelligent emergency response system (GIERS) is a spatial decision support system that aims at facilitating the coordination and implementation of quick emergency response operations such as evacuation and rescue. It not only incorporates important geospatial data about the emergency situation at hand, but also has spatial analytical and modeling capabilities to facilitate better planning and decision making (Birkin, Clarke, Clarke, & Wilson, 1996). A GIERS is an intelligent system in the sense that it has reasoning capabilities for dealing with dynamically changing and uncertain disaster environments. It uses techniques in artificial intelligence (e.g. neural networks and agent-based modeling) to solve ill-structured problems and to provide decision support when facing uncertainty.

In order to enable quick emergency response and effective reduction of the risk to the population, a number of functionalities are critical to a GIERS. These include the collection and dissemination of data in real-time, as well as the capability to analyze disaster events, to model and simulate possible trajectories of change, to formulate alternative decision scenarios, and to communicate decisions and desirable actions effectively among all affected persons and emergency personnel (see Kwan (2003) for a discussion of these functionalities). Further, a GIERS needs to provide information and decision support to emergency operations at a suitable spatial scale and resolution. These functionalities in turn need to be built upon the foundation of several important components in the context of responding to terrorist attacks on multi-level structures in urban areas. They include a navigable 3D GIS, a real-time geographic database, a suite of decision support functionalities, and a distributed information architecture that is implemented through wireless and mobile communications technologies.

A possible system architecture of a GIERS is shown in Fig. 1. It illustrates that a GIERS is part of an emergency management information system (EMIS), and that it integrates the ground transport component based on an intelligent transportation systems (ITS) with the route systems of the multi-level structures in an urban area through a series of intelligent building systems (IBS). Both ITS and IBS were originally developed for purposes other than emergency response, but they can play an important role in GIERS because they have deployed advanced real-time data collection and dissemination technologies that will be particularly useful for acquiring and conveying knowledge about a disaster environment.

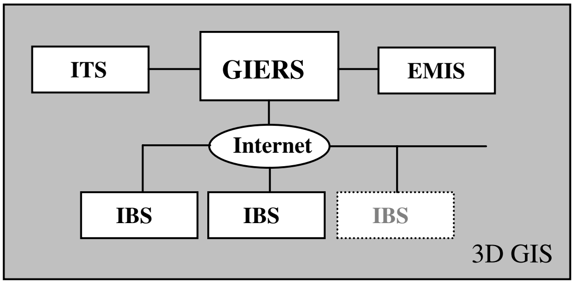


Fig. 1. System architecture of a GIERS.

3.1. Intelligent transportation systems

An important component of a GIERS is an intelligent transportation system (ITS), which uses advanced communications and transportation technologies to achieve traffic efficiency and safety. ITS were originally designed and developed as an innovative application of advanced computer, communications, and sensor technologies in transport and traffic management (Choy, Kwan, & Leong, 2000; Kwan, 1997). The ITS component of a GIERS is based on a geographic database that stores and manages information about the transportation network (such as attributes of its links and its topology). Its real-time traffic detection component acquires and updates dynamic traffic information such as route condition and traffic delays in real-time using various types of sensors (Choy et al., 2000). It performs search for optimum routes and provides navigation guidance to emergency vehicles for quickly reaching disaster sites. The ITS component of a GIERS is therefore responsible for several important functions with respect to the transportation element of an emergency response situation, including data acquisition, data transmission, and control-rescuer equipment interaction (Frenzel, 2001).

3.2. Intelligent building systems

Another important component of a GIERS deals with the internal structure of multi-story buildings such as their internal horizontal and vertical routes. This component will be useful for identifying feasible and safe routes within a multi-level structure and for providing navigation guidance for rescue personnel. It is based upon a set of interconnected intelligent building systems (IBS) (Fig. 2). These systems were originally developed to provide a productive and cost-effective environment through optimization of a building's four basic components—structure, systems, services and management—and their interrelationships (Bushby, 1997; Carlson & Giandomenico, 1991). Each IBS is composed of numerous sensors, effectors and control units that are interconnected. Sensors used include temperature and light-level detectors, movement or occupancy sensors, pressure pads, smoke or gas detectors, and fire detectors. Devices being controlled by the system include heating, lighting, ventilation, alarms, automatic doors, and vertical transportations (e.g. escalators and elevators). An IBS optimizes operations across building control systems. For example, in the case of fire, the fire alarm communicates with the security system to unlock the doors. The security system communicates with the heating, ventilating and air conditioning (HVAC) system to regulate the flow of air to prevent a fire from spreading (Fig. 2).

Because an intelligent building consists of a network of room-based embedded agents covering the entire building (Reyes, Barbr, Callaghan, & Clarke, 2001), the physical and logical unit of an IBS is a single room. A building is regarded as a combination of different types of rooms, compartments, and connecting conduits (e.g. rooms, corridors, elevators and stairways). In addition, the control functions of an IBS are assigned and allocated based on room units because human behavior is often associated with a particular type of room (Sharples, Callaghan, &

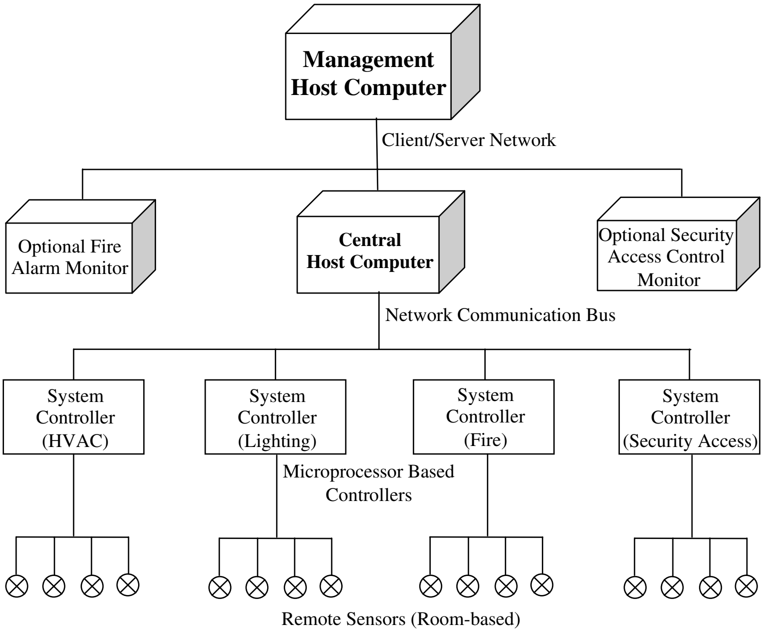


Fig. 2. Architecture of an intelligent building system (IBS) (adapted from Carlson & Giandomenico (1991)).

Clarke, 1999). Each room contains sensors and output devices, which are monitored and controlled by an IBS and are connected together via a communications protocol—like BACnet (Bushby, 1997) or Universal Mobile Telecommunications System (UMTS) (Reyes et al., 2001)—to transfer the sensed data among the control systems. Using Intranet and Internet network technologies to access information and to control multiple building subsystems, an IBS is able to communicate with different agencies and organizations such as the police, fire stations, shopping malls, banks, and other IBS systems. A Web-enabled IBS can be accessed to control or monitor important systems or events from any PC with an Internet connection.

In order to provide the real-time data necessary for emergency response operations in multi-level structures, the data-acquisition system of an IBS needs to be extended to include specific types of sensors that can detect and communicate critical real-time data such as the presence and number of occupants and the disaster situation (e.g. temperature). All of the sensed data are transmitted by Web-enabled technologies to a GIERS control center for analysis and compilation for its ultimate use. The GIERS control center is set up to acquire, process and communicate information about various emergency environments in real-time. Using Internet GIS technologies, mobile emergency response crews can access real-time information about the disaster situation and environment. The leaders of rescue teams can also transmit instructions to coordinate rescue operations among rescuers in action over a disaster site.

4. Mobile and wireless implementation of GIERS

Some important lessons about the deployment and implementation of GIERS in real world situations were learned from the WTC experience. After the WTC attacks, critical emergency response and information infrastructure was seriously disrupted. Affected facilities include New York City's Emergency Operations Center at 7 WTC, the switching facility of a major phone company in WTC, and part of the mobile phone infrastructure at the site (Cahan & Ball, 2002; Kant, 2002). Further, as emergency crews undertake rescue operations in a disaster site, they are mobile and cannot rely on wired connections for information and decision support from a real-time GIERS. To remain operational even in a disaster situation, a GIERS needs to be built upon a highly flexible and distributed system architecture, where the 3D GIS database and decision support functionalities remain accessible to emergency personnel through multiple channels via wireless and mobile communications technologies. These include notebook computers as well as various handheld and mobile devices with wireless communications capability. These channels and devices, as well as the information architecture that describes the data flows across the system are shown in Fig. 3.

First, a GIERS uses the sensed data obtained from a series of IBSs to identify event locations (e.g. fire) based upon sensor locations or sensor identities; to identify current occupancy pattern and the number of users in each room from access control systems such as the SmartCard system; and, finally, to implement quickly and accurately emergency response plans. All of the sensor data obtained through IBS are transmitted through hard-wired or wireless networks to the central unit of a GIERS.

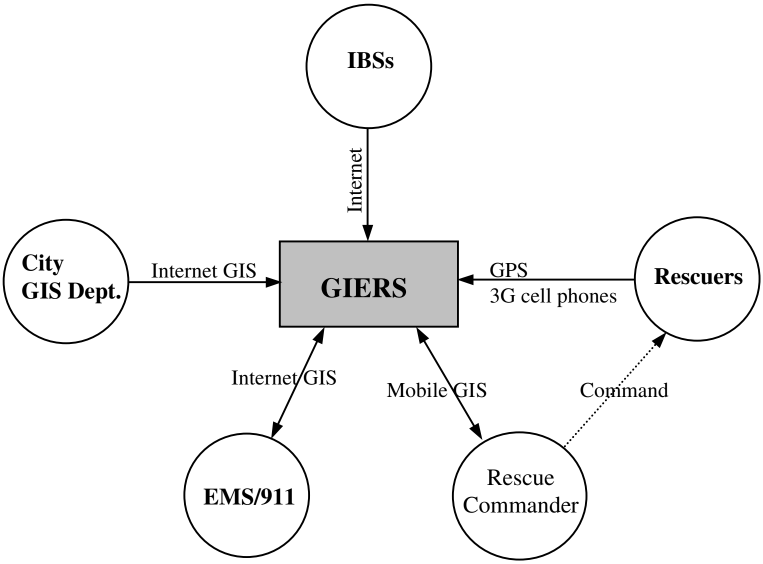


Fig. 3. The information architecture of a GIERS.

This unit then incorporates the IBS data into a real-time 3D geographic database that allows for GIS-based analysis and visualization.

To be operational and effective, a GIERS requires detailed knowledge of both the disaster situation with respect to the internal structure of a building and its current occupants. While the information on the building's structure, control systems and occupancy is transmitted from a series of IBSs connected to a GIERS, reliable information on occupancy and their locations within the building cannot be obtained solely with conventional sensors in IBS—especially in the cases where a building does not have an advanced access control system. An additional source of the locational information of current building occupants, as conceived in our information architecture, is transmission via their 3G (third generation) cell phones. These phones are currently under development in order to meet the Phase II requirements of the US Federal Enhanced-911 (E911) mandate, which requires wireless carriers to provide the 911 caller's location to the appropriate public safety answering point (PSAP). Under this Federal mandate, all cell phones are required to have the capability to announce their location (location notification) and communicate this information effectively through an emergency E911 call center (Fig. 3). Cell phone carriers are developing location notification capability for their cell phones either through an embedded GPS receiver or a proprietary location system they designed and developed. Some carriers use the signals from their cellular network and triangulation to identify the position of a cell phone user (Frenzel, 2001).

Further, emergency and rescue crews operating within multi-level structures under a disaster condition will be equipped with GPS receivers and other mobile or handheld communications equipment that interact in real-time with the rescue command center of a GIERS. These GPS receivers provide location information that is transmitted via cell phones or mobile GIS devices. In addition, these locational devices are equipped with mobile GIS software (such as ArcPad) and can generate on-screen georeferenced maps to support rescuers' operations on-site (e.g. providing navigational guidance). The location information generated by these GPS is in turn transmitted back to the rescue command center in real-time for the purpose of locating emergency crews and disaster events and conditions within the multi-level structure. 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. Although there is currently some development in the location-based service (LBS) sector that seeks to provide better coverage of location information inside buildings, and the network-based or hybrid positioning technology used by most LBS providers can achieve a positional fix faster and easier than conventional GPS-based technology, the problem of loss-of-fix in LBS-derived location data cannot be entirely eliminated. Much future research is still needed to address this problem (Kwan, 2001).

Fig. 3 provides an overall picture of this information architecture. It describes the communication and data flow among the mobile and non-mobile components of a GIERS across the system. In summary, a GIERS can access geographic data about the urban environment—including the transportation network, land parcels and building footprints—via Internet GIS technologies and infrastructure operated by city/municipal GIS department. Real-time information about individual units within multi-level structures such as current room use is transmitted from a series of intelligent building systems (IBS) through a hard-wired or wireless network. A GIERS can also acquire additional data about the locations and conditions of the disaster environment within a building through fire and heat sensors, as well as other access control detectors. When an IBS fails or has been destroyed by a disaster, other real-time data on the disaster may be obtained from emergency crews with GPS receivers and mobile and wireless communications devices. The collected data are analyzed and transmitted to the emergency response command center for supporting spatial decisions pertinent to various rescuer operations, including the search for optimal routes for reaching certain units in a multi-level structure or for evacuating the affected population. Through this distributed and wireless information architecture, information about the current condition of the disaster environment can be collected and disseminated in real-time to support emergency operations.

5. Network-based functionalities of GIERS

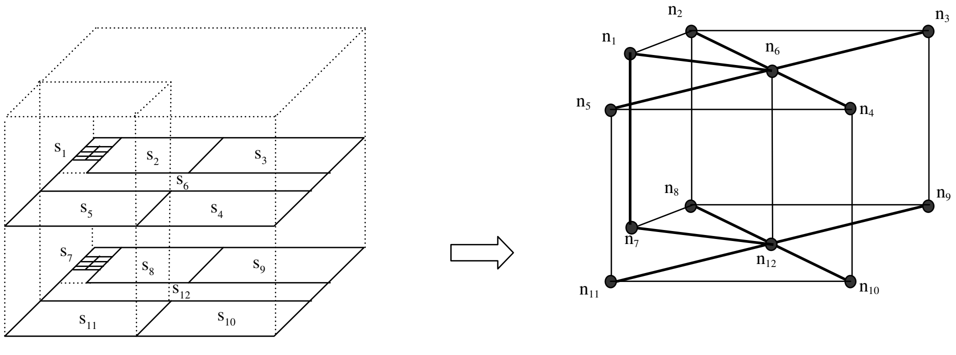
A critical element of a GIERS is its decision support capabilities, which in turn depend on a suite of analytical, modeling and simulation functionalities. These include interactive 3D geovisualization (Kwan, 2000; Kwan & Lee, 2003), multi-dimensional GIS modeling (Raper, 2000), rule-based methods, agent-based modeling, pattern recognition and spatial data mining algorithms (Abler & Richardson, 2003; Galloway, 2003; Miller & Han, 2001). These will be especially useful in emergency situations because the limited human knowledge and ability to deal with highly unstructured and complex problems may be assisted through these methods. Another important area is the capability to simulate current disaster situation and generate alternatives using all the information available at the moment. Simulation models also need to be developed for evaluating the propagation of risk to the adjacent areas of the disaster site, and to predict how a disaster situation will evolve and affect additional population and areas. Further, the real-time 3D GIS of a GIERS also needs to incorporate various types of geographic information, especially remotely sensed images or elevation data collected through laser-based light detection and ranging (LIDAR) technology before and after a terrorist attack (Bruzewicz, 2003). It should be able to represent a variety of less structured phenomena associated with the consequences of different kinds of terrorists attacks, and be highly editable and adaptable to real-time changes in the disaster environment.

Given that the notion of lifelines is important in the emergency management literature, and that lifelines are physical or virtual networks that are vital to the well-being of everyday life (Platt, 1995), network-based analytical capabilities are essential in a GIERS. These capabilities include finding the fastest route to reach a disaster site based on real-time traffic conditions, providing navigation guidance to emergency personnel operating inside a multi-level structure, finding the most effective and safest route for evacuating the affected population, and assessing the risk of various rescue or evacuation plans (Cova & Church, 1997; Kwan, 2003). Conventional 2D GIS and emergency response systems, however, do not allow for these kind of network-based analytical tasks when multi-level structures are involved in a disaster situation. This limitation is not only due to the unavailability of data about the internal structure of buildings, but also due to a lack of navigable 3D GIS data models that support network functionalities. For instance, the 3D GIS data models developed in recent years, such as those by Billen and Zlatanova (2003) and Coors (2003), are not navigable and therefore cannot be used to perform path-finding or routing algorithms that are important to emergency operations. To determine the optimal route for rescue and evacuation in a multi-level disaster environment in real-time, a GIERS therefore needs to be built upon a 3D network data model, which integrates the 2D GIS that handles the ground transportation system with the 3D GIS that deals with the relevant micro-spatial environment (e.g. internal structure of multi-level buildings).

In what follows, we describe such a 3D network data model based upon the work of Lee (2001a, 2001b). The data model is used to represent the internal structures of buildings and to integrate these structures with that of the ground transportation system into a navigable 3D GIS. We begin with a description of the node-relation structure, and then outline the derivation of a logical network data model and a geometric network data model that can be used for network-based analysis such as optimal route algorithms. The next section discusses an experimental implementation of this network data model for evaluating its potential for improving the speed of emergency response.

The fundamental element of the 3D network data model used in this study is a node-relation structure (NRS), which is a topological data model representing the adjacency, connectivity and hierarchical relationships among discrete objects in 3D space. Due to the complexities and the variety of connected objects in micro-spatial environments (e.g. rooms and corridors inside a building), the NRS is derived using two data models: the logical data model and the geometric data model (see Lee (2001a) for a detailed exposition of the steps involved, and also Chapter 8 of Zeiler (1999)). The logical data model is used to abstract and represent the topological relationships among discrete 3D objects. It is derived through Poincaré Duality using a graph-theoretic framework and a hierarchical representational schema (Lee, 2001a, 2001b). The geometric network data model is used to represent the geometric properties of objects in 3D space (e.g. location in 3D space, distance between two rooms and length of a corridor). As distances are accurately represented in the geometric network and topological relations are represented in the logical network, the NRS allows for the implementation of network-based analysis such as shortest path algorithms (Figs. 4 and 5).

The logical data model of the node-relation structure (NRS) is derived through Poincaré Duality, which abstracts the topological relations among a set of 3D objects and transforms '3D to 2D relations' in primal space to '0D to 1D relations' in dual space (Lee, 2001a). It represents adjacency relations among objects in 3D space as a dual graph, $G = (V(G), E(G))$. For connectivity relations in the NRS, the graph $H = (V(H), E(H))$ is a subgraph of the graph $G = (V(G), E(G))$ because of $V(H) \subseteq V(G)$ and $E(H) \subseteq E(G)$. Because the logical data model is a dual graph, which consists of sets of 0-cells (nodes) and 1-cells (edges), the graph structure of the

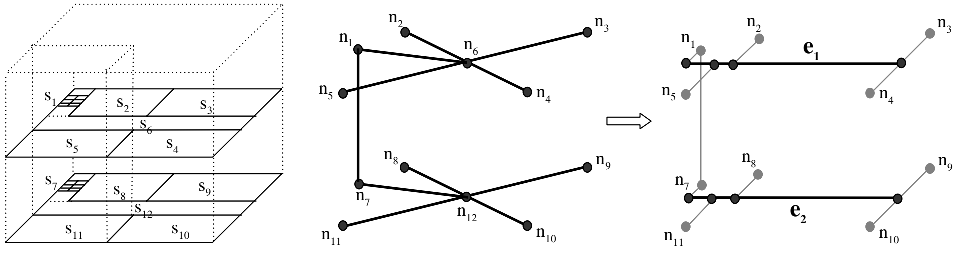


(a) (b)

Nodes:
$N = \{n_1, n_2, n_3, \ldots\ldots, n_{12}\}$

Edges:
Adjacency Relations:
$E(G) = \{ea_1, ea_2, \ldots\ldots, ea_n\}$
Connectivity Relations:
$E(H) = \{ec_1, ec_2, \ldots\ldots, ec_m\}$
$E(H) \subseteq E(G)$

Fig. 4. An example structure (a) and its node-relation structure (b).



(a) (b) (c)

Fig. 5. A node-relation structure (NRS) for representing topological relations among objects in 3D space. (a) 3D spatial objects, (b) logical network, (c) geometric network.

duality of 3-complexes can be formalized using graph theory (Fig. 4b). Finally, the connectivity relationships between 3D objects in each floor within a building are represented as subnetworks and consolidated to a single node in the higher level, and as the relationships between different levels of subnetworks.

The logical data model is a pure graph that represents the adjacency, connectivity and hierarchical relationships among the internal units (e.g. rooms and corridors) of a building. It does not represent the geometric properties (e.g. size or distance) of and between these units. In order to implement network-based analysis such as shortest path algorithms in the NRS, the logical network data model needs to be complemented by a geometric network model that accurately represents these geometric properties (Fig. 5b and c). One key step in the process is to identify linear features from a simple polygon (a corridor) using straight medial axis transformation (S-MAT) instead of abstracting a node in the logical data model (Lee, 2001a).

Based upon S-MAT, hallways are transformed into linear features, which are subnetworks consolidated into hallway nodes in the logical network (Fig. 5c). Each node representing a room of a building is projected and connected into the medial axis if there is a connectivity relation. The graph $Nh_i = (V(Nh_i), E(Nh_i))$ representing the geometric network within floor i is combined with the graph $Nv = (V(Nv), E(Nv))$ using a UNION operation to produce the graph $N = (V(N), E(N))$, which is the geometric network model of the NRS. The graph $Nv = (V(Nv), E(Nv))$ is a subgraph of the logical network model, which represents the connectivity relations of rooms in the vertical direction. The reconstructed geometric network model generated after the transformation can be used as the 3D GIS data model for analyzing the complex spatial relations among rooms of a building and for performing network-based routing and search algorithms.

Based upon the above processes, the 3D geometric network model ($N_i = (V(N_i), E(N_i))$) representing the connectivity relations between the rooms of a building i is generated (Fig. 5c). The 3D geometric network, $N_i = (V(N_i), E(N_i))$, needs to be integrated with the 2D network of the ground transportation system for implementing a GIERS using a 3D network, $R = (V(R), E(R))$. The 2D street network can be represented by a graph, $S = (V(S), E(S))$. The first step for the integration is to define the connectivity relations between a building and the street network, which is abstracted to Connected_edges, where Connected_edges, $E(C) = \{(n_i, n_j)/n_i \in V(N_i) \text{ and } n_j \in V(S)\}$. The node n_i represents entrance halls of the buildings and the node n_j are defined by projection $p(n_i, E(S))$ of node n_i onto edge $E(S)$ of the street network, S. The connectivity relation is represented by a connecting network, $C = (V(C), E(C))$. In the final step of constructing a 3D network $R = (V(R), E(R))$ of a GIERS, the 3D geometric network ($N_i = (E(N_i), E(N_i))$), 2D street network ($S = (V(S), E(S))$) and the connecting network ($C = (V(C), E(C))$) are combined using a UNION operation because each network graph is equivalent in class. The combined network describes the connectivity relationships not only between objects in 3D space (e.g. rooms and corridors) within a building but also between buildings within the urban area.

To formalize a network structure consisting of nodes V and edges E, the schema of the objects is shown in Fig. 6. The primal classes of the model are Node, Edge, and Network. A node consists of an identifier and a position data in 3D (x, y, z-coordinates), and an edge consists of an identifier, start node, and end node. The class Network consists of an identifier and lists of all nodes and of all edges in a network. The database schema for attribute data of class Node and Edge is as follows:

NODE(Node_ID, RoomUse, Occupancy, Sensor_Data, Disaster_Status)

EDGE (Edge_ID, Length, Traffic_Capacity, Speed, Occupant_NO, Impedance)

```
class Node {                        class Edge {
             Int Node_ID;                        Int Edge_ID;
             Double x, y, z;                     Node initial_node;
             };                                  Node end_node;
                                                 };


class Network {
             Int Network_ID;
             Node ArrayNode = new Node[];
             Edge ArrayEdge = new Edge[];
             };
```

Fig. 6. A network data model.

Each node in the database has an identifier, room use, occupancy data, and sensed data collected by numerous sensors including temperature, smoke, gas, and fire detectors. Because the unit of IBS is a single room, the sensed data provide room-based information that is also a description of node characteristics in the 3D network. An edge has an identifier, population in each room, occupant movement, elevators/stairway capacity, corridor capacity and traffic flow impedance. Most of these data can be obtained by various types of sensors and transmitted via the communications infrastructure of an IBS in the context of a GIERS.

6. Experimental implementation of the 3D network data model

To evaluate the potential benefit of a navigable 3D GIS for improving the speed of emergency response, we undertake an experimental implementation of a system based upon the 3D network data model described in the last section. The components of the system were constructed in the Visual Basic development environment. These components include a 3D node-relation structure (NRS) implementation module, a relational database system accessible via Open Database Connectivity (ODBC) or ActiveX Data Object (ADO), a GIS software package accessible via Object Linking and Embedding (OLE) or ActiveX controls, and other program routines stored in Dynamic Link Libraries (DLLs) (Lee, 2001a). The data set used for our implementation is drawn from a comprehensive GIS database of Franklin County (Ohio, USA), where the study area Columbus City is located. This data set provides GIS data for the 453,536 buildings and 346,431 parcels in Franklin County. The digital street network we use contains 47,200 arcs and 36,360 nodes. Preparatory work in transforming and visualizing these data in 3D has generated over 1.4 GB data. For the implementation of the 3D network, we extract the node-relation structure (NRS) of Franklin County Municipal Building located in downtown Columbus (Ohio) using the procedures outlined in the last section. This NRS is then connected with the street network at the building's entry points to create the final network used for the study.

Using the system and the GIS data of the study area, we evaluate the impact of three types of uncertainty responders often encounter in emergency situations on the speed of response: (a) road network uncertainty; (b) entry point uncertainty; and (c) route uncertainty within a building. Road network uncertainty is the uncertainty about the fastest route for traveling from the dispatching location of the rescuers (e.g. a fire station) to the entry point of the building hit by a disaster. This type of uncertainty exists because the shortest path (evaluated by travel time) under normal circumstances from the fire station to the disaster site may not be the shortest path under emergency situations due to the sudden evacuation of people, the blockade by debris or unexpected traffic. It may lead to considerable delay in reaching the disaster site if the actual shortest path is not used. Entry point uncertainty is the uncertainty about which entry point of the building hit by disaster is feasible. Without prior knowledge about the feasible entry points, emergency responders may arrive at a ground-level entry point that cannot be used (e.g. blocked by debris). They may need to walk around the building in order to use another entry point on the other side. This introduces additional delay in the speed of emergency response. Route uncertainty within a building is the uncertainty about the feasible and fastest route from a feasible ground-level entry point to a destination point within the building. For instance, in an attempt to reach a room without prior knowledge of which stairways are feasible and safe, rescuers may be blocked in the middle and have to go back down to the ground level and use another stairway to go up again.

To evaluate the effect of these three types of uncertainty on the speed of emergency response, the 3D network $R = (V(R), E(R))$ of a GIERS is implemented as a directed graph (or digraph). It is operationalized to identify the optimal route from source node a (a fire station) through an intermediate node b (the entry point of the destination building) to the destination node c (a room on the 42th floor of a building). Many individual paths $Route(a, c)$ can be identified between node a and node c on the 3D network. The travel time for $Route(a, c)$, $RDist(a, c)$, can be represented as:

$$RDist(a, c) = SDist(a, c) + \delta(a, c)$$

where $SDist(a, c)$ is the travel time of the shortest route between the origin node a and the destination node c, and $\delta(a, c)$ is the sum of delay times for $Route(a, c)$ due to the use of non-optimal routes and/or entry points. To represent the three elements of uncertainty for $Route(a, c)$ between the fire station a and the disaster location c, the total delay time $\delta(a, c)$ can be expressed as:

$$\delta(a, c) = \delta(a, b') + \delta(b', b) + \delta(b, c)$$

where node b is the optimal building entry point, and node b' is any non-optimal building entry point. The total delay in travel time $\delta(a, c)$ is affected by the delay due to road network uncertainty $\delta(a, b')$, entry point uncertainty $\delta(b', b)$, and route uncertainty within a building $\delta(b, c)$.

Figs. 7–10 illustrate the implementation of the system for evaluating the impact of these three types of uncertainty on response time. The study area for this experimental case is an area in downtown Columbus, Ohio (USA), located in the east of Scioto River. We assume that a 250-pound high-explosive bomb exploded on the 42th floor of Franklin County Municipal Building (labeled "Disaster Site" in Fig. 7), and that the shock also caused minor damage on some other floors as well as part of the stairways inside the building. Fig. 7 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 Fig. 7) 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 Fig. 7 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

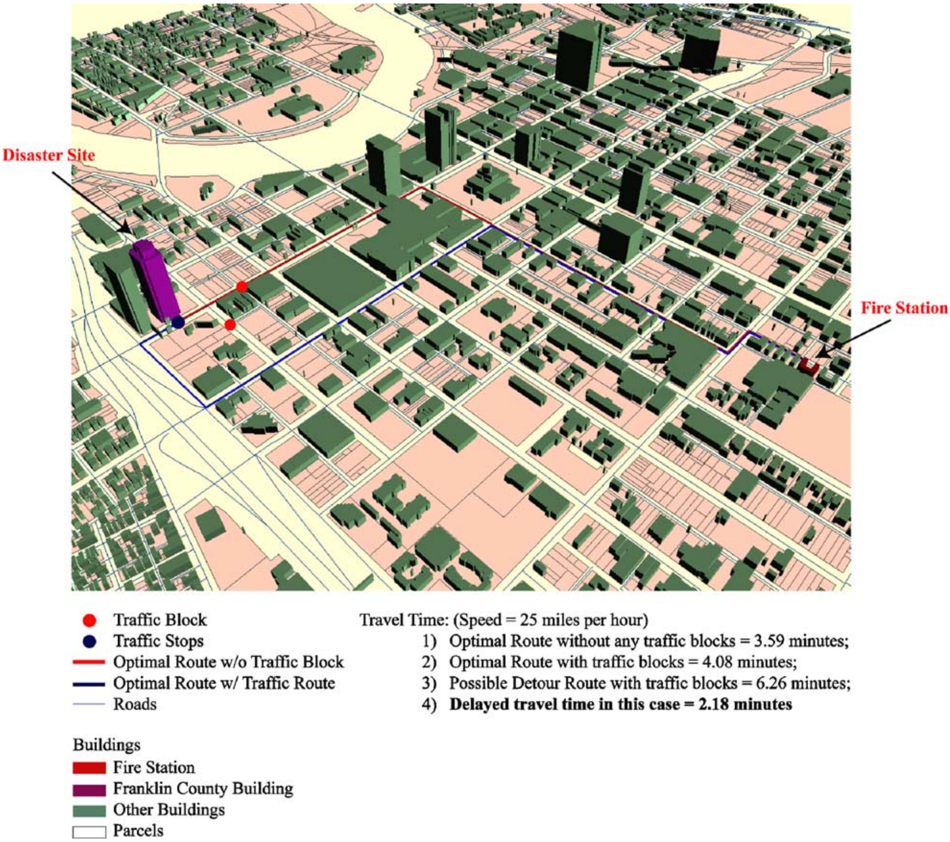


Fig. 7. The shortest path between a fire station and a disaster building (Downtown Columbus, Ohio).

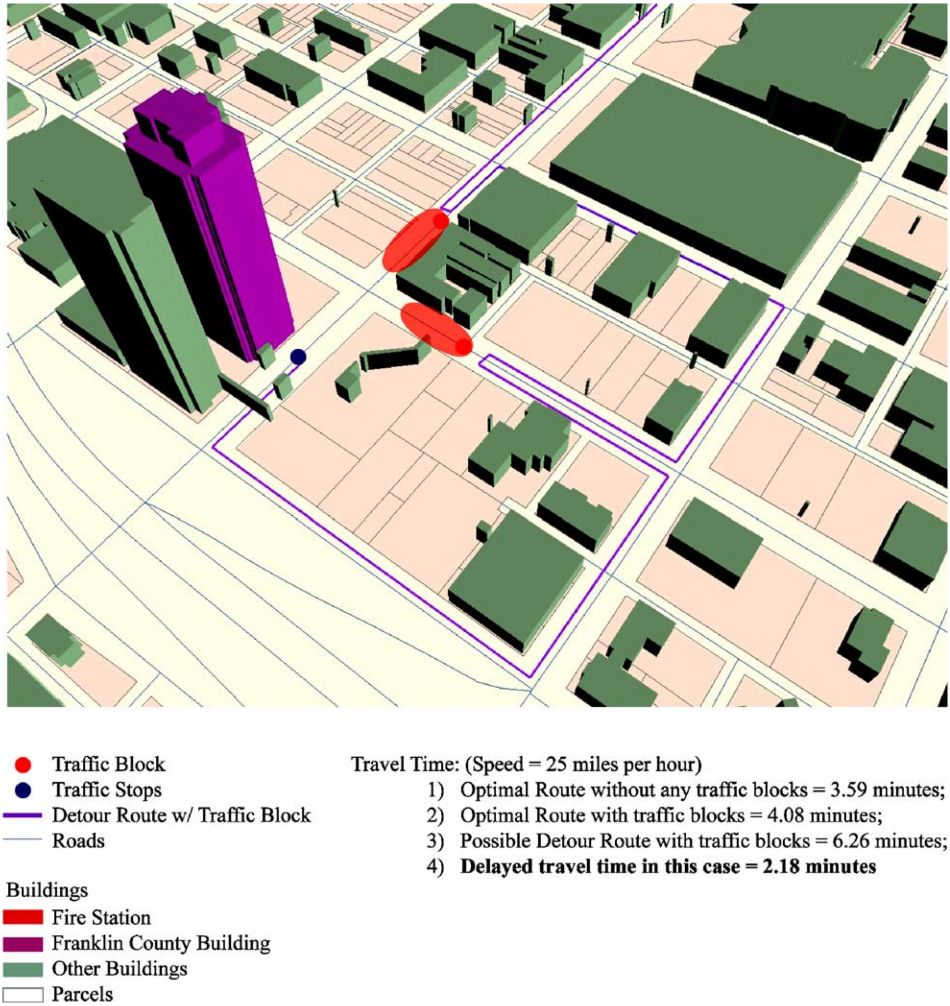


Fig. 8. A close-up view of the disaster site (Downtown Columbus, Ohio).

then, in this scenario, need to reroute twice because of the two unexpected traffic blocks (red zones in Fig. 8). The additional delay between the new optimal route (blue route) and the hypothetical detour route (purple route in Fig. 8) represents the effect of road network uncertainty on emergency response time.

After arriving at the disaster building at Entrance A (Fig. 9), emergency responders discover that this entrance is blocked by debris and cannot be used to reach the destination room (disaster site) on the 42th floor (Fig. 10). They then walk to another side of the building in order to use Entrance B (Figs. 9 and 10). These responders are, however, blocked at the 28th floor as they attempt to walk up to the 42th floor using the stairway. They then walk down to the ground level and use another stairway to go

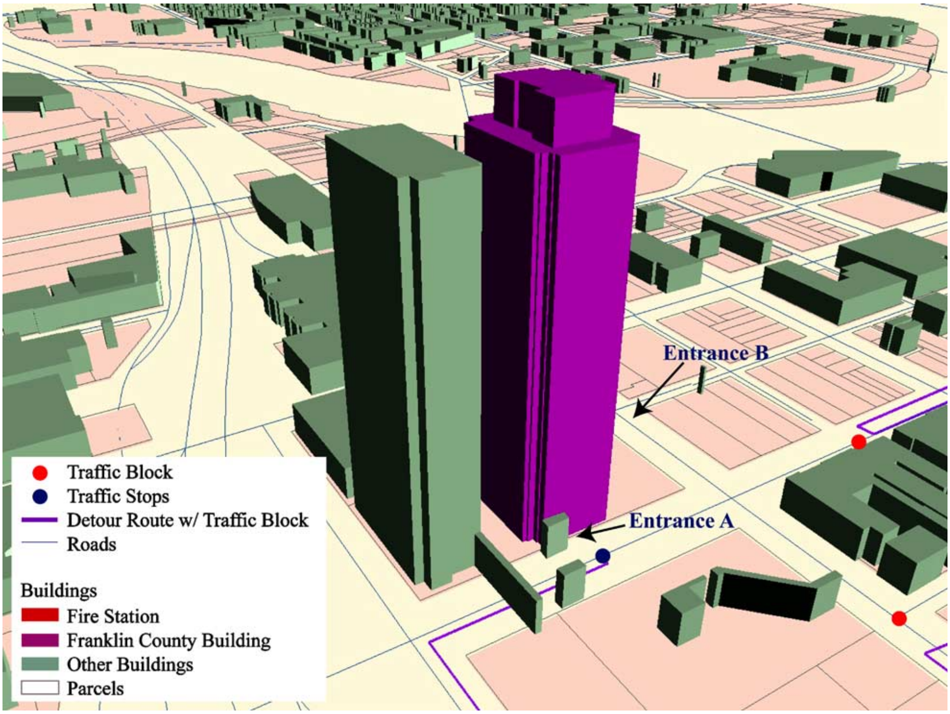


Fig. 9. Two possible entrances of the disaster building—Entrance A (visible in the figure) and Entrance B (not visible in the figure as it is on the other side of the building).

up again (Fig. 10). They are blocked on the 28th floor again and have to walk down a couple of floor and walk through some corridors to go up using another stairway (Fig. 10). The additional delay between the optimal route (green line) and the hypothetical detour route (red dotted line in Fig. 10) represents the effect of entry point uncertainty and route uncertainty in 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. Each side of the building is assumed to be 300 feet, and each floor is 16 feet in height. Thus, the 42th floor is 672 feet from the ground and will take responders 16.8 min to reach from the ground level. The shortest path from the source node a to the destination node c is found using a modified Dijkstra's algorithm that operates on the 3D network.

The results of the experiment are summarized in Table 1. It shows the additional time $\delta(a,c)$ for traveling from the fire station (*node a*) to the disaster site (*node c*) taking into account the delays caused by the three kinds of uncertainty. The total travel time it takes to reach the destination node c without using the system is 39.83

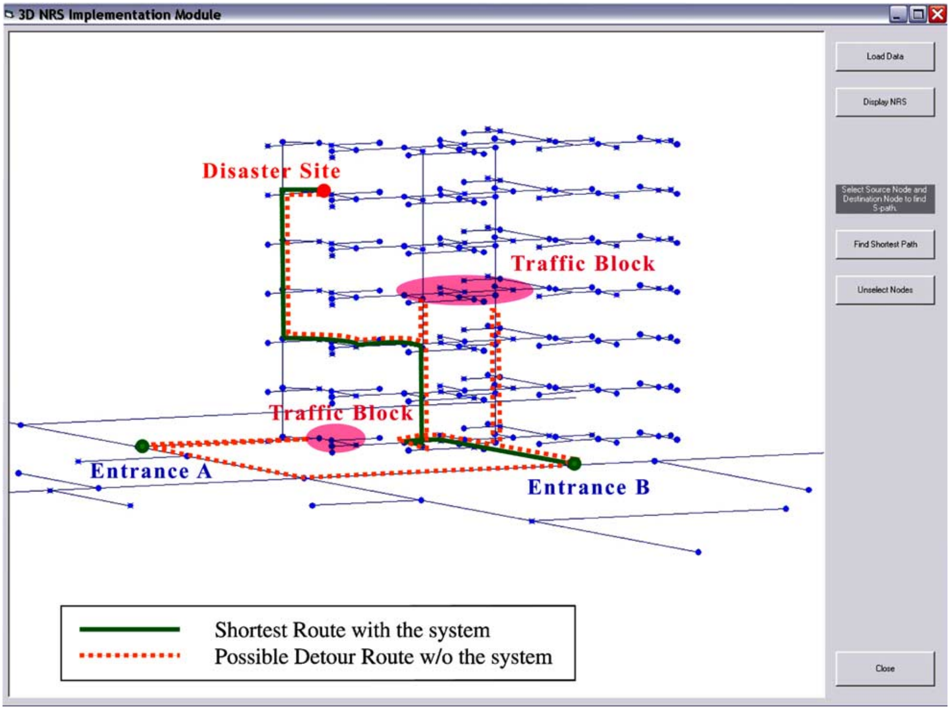


Fig. 10. The shortest path between two entrances (A and B) and a disaster site on the 42th floor of the building.

Table 1
Travel times for *Route*(a, c) with and without using GIERS

Source of uncertainty	Travel time without using GIERS (in min)	Travel time using GIERS (in min)	Delay (in min)
Road network	6.26	4.08	2.18
Entry point	3.73	0.00	3.73
In building	29.84	20.11	9.73
Total travel time or delay for *Route*(a, c)	39.83	24.19	15.64

min, while it is only 24.19 min when the optimal route found by the system is used. This means that emergency responders can reach the destination node 15.64 min 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 min 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 min. 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.

The benefit of a GIERS based upon an integrated and navigable 3D network data model would be even greater when the real world scenario is worse than that conceived in this experiment. For example, there may be more traffic blocks nearby the disaster building; the responders may have to reach the 70th floor (as in the case of the WTC disaster); and decision making without a GIERS may need considerably longer time for coming up with a desirable course of action. In addition to improving the speed of rescue operations, real-time information about the building's feasible routes disseminated to those inside may also help improve the speed and effectiveness of the evacuation process, because they can start exiting the building once they received this information. This means that evacuation can begin long before emergency responders arrive at the disaster site, and this may have the effect of saving many lives, especially if the building is becoming structurally unstable after a bomb attack or being hit by a plane.

7. Conclusion

GIS technologies and methods were useful at the WTC disaster site (Barnes, 2001; Cahan & Ball, 2002; Cutter, Richardson, & Wilbanks, 2003; Kant, 2002; Showstack, 2001). There are many lessons to be learned for the development and implementation of GIS-based intelligent emergency response systems (GIERS), and in other applications of geospatial technologies on responding to the consequences of terrorist attacks on multi-level structures in the future. This paper outlines the important elements of GIERS, including 3D GIS network data models, real-time and distributed geographic databases, mobile GIS technologies, and analytical and modeling methods. The results of an experiment conducted using the 3D network we developed and GIS data of Columbus, Ohio indicate that an integrated and navigable 3D GIS has potential to contribute in significant ways to quick emergency response to terrorists attacks.

While focusing on quick emergency response systems and the usefulness of 3D network data models, this article ignores several important issues pertinent to the development and deployment of GIERS. First, successful implementation and use of GIERS depend heavily on the availability of accurate real-time information from diverse sources. As a result, not only issues of interoperability but also issues of the willingness of various government agencies to share data are important considerations (Abler & Richardson, 2003; Goodchild, 2003; Logan, 2002; Thomas, Cutter, Hodgson, Gutekunst, & Jones, 2002). As apparent in the 9/11 experience, development of GIERS can be hampered by problems of interoperability and data sharing in addition to the technical difficulties associated with the development of new data models or emergency response systems.

Second, the comprehensive GIS data of GIERS themselves raise serious concerns about issues of data security, as data assembled for emergency response operations can be used by terrorists if they can break in the system and access these data. Means for preventing access to these data by terrorists should therefore be an integral component of GIERS. Lastly, the real-time data collection systems (e.g. occupancy sensors) of GIERS raise questions about surveillance and violation of personal privacy (Armstrong, 2002; Curry, 1997; Monmonier, 2002). There is an inevitable trade-off between the need for critical information for rescue operations on the one hand, and protecting individual human rights and personal privacy on the other (Richardson, 2002). It is important to have guidelines in place before the implementation and deployment of GIERS to ensure that private information is used ethically and according to the need of a particular emergency response situation.

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