The application of geometric network models and building information models in geospatial environments for fire-fighting simulations

Liang-Chien Chen, Chia-Hao Wu, Tzu-Sheng Shen, Chien-Cheng Chou

1. Introduction

A public fire department provides vital assistance to victims of fire in protecting their lives and property (Deng, Hsieh, Yang, & Sheu, 2001). After a fire starts, it usually spreads rapidly, and often causes a great deal of damage in a very short period of time (Mattsson & Juás, 1997). Unfamiliarity with the interior of a building may affect a firefighter’s ability to fight a fire. In a real emergency situation, the task of finding one’s way into a building becomes a challenge, especially when there is little or no visibility due to smoke or power failure. High levels of mental and physical stress may add to the difficulty. Getting lost in a burning building can have fatal consequences to a firefighter if his oxygen supply runs out. On the scene, firefighters typically have no knowledge of the interior structure, hallways, exits, etc. of a building. Typically, the only information available to fire brigades is 2D floor maps. However, floor maps do not provide detailed semantic information. In addition, a real fire scene is actually a 3D environment that includes both the interior and exterior of a building. Important information, e.g., the size and type of doors and windows, the distance from the entrance to the incident site (which is needed for the deployment of fire hoses), rescue routes, which window is accessible to the fire truck, etc., is needed for successful fire-fighting operations at a fire scene. A potential source of 3D building data is a building information model (BIM). The most important characteristics of BIMs are 3D information and semantic information. In this study, BIMs were implemented to facilitate emergency response operations in a fire situation.

At many fire scenes, especially in urban areas, fire departments have to deploy ladder trucks (with aerial equipment) for rescues, ventilation, access to upper floors and fire suppression. The greatest challenge for ladder trucks is overcoming their aerial limitations. Firefighters can add length to hoses to reach the fire, but they cannot stretch the ladders to reach the building. The operating procedures of a ladder truck include: (1) positioning truck, (2) outrigger leveling, (3) operating ladder, (4) fire-fighting operations, and vice versa. Once the parking brake is set and the outriggers are dropped, the ladder truck is in position for the remainder of the job. Repositioning will require a significant investment of effort and time. Therefore, firefighters should make all efforts to get it right on the first try. The first-in members of the crew need to evaluate the fire scene for optimal ladder truck placement, placing their trucks close enough to the building so that firefighters can use the aerial position to fight the fire. However, this can become a challenge because of competition for space at the scene (Bernocco & Andrus, 2003). For example, the placement of ladder trucks may be complicated by the positions of other fire trucks, ambulances, police cars and hose lines. Virtual 3D city models can be used in different application areas such as disaster management (Over, Schilling, Neubauer, & Zipf, 2010). Virtual reality, which involves modeling, simulation, and visualization, is a powerful technology for users to interface and interact with virtual environments. Virtual
reality has already had a significant impact on emergency management, including advanced data visualization systems within geographic information systems (GIS). Many advanced decision support systems for emergency management rely on GIS technology and virtual instrumentations (Beroggi, Waisel, & Wallace, 1995). In addition, performing a fire drill in modern cities under realistic fire conditions can be difficult. A virtual environment could provide a variety of fire-fighting scenarios for instruction and evaluation in a more realistic manner than verbal or written material and with less risk and expense than fighting real fires.

This study was motivated by the need to develop a micro-GIS to represent and analyze 3D spatial data for fire-fighting simulations. The main objective was to simulate the operation of ladder trucks in a virtual 3D environment. Before firefighters’ arrival at the scene, the best position for the ladder trucks can be determined, as well as how other vehicles should be moved to other positions to avoid blocking the ladder trucks, which is a priority. This manual operation can be performed with a graphical user interface (GUI) of the system. The area of reach of the ladder trucks can therefore be maximized and opportunities for access, rescue and elevated master streams can be identified. The rest of this paper is structured as follows. Section 2 reviews related works and Section 3 describes the system architecture. Section 4 outlines fire scenario case studies. The simulated drill is described in Section 5. Conclusions and plans for future research in Section 6.

2. Related works

GIS have been used to optimally site fire stations to minimize the response time for dispatching a crew to a fire scene (Liu, Huang, & Chandramoulli, 2006). However, in the event of a fire, the complex internal structures of buildings and traffic congestion can also make pedestrian evacuation and rescue operations difficult. Emergency response to incidents requires optimal routes not only on the streets but also within buildings (Kwan & Lee, 2005). GIS were originally developed by representing 3D real-world entities as 2D objects, i.e., points, lines and polygons, in either vector or raster data structures. However, these 2D models cannot fully represent the real 3D world, especially when we are interested in a detailed description of the internal structure of a 3D spatial entity (Shi, Yang, & Li, 2003). Several 3D GIS methods have been developed in the past decade. However, recently developed 3D GIS data models have limitations in terms of geometric and topological representations of the complex internal structure of buildings at the 3D subunit level (i.e., not many previous studies are concerned with visualizing interior structures of buildings).

Lee and Kwan (2005) developed a new way to represent the topological relationships among 3D geographical features, namely, the combinatorial data model (CDM). The CDM for a node-relation structure (NRS) can be derived through Poincaré duality, abstracted from the topological relationships among a set of 3D objects, transforming “3D to 2D relationships” in primal space to “0D to 1D relationships” in dual space. Adjacency relationships among objects in 3D space are represented by a dual graph, \( G = (V(G), E(G)) \). For connectivity relationships in the NRS, the graph \( H = (V(H), E(H)) \) is a subset of the graph \( G = (V(G), E(G)) \). The CDM 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 these units. To perform 3D analysis, such as shortest path analysis, the CDM needs to be transformed into another data model, called the geometric network model (GNM). Fig. 1 shows an NRS for representing topological relationships among 3D units. Their GNM with the shortest path algorithm in emergency response can reduce the response time required to reach a disaster site inside a multistory building. However, their GNM does not account for temporal variations (e.g., movement of smoke at different times during a building fire). Wu and Chen (2012) proposed a spatio-temporal analysis method for finding fire-fighting rescue routes that could quickly locate a destination and show the shortest safe path within a building. They used a GNM and the Dijkstra algorithm to consider smoke movement during different time of a building fire. Therefore, the route calculation can avoid routes through heavy smoke within buildings. In their future work, the GNM should be integrated with an outdoor GIS system. Thus, the proposed routes would not only for use within the buildings but also for street transportation.

Thill, Dao, and Zhou (2011) developed a network-based 3DCityNet for urban analytical functionalities such as route planning, spatial accessibility assessment, and facility location planning. Their 3DCityNet offers significant analytical capabilities of built environments also in micro-scale spaces (i.e., their route planning enables users to query the least-effort route between any two points, whether these points are situated indoor or outdoor). However, future research on 3DCityNet is needed to develop enhanced visualization tools which provide greater interactivity (e.g., attribute queries by clicking on the screen). Isikdag, Underwood, and Aouad (2008) applied BIMs in geospatial environment in order to facilitate the data management in site selection and fire response. Their research demonstrated that BIMs can provide the required geometric and semantic information about buildings in support of site selection and fire response management process (i.e., BIMs can provide attribute queries about building elements). However, a real fire scene is a dynamic progress. Some variations may change during a building fire (e.g., movement of smoke, positions and operations of a ladder truck, etc.). Therefore, an interactive 3D environment is needed to simulate a fire scene.

In this study, we proposed a method involved exploration of an interactive 3D GNM-based, BIM information-supported framework for fire-fighting simulation, which could be notified as the scientific contribution of this research. This study provided useful decision support of fire-fighting operations such as route navigation for firefighters in a virtual 3D environment, demonstration of movement of smoke at different stages during a building fire, deployment of a virtual ladder truck in a fire scene, and attribute queries of building elements using BIMs, etc.

![Fig. 1. An illustration of the node-relation structure: (a) 3D spatial units, (b) combinatorial data model, and (c) geometric network model.](image-url)
3. System architecture

The system was implemented in a C++ and OpenGL® environment. The Unified Modeling Language (UML) diagram for the data model described in this paper is shown in Fig. 2. It consists of (1) features (buildings, roads, fire stations, and fire hydrants), (2) orthoimages, and (3) a BIM and a GNM of a target building. The study area was Taoyuan City, located in Taoyuan County, Taiwan. GIS data are provided for the city’s 102,661 buildings, 3 fire stations and 867 fire hydrants. The digital street network for route analysis contains 14,792 arcs and 11,228 nodes. A 3D GNM is performed for optimal path analysis and for 3D navigation within a target building. A BIM contains information about walls, windows, doors, stairs, etc. of a target building, which is used for 3D visualization and attribute query. Virtual ladder trucks allow users to simulate the positioning and operation of aerial ladder maneuvers. In addition, a fire simulation is performed using the Fire Dynamics Simulator (FDS) software (McGrattan, Klein, Hostikka, & Floyd, 2009). Fire simulation data is used to demonstrate the movement of smoke of a target building in fire.

3.1. Geometric network model (GNM)

In this study, we used the method proposed by Wu and Chen (2010) to generate a 3D GNM from 2D Computer-Aided Design (CAD) building plans, as shown in Fig. 3. Two-dimensional polygon layer data are derived from 2D building plans which are converted from BIMs. The polygon layer data are divided into four parts: stairs, rooms, hallways and doors. For rooms and stairs, the location (x and y coordinates) of the nodes are derived from the centroids of polygons; the z values of the nodes are obtained from elevation drawings. For a simple polygon P with n vertex vectors \((x_1, y_1), (x_2, y_2), \ldots, (x_n, y_n)\), where \((x_1, y_1) = (x_n, y_n)\), the area of the polygon is determined with Eq. (1), and the x- and y-coordinates of the centroid are calculated with Eq. (2).

**Area of a polygon**

\[
\text{area}(P) = \frac{1}{2} \sum_{i=1}^{n-1} x_i y_{i+1} - x_{i+1} y_i \tag{1}
\]

**Centroid of a polygon**

\[
\text{centroid}_x(p) = \frac{1}{6 \times \text{area}(P)} \sum_{i=1}^{n-1} (x_i + x_{i+1}) (x_i y_{i+1} - x_{i+1} y_i) \tag{2-1}
\]

\[
\text{centroid}_y(p) = \frac{1}{6 \times \text{area}(P)} \sum_{i=1}^{n-1} (y_i + y_{i+1}) (x_i y_{i+1} - x_{i+1} y_i) \tag{2-2}
\]

For the mapping of hallways, the medial axes are drawn to represent the routes (edges) along the hallways, which is a medial axis transformation (MAT). Each node representing a room is connected with its doors. Each node that represents a door is then projected and connected into the medial axis when there is a connectivity relationship. The projection point \(P\) of a point \(P'\) onto a medial axis (edge) \(L\) is the intersection of the edge \(L\) and the edge perpendicular to the edge \(L\) through the point \(P\). The distance from point \(P\) to edge \(L\) can be determined with Eq. (3), and the coordinates of projection point \(P\) can be calculated with Eq. (4).

**Distance from a point to an edge L:**

\[
\text{distance}(P, L) = \frac{ax_0 + by_0 + c}{\sqrt{a^2 + b^2}} \tag{3}
\]

**Coordinates of the projection point \(P\):**

\[
x_1 = \frac{(b) (b_0 - ay_0) - bc}{\sqrt{a^2 + b^2}} \tag{4-1}
\]

In the case of an emergency such as a fire, the use of elevators or escalators inside buildings is excluded by firefighters; therefore, vertical connectivity is defined only by the locations of stairways. Finally, a 3D GNM of the building is constructed using these nodes and edges. Because the node and edge data are stored in a database, attribute queries can be performed to find attribute data using the SQL query language. A node consists of an identifier, a 3D position data \((x, y, z)\) coordinates, a floor and a name (IfcSpace). An edge contains an identifier, a start node, an end node, a name and a length. Once the 3D GNM is generated, the model can be used to perform shortest path analysis using Dijkstra’s algorithm (Dijkstra, 1959).

Dijkstra’s algorithm is used to find the shortest path between any two vertices in a weighted graph, in which each edge has a nonnegative edge weight (distance). For a graph \(G = (V, E)\), the algorithm for computing shortest paths visits all nodes of \(G\) located nonnegative distance from a given source \(s \in V\). Therefore, the algorithm maintains a priority queue \(Q\), for which the key of a node \(u\) is given by the tentative distance to \(s\), denoted by \(d[u]\). During initialization, all tentative distances, except for \(s\), are set to \(\infty\), whereas \(s\) is inserted into the priority queue with a key of 0. Then, for each iteration, the node \(u\) with the minimum key is extracted from the queue, that is, the node \(u\) is settled, and all edges \((u, v) \in E\) are relaxed. Relaxation of an edge is done by determining if the following inequality holds: \(d[u] + \text{len}(u, v) < d[v]\), where \(\text{len}(u, v)\) denotes the edge weight of \((u, v)\). If it holds, the path via \(u\) yields an improvement on the distance from \(s\) to \(v\). Thus, \(v\) is either added to \(Q\), or if \(v \in Q\), its priority is decreased. The algorithm stops as soon as all nodes are settled. However, if we are only interested in the distance from \(s\) to a given target \(t\), we may stop the algorithm as soon as \(t\) is settled. Dijkstra’s algorithm is one of the best approaches to solving the simple shortest path problem where all edges have nonnegative lengths (Zeng & Church, 2009).

In this study, a 3D GNM is performed for optimal path analysis and for 3D navigation within a target building. While the start point (e.g., the entrance) and the end point (e.g., the fire site) are input into the system, the GNM is used to perform shortest path analysis. Then the system shows the calculated route in the 3D view. Once the rescue route is determined, it can be used as a navigation tool for firefighters with BIMs. In addition, while querying the name of a room with the GNM, the system shows the attributes of the room and its corresponding space (IfcSpace) of BIMs in a 3D view.

3.2. Building information model (BIM)

A BIM is intended to provide information about a building throughout its life, from layout and design to construction and maintenance. It enables reuse of building information throughout the whole building life cycle (Hijazi, Ehlers, & Zlatanova, 2011). The Industry Foundation Classes (IFC) model developed by the International Alliance of Interoperability (IAI, also known as buildingSMART®) has matured as a standard BIM for supporting and facilitating interoperability across the various phases of the construction life cycle. The latest available version is 2.3, which covers nearly nine domains in building construction, including HVAC systems, electrical systems, architecture, construction management, facility management, structure component, structure analysis, tube and fireproofing and construction control (Björk & Laalaso, 2010). In this paper, the discussion of the IFC standard is based on this version.

The IFC standard has a hierarchical and modular framework divided into four bottom-up layers, i.e., a resource layer, a core layer,
Fig. 2. The Unified Modeling Language (UML) diagram for the data model.
an interoperability layer and a domain layer. Each layer consists of a number of modules, each of which contains various entities, types, enumerations, rules and functions. Among them, the entity represents the abstraction of objects that have the same properties and is the information agent used to describe the information for the building and surrounding components. Building products are defined using the entity IfcProduct, which represents an object by a description of its geometric representation and local placement. The entity IfcBuildingElement that is inherited from IfcProduct can be used to describe the components of a group of design products and those in a group of decoration/accessory products (Zhiliang, Zhenhua, Wu, & Zhe, 2011). Here IfcBuildingElement is a major functional part of a building, and examples are walls (IfcWall), doors (IfcDoor), columns (IfcColumn) and stairs (IfcStair), etc. Information about windows, walls, doors, stairs, etc. is necessary for successful fire-fighting operations at a fire scene. Therefore, we used 13 kinds of building elements (e.g., IfcWindow, IfcWall, IfcColumn, IfcSlab, IfcBeam, IfcDoor, IfcRoof, IfcCovering, IfcStair, IfcCurtainWall, IfcRailing, IfcBuildingElementProxy and IfcStairFlight) for 3D visualization and attribute query in this study.

The IFC model is represented with space-enclosing structures (IfcSpatialStructureElement). Special space-enclosing structures are the project (IfcProject), sites (IfcSite), buildings (IfcBuilding), storeroys (IfcBuildingStorey) and rooms (IfcSpace). The space (IfcSpace) is one of subtypes of IfcSpatialStructureElement that is the generalization of all spatial elements defining a spatial structure. Space in IFC is geometrically associated to a building storey and may be divided into partial spaces.

3.3. Geographic information system (GIS)

A GIS uses vector and raster data models to represent spatial features. A vector data model uses points with x, y, and z coordinates to construct spatial features (points, lines, and polygons), where features are treated as discrete objects in the space. A raster data model uses a grid to represent the spatial variation of a feature, where each cell of a grid has a value that corresponds to the characteristic of the spatial feature at that location (Chang, 2002). In this study, the building data were polygon features, the road data were line features, the fire hydrant data were point features, and the orthoimages were raster data. In addition, the road data (lines) form spatial networks that are modeled with graphs. The graph's arcs correspond to street segments and its nodes correspond to street segment intersections. Each arc has a weight associated with it, representing the cost (length) of traversing it. In this study, Dijkstra’s algorithm was used to perform shortest route analysis for the road network.

3.4. Virtual ladder trucks

According to the U.S. National Fire Protection Association (NFPA)'s 1901 standard, a ladder truck (aerial apparatus) is a vehicle equipped with an aerial ladder, elevating platform, aerial ladder platform, or water tower that is designed and equipped to support fire-fighting and rescue operations (NFPA, 2003). In general, a ladder truck contains a driver's cab and a chassis, a base support system, a turntable, telescopic booms, an articulated arm and a cage. Fig. 4(a) shows the components of an aerial ladder platform. In this study, the ladder truck can be interpreted as a large-scale robot with four rotary axes and one translational axis represented as follows: (1) raising-lowering (−10° to 80°), (2) running in-running out (0–20 m), (3) rotating (not limited), (4) articulated arm flexing (0–175°), and (5) cage rotating (−50° to 50°). Fig. 4(b) shows the rotation and translation of a ladder.

When choosing the placement position for the aerial ladders, firefighters should consider the following: (1) whether immediate rescue is apparent, (2) where no immediate rescue effort is required, the size of the frontage of the building to be covered in case of future need, (3) smoke, heat or fire causing an exposure that would endanger a victim, a member of the ladder, and (4) area or street conditions that might hamper optimum positioning (NYCFD, 1986). After choosing an optimal placement location by moving a ladder truck in a virtual environment, we can perform raising-lowering, running in-running out, rotating, articulated arm flexing, and cage rotating of the ladder to reach the target building. While moving a ladder truck in a 3D view, the system can show the positions (x and y coordinates) of the ladder in the Taiwan Datum 1997 (TWD97) coordinate system. In addition, while operating a virtual ladder truck in a 3D view, the system can show the current height of the ladder from the ground level.

3.5. Fire simulation

The FDS developed by the U.S. National Institute of Standards and Technology (NIST) was used in this study to simulate various potential fire and smoke scenarios. The simulation results can be used as temporal data for optimal path analyses. FDS is a computational fluid dynamics (CFD) model for fire-driven fluid flow used to solving a form of the Navier–Stokes equations appropriate for low-speed, thermally driven flow, with an emphasis on smoke and heat transport from fires. The inputs of the FDS include information about the numerical grid, ambient environment, building geometry, material properties, combustion kinetics, and desired output quantities. The FDS computes the temperature, density, pressure, velocity and chemical composition within each numerical grid cell at each discrete time step. FDS outputs 3D smoke data at fixed time intervals. The smoke data contain alpha values used to draw semi-transparent planes that represent smoke and fire. The alpha parameter is used by OpenGL to blend these smoke planes with the current background, which changes with time. It is pre-computed by the FDS using Beer’s law with Eq. (5), where Δx is the grid cell size, k is the mass extinction coefficient (7600 m²/kg), and s is the soot density (Forney, 2009). In this study, we use soot density (s), derived from the alpha values obtained from Eq. (5), as the temporal data for optimal path analyses. The system also shows a clear view of smoke movement according to the temporal data created by FDS with BIMs.

\[ \alpha = 1 - \exp(-ks \Delta x) \] (5)
3.6. Attribute query

In a BIM, the space (IfcSpace) is bounded by related building elements (IfcRelSpaceBoundary) that surround the space, such as walls (IfcWall), doors (IfcDoor), columns (IfcColumn), slabs (IfcSlab) and windows (IfcWindow), as shown in Fig. 5. Because the node and edge data of the GNM are stored in a database, attribute queries can be performed to find attribute data using the SQL query language. In this study, while querying the name of a room from the node data with Eq. (6), the system shows the attributes (e.g., height (Z value)) of the room and its corresponding space (IfcSpace) with the surrounding elements (e.g., IfcWindow, IfcDoor, etc.) in the 3D view. In addition, while choosing an element by clicking on the screen, the system can show the attributes of it. For example, when we select a window by clicking on the screen, the system shows the type, size, etc. of the window, as shown in Fig. 6. This information can provide firefighters a reference to decide whether the window is appropriate for entry or not.

\[
SQL = \text{"SELECT } * \text{ FROM node WHERE name = IfcSpace"} \quad (6)
\]

3.7. Path analysis

Once the 3D GNM is generated, the GNM can be used to perform a shortest safe path analysis using Dijkstra's algorithm for a given destination within a building. Because the start node (entrance) and end node (destination) are known, to calculate the shortest safe path from the start node to the end node, Dijkstra's algorithm is executed in the 3D GNM with temporal smoke density data. Smoke generated from a fire reduces visibility, which in turn, reduces the walking speed of humans. Korhonen and Hostikka (2009) conducted experiments to determine the effect of smoke density on the walking speed of humans using Eq. (7), where \(K_s\) is the extinction coefficient and the values of the coefficients \(\alpha\) and \(\beta\) are 0.706 m/s and \(-0.057 \text{ m}^2/\text{s}\), respectively. The average walking speed \(v^0\) is 1.5 m/s, whereas the minimum walking speed \(v_{\text{min}}^0\) is 0.1 \(v^0\). In this study, we use soot density \(s\), derived from alpha values in Eq. (5), as the temporal data in optimal path analyses. Once the smoke density \(s\) of a node is given, the extinction coefficient \((K_s = K \cdot s)\) is obtained, and the walking speed of a node can be derived from Eq. (7). Therefore, the traversal time of an edge can be calculated by comparing the walking speed with the length of a given edge. Fig. 7 shows the shortest safe path process in a flowchart.

\[
v^0(K_s) = \text{Max}\left\{v_{\text{min}}^0, \frac{v^0}{2}(\alpha + \beta K_s)\right\} \quad \text{where} \ K_s = k_s \quad (7)
\]

In the proposed method, the distance is replaced by the weight calculated with respect to the traversal time computed by comparing walking speed with edge length. In addition, the time interval for performing the shortest safe path analysis is 0.6 s (i.e., the smoke density, walking speed and traversal time may change with the time). Therefore, the route calculation algorithm is more realistic and can avoid routes through heavy smoke within buildings (i.e., heavy smoke may reduce the walking speed and increase the traversal time).

4. Examples and tests

Hotels are high-risk buildings. Saving lives in high-rise hotel fires depends on locating the fire quickly, attacking it aggressively,
and reaching any occupants who may be trapped in the interior of the building (Tracy, 1998). In the example used in this study, the target was a 13-story hotel located in Taoyuan County, Taiwan. A fire scenario with three different stages is described below to illustrate the application of GNMs and BIMs in a geospatial environment for fire-fighting simulation scenarios.

4.1. Fire stage I (dispatch to a fire scene)

Suppose that a fire occurs in Room 719 on the 6th floor of the hotel. A witness first informs the emergency response center at the Taoyuan County Fire Bureau, Taiwan. The emergency response center determines which fire brigade station should respond (i.e., which is the closest that has suitable vehicles) and dispatches firefighters to the scene to rescue people and put out the fire. Since the start point (the fire station) and the end point (the fire scene) are located in the street network on the 2D map, the system illustrates the original shortest route from the fire brigade station (the phoenix logo) to the burning building. Because only streets with more than two lanes are considered, to avoid traffic jams, the system shows the alternate shortest route (in red) from the station to the building (Fig. 8). After receiving the mission, the brigade officer uses his mobile device to obtain a view of the burning building and

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**Fig. 7.** Flowchart of shortest safe path analysis.

**Fig. 8.** The alternate route (in red) from the fire station to the hotel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Fig. 9.** The target building and its neighborhood.
its neighborhood, as shown in Fig. 9. There are three fire hydrants near the burning building that can be used for fire suppression. While choosing the fire hydrants by clicking on the 2D map, the system shows the attributes of them (Table 1). In addition, according to the BIM of the burning building in the 3D view, the building is equipped with two fire hose cabinets (IfcBuildingElementProxy) on the 6th floor. Thus, the staff of the hotel can use the fire hoses in the cabinets to keep the fire from spreading. Fig. 10 shows the locations of the fire hose cabinets (red boxes) on the 6th floor in the 3D view.

For traditional fire-fighting methods, travel routes from the fire station to the scene only depend on drivers’ experience. Using this system, firefighters can get information about the shortest route to the fire scene after receiving their mission from the emergency response center. In addition, information about hydrant locations is from printed data which may sometimes hard to read. Using this system, firefighters can immediately get information about the hydrant locations on their way to the fire scene.

4.2. Fire stage II (on the way to the fire scene)

Suppose that smoke spreads rapidly and fills the corridor on the 6th floor and that some people are trapped by the smoke in Room 721 on that floor. The brigade officer uses his mobile device to obtain a clear view of smoke movement according to the temporal data created by FDS with the BIM (Fig. 11). Smoke may fill the corridor on the 6th floor after 120 s passed, which is before firefighters’ arrival. The people trapped in that room call the emergency number and tell the firefighters where they are by cell phone. Fig. 12 shows the flowchart for the window selection and deployment of ladder trucks. The name of the room is input into the system and the result shows the attributes of the room (Table 2). According to Table 2, the height of Room 721 is 21.4 m from the ground level, which is accessible for a 32-m ladder truck. Therefore, firefighters decide to rescue the people using the ladder. In addition, while querying the name of “Room 721” with Eq. (6), the system also shows the corresponding space (IfcSpace) and its

<table>
<thead>
<tr>
<th>ID</th>
<th>X (m)</th>
<th>Y (m)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0705</td>
<td>280441.7</td>
<td>2767230.3</td>
<td>No. 313, Sec. 1, Daxing W. Rd.</td>
</tr>
<tr>
<td>T0706</td>
<td>280640.5</td>
<td>2767201.7</td>
<td>Intersection of Daxing W. Rd. and Xinpu 6th St.</td>
</tr>
<tr>
<td>T0645</td>
<td>280688.4</td>
<td>2767424.3</td>
<td>No. 163, Tong’an St.</td>
</tr>
</tbody>
</table>

Table 1: Attributes of the three nearest fire hydrants.

<table>
<thead>
<tr>
<th>ID</th>
<th>X (m)</th>
<th>Y (m)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>136</td>
<td>5140</td>
<td>429</td>
<td>2140 6F R721</td>
</tr>
</tbody>
</table>

Table 2: Results of the attribute query (Room 721).

| Cross Length Road No. Road, ENG Width |
|--------------------------------------|-------------------------------------|
| 869                                  | Sinpu 6th St. 19                    |
surrounding elements (e.g., walls (IfcWall), doors (IfcDoor), columns (IfcColumn), slabs (IfcSlab) and windows (IfcWindow)) of BIMs in the 3D view (Fig. 5). While choosing the window of Room 721 of the BIM by clicking on the screen, the size of the entrance window is shown as 280 x 210 cm (width x height), which is appropriate for entry of the firefighters (Fig. 6). Thus, the firefighters on the ladder decide to enter the building through the window of Room 721.

According to the 3D view, the facade of building is next to a two-lane road. While selecting the road by clicking on the screen, the width of the road is shown as 19 m, which is wide enough for the placement of the ladder (Table 3). Therefore, after choosing an optimal placement location by moving a ladder truck on the road in the 3D view, realistic behavior (e.g., raising–lowering, running in–running out, rotating, articulated arm flexing, and cage rotating) of the ladder can be simulated in order to reach Room 721. The best position for the ladder truck is obtained as (280571.2, 2767340.1) in the Taiwan Datum 1997 (TWD97) coordinate system. Fig. 13(a)

![](image1)

Fig. 13. (a) Location of the ladder truck and (b) entrance to Room 721.

<table>
<thead>
<tr>
<th>ID</th>
<th>X (cm)</th>
<th>Y (cm)</th>
<th>Z (cm)</th>
<th>Floor</th>
<th>Name (IfcSpace)</th>
</tr>
</thead>
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<tr>
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<td>4204</td>
<td>331</td>
<td>2140</td>
<td>6F</td>
<td>R719</td>
</tr>
</tbody>
</table>

Table 4

Results of the attribute query (Room 719).

Fig. 14. Shortest path analysis: (a) GNM and (b) GNM with BIMs.

Fig. 15. Rescue route navigation with BIMs: (a) in a hallway and (b) in a stairwell.
shows the location of the ladder truck and Fig. 13(b) shows the entrance to Room 721.

At the fire scene, the placement of ladder trucks may be complicated by the positions of other fire trucks, ambulances, police cars and hose lines. Using this system, firefighters can obtain the best position for the deployment of the ladder truck on their way to the fire scene. Other vehicles (e.g., fire trucks and ambulances) should be moved to avoid blocking the ladder truck.

4.3. Fire stage III (after reaching the fire scene)

Suppose that a local fire brigade that has a 32-m ladder truck has reached the fire scene. Firefighters with fire hoses decide to walk to Room 719 from the ground level to extinguish the fire. The building’s fire alarm system has acquired a signal about the location of the fire through fire detectors. The name of the room is then input into the system. The results show the attributes of the room (Table 4). Since the start point (the entrance) and the end point (Room 719) are input into the system, the result shows the shortest path (the blue line) from the entrance of the building to the site (Fig. 14). Once the rescue route is determined, it can be used as a navigation tool for firefighters in a virtual environment with BIMs (Fig. 15). In this case, the shortest path is 65 m. This information provides firefighters a reference for preparation of fire hoses when they arrive at the scene. In this study, we use 92 \((65 + \sqrt{2})\) meters for preparation of fire hoses to meet the actual stairs and redundancy. In addition, because the height of Room 719 is 21.4 m from the ground level, which is also accessible by the ladder truck, firefighters on the ladder decide to discharge water into that room to put out the fire after they finish the rescue mission. Therefore, after choosing an optimal placement location by moving a ladder truck on the road in the 3D view, realistic behavior of the ladder can be simulated in order to reach Room 719. Fig. 16 shows the simulation of the rescue and fire suppression utilizing the ladder truck with BIMs.

Firefighters have no knowledge of the interior structure, hallways, exits, etc. of a building. The only information available to fire brigades is 2D floor maps. However, floor maps do not provide detailed semantic information. In addition, a real fire scene is actually a 3D environment that includes both the interior and exterior of a building. Using this system, the rescue route with BIMs can be used as a navigation tool for firefighters. For traditional fire-fighting methods, firefighters prepare hose lines according to evaluating the floor’s height. Using this system, firefighters can immediately
prepare fire hoses to put out the fire when they arrive at the scene according to the calculated path.

5. Drill emulation

In this study, a real fire-fighting drill was also conducted. The Taoyuan fire brigade and its 32-m ladder truck participated in this drill. Because conducting fire drills in modern buildings under realistic fire conditions can be difficult, this drill did not feature dynamic events such as fires in rooms, smoke filling corridors or shooting of water by the firefighters.

After the fire brigade received a fire alert from the building, it rushed to the scene along the calculated route (Wenzhong N. Rd. → Yong’an Rd. → Ciwen Rd. → Zhongzheng Rd. → Sec. 1, Daxing W. Rd. → Xinpud 6th St.). The total distance along that route was approximately 2.2 km, and it took approximately 8 min for the fire brigade to arrive. On the way to the fire, the brigade officer deployed the vehicles and made assignments before the firefighters’ arrival at the scene. Some firefighters were asked to park their fire trucks near the fire hydrants to use the water for fire suppression. One group of firefighters prepared at least five segments of fire hose to reach the calculated distance (65’ × 2 m) and then deployed the hose lines to the entrance to Room 719 to put out the fire. Fig. 17 shows the deployment of the fire hoses. Another rescue team parked its ladder truck (the front part) at the proposed position (280571.2, 2767340.1) and then entered the building from the window of Room 721 to rescue the victims, as shown in Fig. 18. The simulation results provided firefighters with useful information for calculating the optimal routes, deploying the fire hoses and positioning the ladder truck in the fire drill.

6. Conclusions and future research

The 3D GNM enables shortest path analysis for emergency response incidents. The BIM was added to a 3D view for geometric representation and attribute queries. A ladder truck was added in the 3D view to simulate fire-fighting and rescue operations from the exterior of the building. The model developed in this study can be used by firefighters to quickly locate destinations and identify the shortest paths along the road network within a building, which can reduce response times. This study also provides a virtual fire-fighting environment for firefighters to simulate the positioning and operations of their ladder trucks. Before arrival at the scene, the best position for deployment of the ladder truck, and how other vehicles (e.g., fire trucks and ambulances) should be moved to avoid blocking the ladder truck, can be determined. The area of reach of the ladder trucks can be maximized for any potential objective. In addition, because conducting fire drills in modern buildings under realistic fire conditions can be difficult (Smith & Trenholme, 2009), the model developed in this study provides a virtual fire drill environment that local fire departments can use to simulate fire-fighting operations. The virtual environment can provide a variety of fire-fighting scenarios for instruction and evaluation that are more realistic than verbal or written materials and that incur fewer risks and expenses than fighting real fires.

A full-fledged system could be applicable to a large city provided that a large enough computer system can handle all of the building models. Considering that some information systems could not handle such a large data volume, this research focuses instead on the buildings that fire-fighting operations may be difficult and heavy casualties may occur (e.g., high-rise buildings, complex buildings, underground spaces, etc.). Therefore, after receiving a fire call from such buildings, GNM and BIM data of the building are just loaded into our system. In addition, in order to perform fire-fighting simulations, different kinds of ladder truck (e.g., 32-m, 38-m, 52-m, 60-m ladder trucks) can be selected in this system. Simulations of ladder trucks are not limited in this system.

However, there are some limitations to this method that must be addressed. First, the “intelligent Building Response” (iBR) project is working to obtain sensor information from buildings while four main goals of the project are to: (1) gather what information first responders need; (2) develop a standard to move data from buildings to first responders; (3) show the proposed technology with a video for demonstration; and (4) concern security of the information transfer. This real-time data can be used by firemen, police officers and others when responding to an emergency (Holmberg, Davis, Treado, & Reed, 2006). Therefore, we may find ways to integrate intelligent building systems with our system in the future. Second, traffic conditions may change with the time. Therefore, real-time data from traffic sensors will be used in the future to predict traffic conditions and adapt the optimal routing accordingly (Derekenaris et al., 2001). Lastly, we use affine transformation of the footprint of the building to integrate 2D GIS with the building in this study. We consider that road data (lines) of 2D GIS are used for the movement of fire trucks while BIMs and GNM of buildings are used for the movement of firefighters. In addition, the main issue in the integration of BIM with GIS occurs at the transfer of geometric information from building into geospatial models, as building models represent objects with different...
representations such as Constructive Solid Geometry (CSG) and Sweeping, while GIS mainly use Boundary Representation (BRep) as the main geometrical representation method. Recently, the integration between BIM and CityGML has been discussed intensively. CityGML is the international standard for the representation and exchange of 3D city models issued by the Open Geospatial Consortium (OGC®). Using CityGML with BIM for fire-fighting simulation will be the next step in our research.

Acknowledgements

The authors would like to thank the Taoyuan City Government, Taiwan for providing the data for this study. The authors are also grateful to the staff of the Taoyuan County Fire Bureau, Taiwan for their participation in the drill.

References