Three-Dimensional Modeling for Buildings Evacuation Management

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Abstract

The terrorist attacks on New York City on September 11, 2001 heightened awareness about the need to plan for emergency evacuation measures. As a result, three-Dimensional (3D) city and building models have become an important part of GIS analysis. The technology can be used to plan evacuations in complex indoor environments. This thesis had two main objectives. The first goal was to conduct a 3D network analysis of a building for emergency management, which was based on a 3D model of a building in the city of Gävle, Sweden. This 3D model identifies the shortest path from any room to the defined exit. The second objective was to test the predicted evacuation times with a simulation experiment. The 3D model was built by Google Sketch Pro 8 and the 3D network analysis was mainly conducted in the ESRI’s ArcGIS software. The simulation experiment involved 18 volunteers at the organization Future Position X. The 3D network analysis was based on distance measurements instead of GNSS coordinates. The simulation experiment was conducted in four different situations. Crowding was found to be a critical problem during evacuation. Evacuation speeds varied from normal walking to running. However, crowding always increased the evacuation time and thus would affect the survival rate. Evacuation routes should be distributed differently to reduce this problem. The thesis also identifies other factors to be considered when planning emergency routes and challenges posed by the software at this time.

Keywords: Three-Dimensional Geographic Information System (3D GIS), 3D indoor network analysis, emergency management, evacuation.
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Yuan Cao and Fei Lu

May, 2012
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### List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>Two dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three dimensional</td>
</tr>
<tr>
<td>BIM</td>
<td>Building Information Modeling</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>FME</td>
<td>Feature Manipulation Engine</td>
</tr>
<tr>
<td>GIRS</td>
<td>GIS based Intelligent Emergency Response System</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information System</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>TIN</td>
<td>Triangular Irregular Networks</td>
</tr>
</tbody>
</table>
1. Introduction

1.1 Background

Many airports, office buildings and department stores have complex floor plans. For example, the Lafayette shopping mall in Paris is composed of several buildings joined together with long passageways, stairwells and elevators. In such environments, it can be difficult for people to move efficiently from one place to another. Two-dimensional (2D) maps help people navigate but may not be sufficient to plan optimal especially emergency routes. A better approach for identifying evacuation routes is to use 3D models and network analysis algorithms. This thesis explores the value of these tools using an office building in Gävle, Sweden as a test case.

GIS and Emergency

Geographical Information Systems (GIS) are used in many fields of study and application, including transportation network analysis. GIS allows users to manage, visualize, present and analyse spatial data. Navigation systems are the fast developing area of GIS. Global Positioning Systems (GPS) provide information of the latitude and longitude coordinates and heading directions for navigation. This positioning information can be used in a GIS to analyse the real world or create models (Xu, 2003).

In combination, these technologies provide sophisticated tools for emergency management. Emergency evacuation is an important issue for large buildings and facilities. The purpose of evacuation management is to evacuate people from danger zones through exits within in the shortest time (Chen & Feng, 2009). Examining the catastrophe of September 11th, 2001, Erden and Coksun (2007) argued that it is possible to reduce injuries and the loss of life with good planning and emergency preparedness. The collapse of the World Trade Centre (WTC) and serious structured
damage to the Pentagon on that day restricted access spots and influenced the evacuation speeds significantly. The implementation and support of network-constrained navigation systems could help address these evacuation problems (Musliman et al, 2008). Network analysis can help identify the fastest route to an exit and assess how factors such as crowding and walking speed affect evacuation.

**3D GIS and Indoor Environments**

Three-dimensional (3-D) models are more useful rather than two-dimensional (2-D) maps because they provide more representation (such as colours and shapes) and thus a better resemblance of real world objects (Skarkawi, et al. 2008). 3D Geographic information systems (3D-GIS) are also needed in more and more fields. As Ying, Li and Guo (2011) argued that with the increasingly population in amount and density, 3D land use and development had attracted more and more attention from governments. The requirements for 3D GIS have risen rapidly. The functionalities of 3D GIS models have been tested in many scenarios. The determination of shortest routes and simulations of complicated phenomena, such as cyber cities or digital cities are examples. Cyber cities require sophisticated visualization models and the comprehensive information and integrated layouts of features in the real world (Tsai & Lin, 2006).

Skyscrapers and other kinds of huge buildings were built during the 20th century all over the world in order to save land space of the cities. These constructions may have very complex indoor environments: multiple levels, labyrinth floor plans, dense populations, and elaborate flow patterns. All of those complicated situations make indoor navigation more difficult in times of emergency. GPS can be difficult to use in many indoor environments. Many GIS applications have been developed for indoor applications, such as integrated GIS, 3D navigation, and mobile with 3G capabilities for GPS. Nevertheless, all of those technologies were initially designed for outdoor
application. Li and He (2009) argue that GPS information can be transferred fluently in the open areas; nevertheless the signal will be interfered by walls when used in the circumstances inside the buildings. The use of GIS applications in indoor environments is also limited by the 3G capabilities of mobile devices and by computing power needed for analysing complex systems (Coors, Kray, Laaksi & Elting, 2004). Individual networks must be built to reduce these limitations from the start.

1.2 Previous studies

Dijkstra’s Search Algorithm for 3D Network

Most contemporary GIS based network analyses focus on two-dimensional (2D) environments and use 2D or 2.5D data to find the best route. 3D data contains the x, y and z value. But the 2.5D data only includes the x and y data with one height value separately. Other researchers use Triangular Irregular Networks (TIN) model for visualizing indoor scene. However, the shortest path results are still calculated by 2D horizontal plan (Musliman et al, 2008). The geometric 3D model is developed from 2D plan, and calculated the suitable route by Dijkstra algorithm by C++ programming language (Chia & Liang, 2007). The calculation of distance between two nodes is based on the Pythagorean equation when the coordinates of two nodes are known. Delta x is the difference of x coordinate between two nodes. Delta y is the difference of y coordinate between two nodes. The roof of the sum of the squared differences for the points is taken to calculate the distance in Euclidean space.

\[
\text{Eq 1. } D = \sqrt{[\Delta x^2 + \Delta y^2]}
\]
Some researchers e.g. Karas et al. (2006) proved the Dijkstra algorithm could be used in 3D environment and Meijers et al. (2005) optimized the algorithm especially for 3D indoor navigation. Figure 1 shows the basic elements needed to calculate the distance between two nodes in 3D space. \(x_1, y_1, z_1\), and \(x_2, y_2, z_2\) are coordinates from node 1 and node 2. Node 1’s extended line and the Node 2’s vertical line intersect. The letter "h" is the distance between Node 1 and the cross point O. Then the distance (D) between node 1 and node 2 can be calculated as these two equations in Eq.2.

![Diagram of basic elements to calculate two nodes in 3D space](image)

\[ E_2 \; h = \sqrt{\Delta x^2 + \Delta y^2}; \quad D = \sqrt{h^2 + \Delta z^2} \]

Then these two equations could be combined to:

\[ E_3 \; D = \sqrt{[\Delta x]^2 + [\Delta y]^2 + [\Delta z]^2} \]

From here, the Dijkstra algorithm could be used in 3D space network.

**3D GIS and Emergency**

Kwan and Lee (2005) show that the optimal routes for evacuation in multi-levelled structure in emergency management can be determined using a 3D data model. The common uses of 3D GIS emergency management system are 2D GIS shortest path
analysing and visualized the result in 3D visualizations (Meijiers et al, 2005). But this kind of method is not suited for representing the micro-scale environments due to their complex internal architecture. A GIS based Intelligent Emergency Response System (GIERS) has been built to accomplish the task of analysing the micro-scale environments by Kwan and Lee (2005). However, the result was not satisfactory due to the un-developing 3D modelling. A suitable 3D model plays an important role in the 3D GIS emergency management. Billen & Zlatanova (2003) developed a 3D data model for emergency management; however, the model has not been tested in their project work. Therefore, the best strategy is to use a normal 3D data model for network analysis to simulate evacuation.

3D Network Analysis

Network analysis is a GIS application for calculating and selecting locations and relationships in networks (Kwan & Lee, 2005). The traditional networks related in 2D GIS can be seen as entities consisting of nodes and arcs structures modelling routes in a plan view with x and y coordinates (Liu et al., 2005). Things are quite different in 3D network; the vertical value z exists in each node and arc. Each geometry feature could be described in 3D visualization; the 3D network thereby can overcome problems faced with 2D network datasets (Musliman et al, 2006). 3D network analysis is commonly used to find the shortest path within indoor built environments.

1.3 Aims

Previous studies have mostly focused on 3D analysis or have used travel time to provide a model of evacuation routes. Only few studies have tried to compare actual evacuation times with model-determined time. The modes can be normal walking, running or crowded walking.

With the increasing need of GIS indoor applications for emergency management, 3D indoor navigation for emergency situations are more and more popular for complex
buildings. The organization *Future Position X* would like to build a 3D model of the *Teknikparken* which could be applied for emergency evacuation. This target model should related on authentic data to reach the evacuate time. This study uses ESRI’s ArcGIS 10 to investigate the accuracy of network analysis for identify evacuation routes within indoor environments. A simulation experiment was conducted to assess the predicted evacuation time results using building on the Teknikparken in the city of Gävle. A 3D model of that building was created within Google Sketch Pro 8, and the network analysis will be done with ArcGIS 10.

The broad aim of this thesis was to create an authentic evacuation 3D model for emergency management. Smaller objectives included creating a 3D network analysis model for emergency management, conducting a simulation experiment of evacuation time, and comparing the results of the 3D network analysis and simulation experiment. The final goal is to provide a reliable 3D model for emergency management.

### 1.4 Organization of the thesis

Chapter 2 describes the data collection process for the study and the modelling process. The methodology used to analyze the 3D environment is also described here, as are the methods used for the simulation experiments. Chapter 3 (Results) examines the results, and displays the results of the 3D conditions in ArcScene. Chapter 4 (Discussion) discusses the results of the analysis, and compares the travel time 3D model and simulation experiments. Future research possibilities are listed in the conclusion.
2. Materials and Methodology

2.1 Study area

The case study for the thesis is a building in the Teknikparken of Gävle, Sweden. Teknikparken is located to the west of the city's core and near the E4 highway (Figure 3). Teknikparken has 4 main buildings and parking lots. Buildings of the Teknikparken have 4 floors. All buildings are connected with each other. Figure 2 shows an architectural sketch of the buildings. The building labelled number “02” is the focus of this thesis work.

Figure 2. The building’s position in the Teknikparken

Figure 3. Teknikparken in western Gävle
2.2 Software

The study can be partitioned into two parts: 3D network analysis and 2D network analysis. The 3D network analysis can be broken into 2 smaller parts: the data collection process and the 3D network analysis process. The main task of data collection process is to build a 3D model of the buildings in question. 3D and interrelated software are indispensable parts of 3D modelling, which should be considered carefully. Using suitable software could make positive contributions to the modelling process and final results. Google SketchUp Pro 8 is a simple but powerful tool for exploring and presenting project. It allows people create 3D models from existing data and textures. For this study, Google SketchUp Pro was used to build the polygon-based 3D building models and indoor 3D construction.

ESRI’s ArcGIS 10 was the main software used for the 3D network analysis process. The interior of the building was inserted into the ArcDesktop and ArcMap applications to digitizing the data and construct the network analysis. ArcScene was used to visualize the building. Since, SketchUp models cannot be directly used in ArcGIS, the Feature Manipulation Engine software (known as FME) was used to transfer SketchUp data format to ESRI shape files. ESRI’s ArcGIS was also the main software used for the 2D network analysis. The whole analysis process was completed in ArcMap.

2.3 Data collection and pre-processing

All the necessary data was collected before creating the 3D model in Google SketchUp Pro 8. Considering to the data’s accuracy, all the outside of the building was measured using a total station. Collected data included the length and height of each wall, the intersection angles of topological planes, and the slant angles of the roofs. Unlike outdoor environments, indoor environments are hard to measure using total stations due to the complexity structure and the presence of people. As a result, most
of the indoor structure data were obtained from architecture drawings. Linen tape was also used to measure source features. The architecture drawings were provided by municipality of Gävleborg (Gävle Kommun) and the company Brynäs Byggnads AB. Figure 4 shows an example (1st floor) of indoor structure. Triple measurements and average values were done during this process.

![Figure 4. Architectural drawing of 1st floor for the target building](image)

(Source: Kontorsbyggnad Plan 1, Teknikparken, Brynäs Byggnads AB, 2005)

After the measurement processes, a polygon based 3D model was built. Figure 5 shows an example 3D model for indoor environment of the objective building. As noted, the data format of Google SketchUp cannot be used directly by ArcGIS. To address this problem, the SketchUp model was exported to AutoCAD data format. The CAD format files were then transformed to ESRI shape files using FME software. Data collection and pre-processing were then completed and the data converted to a form for use in analysis process.

![Figure 5. 3D model of indoor environment](image)
2.4 Three dimensional Network Analyses

There are three main design and construction elements within this particular 3D network analysis process. First of all, a geo-database was built with feature datasets. Secondly, a 3D geometry model was created once the feature dataset was completed. Finally, the network analysis process was done. All these processes were done in ArcMap and ArcCatalog. ArcScene was also used to show the final results in a 3D environment. Figure 6 shows the flow chart of the working process. Dijkstra’s algorithm was the primary tool used to identify paths for the network analysis.

![Flow chart of 3D network analysis process](image)

2.4.1 Geo-database and 3D modeling

All the features which used in this particular study for 3D model and network analysis were stored in a Geo-database by using ArcCatalog. A serviceable database could make huge positive contributions to the network analysis process, and vice versa. Geo-database includes three feature datasets: the Transportation dataset contains the FloorLines, the Floor Transitions (Elevators and stairs), the Transportation_ ND, and the Transportation_ ND_ Junctions; the Analysis dataset has one feature OfficeCenters; and the Base map dataset has four features Building Floor, Offices (floor 1 and floor 2), Surface and Building Footprints. Figure 7 shows the structure of the geo-database.
After the geo-database was created, the 3D model was created. 2D maps, which has been drawn before were inset into the ArcMap. A 2D base map was assembled from this information these 2D maps. Geo-referencing data which referenced target building was added into ArcCatalog so that the vector data could be given in correct scale and reference. Furthermore, it was important to correct x and y values to ensure that the distance calculations between each node were accurate. The real-time coordinates of each offices centre or corner cannot be obtained by GNSS (Global Navigation Satellite System). Thus, the calculation was conducted using the distance of each features’ segment. All the network analysis distance measurements were calculated by coordinates generated from these distances. With the addition of base map feature dataset to ArcMap, the polygon based feature classes were created. Figure 8 shows an example feature class of the polygon layer data.
In order to treat the 2D layers as 3D geometry models, the vertical value $z$ was created for each feature class in ArcCatalog. In this case, all the suitable features were assigned a height attribute, such as floor lines, offices and office centers (Figure 9 and Figure 10). The elevator is going through the two plans to show their dimensions. Since the purpose of this project is to find the shortest path from three specific points to the exit of the first floor in emergency situation, the elevator was not involved in this target path.

In a topology model, the corridors, elevators and stairs are usually represented by linear feature classes. These kinds of routes are easier to create and calculate. Stairs are very important features in 3D network analysis. For this study, the $z$ value of stairs was determined by halving the vertical value between the floors. A $z$ value should also be added to each feature dataset. *OfficeCenters* are basic nodes in the dataset. They were edited with appropriate $z$ geometry value. After all the datasets were created, the features were ready to display using ArcScene. Figure 9, 10 and 11 show the 3D features in the model of the target building.
2.4.2 Network analysis model design

In order to maintain the network analysis, each node and segment of all the features should connect to each other. For this study, all network datasets were based on the feature of the topological model. The attributes of the dataset were also specified, including variable names, units, and data types. Travel time was set as the evaluator of the project’s result. Travel velocity was calculated using equation 3, where \( V \) is the velocity of human’s walking speed, \( D \) the distance between two points, and \( T \) the travel time. The default walking velocity (\( V \)) assigned by the algorithm was 1.2 m/s.

\[
\text{Eq. 4 } V = \frac{D}{T}
\]
A route analysis model was created to make the program run (see Figure 12). A route layer and solve tool were created in ArcCatalog by the ModelBuilder and ArcGIS Network analysis tools. After this step, all the features needed were in place. Figure 12 shows the created route analysis model of 3D network analysis.

![Figure 12. Route model of 3D network analysis](image)

### 2.4.3 Test network analysis

The names of people occupying offices were housed in the attribute table of the OfficeCentre variable. The fastest route from any spot to this office can calculate by emergency managers. This system is very efficient and easy to update.
Table 1. The information of OfficeCenter

<table>
<thead>
<tr>
<th>Floor_Wing</th>
<th>Name</th>
<th>Floor_Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>2w</td>
<td>Meeting Place</td>
<td>Second Floor</td>
</tr>
<tr>
<td>2w</td>
<td>Small Meeting Room</td>
<td>Second Floor</td>
</tr>
<tr>
<td>2w</td>
<td>Small Meeting Room</td>
<td>Second Floor</td>
</tr>
<tr>
<td>2w</td>
<td>Conference Room</td>
<td>Second Floor</td>
</tr>
<tr>
<td>2w</td>
<td>Test Lab</td>
<td>Second Floor</td>
</tr>
<tr>
<td>2w</td>
<td>Machine Room</td>
<td>Second Floor</td>
</tr>
<tr>
<td>2w</td>
<td>Roland Norgren</td>
<td>Second Floor</td>
</tr>
</tbody>
</table>

2.5 Simulation experiment

After the network analysis process, the shortest paths from two offices to the building’s exit were selected. Travel time of each path was calculated using the formula described in Equation 5. Simulation experiments were subsequently conducted to test the reliability of the algorithm’s calculations.

2.5.1 Experimental principles

The basic principle of this simulation experiment was to have volunteers “escape” from the selected rooms to the exit at 3 different paces: “normal walk”, “run” and “walk with crowd” 3 situations. Figure 13 (2D map) shows the evacuation route from these selected rooms to the exit. The reason why we choose the “normal walk” is to confirm the accuracy of the time predicted by the 3D model network analysis. In order to simulate an emergency situation at routine stress-free work time, the “running” mode was used. In this situation, it is assumed that only a few people in that building and the escape routes are not blocked. The mode “walk with crowd” simulates an emergency when the building is at capacity and thus, all possible escape routes are crowded. People can only move very slowly in this case.
2.5.2 Experiment conditions

The simulation experiment was done on Friday 25, May, 2012. During the experiment process, there were no other people but the test objects in the building. For this reason, interference factors were eliminated. The total sample size of this experiment was 18, 9 of which were men and 9 women. The participants were between 20 to 50 years of age. The experiment conditions were almost equal to the normal situation of the modeled building. This condition could reflect the evacuation circumstances when emergency occurs in normal work days. Mobile phones with the stopwatch application were given to the subjects. One researcher monitored at the start point while the second was positioned at the exit. People escaped one by one, except for the crowd simulation. Figure 14 shows the real picture of Route 1 and Route 2. Two kinds of the stopwatch mobile phone applications are displayed in Figure 15.
2.5.3 Experimental procedure

In walking mode

Every subject walked the route individually using a normal. Triple measurements and calculated mean values were used to insure the accuracy of the experiments. The final
travel time of men and women were recorded to compare the results with other sections.

**In running mode**

All volunteers were divided into two groups, one with only men and the other with only women. Each group was divided into 3 sub-groups, thus each sub-group had 3 people. Each sub-group (three persons run together) did the experiments individually to an unobstructed escape. After recording the travel time of each sub-group, the mean values of men group and women group were calculated. The triple measurements were used in this section as well.

**In crowd mode**

All the participants did the crowd walk together to simulate a high volume emergency situation. Walk speeds should decrease when evacuation routs are packed with people attempting to leave at the same time. Triple measurements and mean values were also used to guarantee accuracy. In Figure 16, the black circles indicate the bottleneck delay turns. After the command “Go”, the stop watch began to measure time while all the participants came out from the offices around the start point.

![Figure 16. Bottleneck in crowd mode](image)
2.5.4 Experiment results preprocessing

The experimental results preprocessing is the step to enhance the recorded data from the simulation experiments. Some recorded data may be inaccurate due to mistakes made by the subjects and recorders. Inaccurate data was deleted before the mean value for each test was calculated.

3. Results

After all the modeling and feature designing process were finished, the 3D model results and the data from the simulation experiments were analyzed. The overall results are predicted in two sections. The visualization results display the shortest paths. The analysis results of the 3D model show the distance of the created routes and the travel time. The analysis results of simulation experiments are shown in tables below.

3.1 Visualization results

Seven layers were created to show the FloorLines, FloorTransportation in the 3D model. The shortest paths of each section in 3D model are also displayed in ArcMap and ArcScene. Figure 17 shows the shortest path from first selected office in 3D model. And Figure 18 and shows the shortest path from second selected office in 3D model. The small green flag on the upper stair is the start node. The position of the small flag on the lower first floor is the destination node. The indicated green thick pipe is the fastest route to down downstairs.
3.2 Analysis results

A series of evacuation times were calculated for the 3D model. The selected route is shown in Figure 17 (Route 1) and Figure 18 (Route 2). The travel time was calculated by Equation 4 with V equal to 1.2 m/s.

\[ \text{Eq. 5 } T = \frac{D}{V} \]

Table 2 shows the results for normal walking pace for the simulated experiments. In addition, the actual distance was divided by the measured Mean Time of men and woman to obtain the Actual Velocity column can be obtained from this calculation process. The evacuation time for both running and crowd walking conditions is shown in table 3 and 4.
The new mean velocity is the mean value of the actual velocities of Route 1 and Route 2 in Figure 17 and Figure 18 (see Table 2, 3 or 4). This new velocity was used to calculate new travel times in ArcMap by dividing the actual distance by the “Mean (new velocity)”. The function of this calculation is also based on equation 4. The differences between the two routes were also shown in the bottom row of each table below.

Table 2. Results for normal walking time

<table>
<thead>
<tr>
<th>Items Route ID</th>
<th>Distance (m)</th>
<th>Men Time (Mean value) (s)</th>
<th>Women Time (Mean value) (s)</th>
<th>Mean Time (s)</th>
<th>Actual Velocity (m/s)</th>
<th>Mean (New velocity) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>74.60</td>
<td>73.81</td>
<td>78.95</td>
<td>76.38</td>
<td>0.98</td>
<td>1.06</td>
</tr>
<tr>
<td>2</td>
<td>94.31</td>
<td>81.20</td>
<td>86.42</td>
<td>83.81</td>
<td>1.13</td>
<td></td>
</tr>
<tr>
<td>Diff.</td>
<td>19.71</td>
<td>7.39</td>
<td>7.47</td>
<td>7.43</td>
<td>0.15</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Results for running time

<table>
<thead>
<tr>
<th>Items Route ID</th>
<th>Distance (m)</th>
<th>Men Time (mean value) (s)</th>
<th>Women Time (mean value) (s)</th>
<th>Mean Time (s)</th>
<th>Actual velocity (m/s)</th>
<th>Mean (New velocity) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>74.60</td>
<td>45.61</td>
<td>48.42</td>
<td>47.02</td>
<td>1.59</td>
<td>1.56</td>
</tr>
<tr>
<td>2</td>
<td>94.31</td>
<td>59.20</td>
<td>64.83</td>
<td>62.02</td>
<td>1.52</td>
<td></td>
</tr>
<tr>
<td>Diff.</td>
<td>19.71</td>
<td>13.59</td>
<td>16.41</td>
<td>15.00</td>
<td>0.07</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Results for crowd walking time

<table>
<thead>
<tr>
<th>Route ID</th>
<th>Distance (m)</th>
<th>Time (s) (Mean value)</th>
<th>Velocity (m/s)</th>
<th>Mean (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>74.60</td>
<td>99.62</td>
<td>0.75</td>
<td>0.83</td>
</tr>
<tr>
<td>2</td>
<td>94.31</td>
<td>103.59</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>Diff.</td>
<td>19.72</td>
<td>3.97</td>
<td>0.16</td>
<td></td>
</tr>
</tbody>
</table>

The second column of the Table 5 indicates the evacuation time from selected locations to the exit in the 3D model network analysis. The travel time calculated by the new speed (the last column in Table 2, 3 and 4) are also displayed. For example, the “ArcMap (V=1.06 m/s) (s)” column in the Table 5 is the new travel time for this new mean velocity (1.06 m/s). Each scenario has two sub columns which are the ArcMap Time and the Actual Time except the Network Analysis Results column.
Comparisons between the network analysis calculated travel times with the default speed (1.2 m/s), new travel time in ArcMap and the experimental actual human travel time is displayed in Table 5. The difference between the normal walking travel time for the mean velocity (1.2m/s) and the simulation experiments can be seen clearly.

Table 5. Comparison of observed times

<table>
<thead>
<tr>
<th>Items</th>
<th>Network Analysis Results</th>
<th>Normal walking Evacuation Time</th>
<th>Running Evacuation Time</th>
<th>Crowd walking Evacuation Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route ID</td>
<td>Route Distance (m)</td>
<td>ArcMap (V=1.20 m/s) (s)</td>
<td>ArcMap (V=1.06 m/s) (s)</td>
<td>ArcMap (V=1.56 m/s) (s)</td>
</tr>
<tr>
<td>1</td>
<td>74.60</td>
<td>62.17</td>
<td>70.38</td>
<td>47.82</td>
</tr>
<tr>
<td>2</td>
<td>94.31</td>
<td>78.59</td>
<td>88.97</td>
<td>60.46</td>
</tr>
<tr>
<td>Diff.</td>
<td>19.72</td>
<td>16.42</td>
<td>18.59</td>
<td>12.64</td>
</tr>
</tbody>
</table>

4. Discussion

The main outcomes of this work are 1) a 3D network analysis model that can be used for evacuation planning, 2) a set of concerns of limitation about implementation of the model. The second part of the discussion section addresses the concerns and limitations that arise out of the model’s design and the conduct of the experimental scenario.

4.1 3D Model Analysis

The comparative evacuation times are shown in Figure 19. The experimental time and modeled times are similar for the walking and running modes. However, the difference for the crowd walking mode is large, indicating that the evacuation situation will be very slow and severe. Moreover, the longer the escape route, the more time it takes to exit. In the Figure 19, the model time difference of Route 1 and Route 2 in normal walking mode is much smaller than the difference for the crowd situation. There is no denying that evacuation rehearsals should be conducted and the
Evacuation routes should be distributed differently from office to office.

There are many restricted turns in Route 1 especially near the small kitchen (Left first image in Figure 20). Although Route 2 is much longer than Route 1, the actual experimental time is similar. However, the time gap of the Route 1 and Route 2 in crowd walking mode of model calculation is large, as the model only considers distance not the impact of turns. The evacuation time for the normal walking scenario was used to calculate new times for the model. The differences between the computed results and the “normal walk” experimental results were very small. The measured running time is a little less than the model time value as people go faster when are running downstairs (see Table 5). These four recodes indicated that default speed cannot be assumed when doing the simulation for the emergency analysis (Figure 19).

![Time comparison with ArcMap of 4 situations](image)

**Figure 19. Time comparison line chart**

To sum up, internal and external factors will affect the escape process overwhelmingly. The more aspects are taken into consideration, the more accurate the results will be
and in turn the more effective the planned evacuation routes.

4.2 Evacuation experiment assessment

The scenarios tested only involved in two variables: walking velocity, gender. In the real world several other factors could influence the velocity by which occupants can exit. The factors that affect the escape velocity include internal human factors and external environmental elements.

4.2.1 Influencing factors

Internal human factors

Tang and Ren (2011) claimed that human behavior has to be respected as one of the most essential qualities affecting a person’s reaction to emergency situations. Pires work (2005) also shows evidence that people’s behavior may be affected by the internal or external aspects. Some people can feel anxiousness or scared and become confused. On the other hand, others are emotionally controlled, self-motivated and trained in emergency procedures. Their actions will be more composed and responsive. While, the “run” and “walk with crowd” modes adjust partly for variations in human behavior, internal human factors were not directly taken into consideration during the experiments. The “run” mode assumed that people have necessary escape skills and will stay in calm. This mode was selected as the staff working in the Teknikparken is qualified and capable. Nevertheless, it cannot be concluded with certainty that the experiments reflect real emergency behavior.

Many other human related factors can be considered. Gender was one which was controlled in the scenarios as males and females have different physical abilities (Table 2 and 3). Dress may also affect the result but was not assessed. For instance, women who wear high heels or skirts may as a result have slower velocities. Age is another complicating factor. Other groups that may influence results include the
disabled, blind, deaf or other special people. It is essential to consider these populations in future studies and plans or evacuation procedures.

**External environmental elements**

External environmental elements, such as the restricted turns in the buildings, also definitely affect the speed of escape. The design of the building or the path of the evacuation route can mitigate or magnify this problem. In the “walk with crowd” mode, the travel time of the No.2 longer evacuation route is 103.6 seconds. In contrast, the shorter time is 99.6 seconds of route No.1. The distance of the No.2 route is much longer than No.1 (see Table 5), but the time required for the two routes is similar. Restricted turns are the reason for this result.

![figure20.jpg](attachment:figure20.jpg)

**Figure 20. Barriers in the building**

There are some barriers in the building, such as the narrow path, closed non-automatic doors, automatic doors and small gates (see Figure 20). All these barriers will increase the escape time. People have to open the closed doors or wait for the doors to open automatically. In addition, the width of corridors is another complicating factor. If many people gather at a bottleneck, the speed will drop sharply. The escape routes in the skyscrapers at the World Trade Center (WTC) in New York City were complicated and too narrow for that overwhelming number of people to go through. And the surrounding streets are too narrow to let people evacuate in time as well (Kwan and Lee 2005). In Table 5, the time differences between ArcMap and the practical result
are similar in the Normal walking and running model. But the time gap of the Crowd walking is large. Crowding should be a concern for emergency management officers.

4.2.2 Electricity and lighting

In emergency situations, electricity may not be available. Elevators may not work or their use be prohibited. Lighting may also fail which is a real issue in Sweden given its long winter nights. In these situations, the default travel velocity of 1.2 meters per second may not accurately reflect actual exit speeds. Complicated indoor obstacles may also affect the accuracy of estimates.

4.3 3D Model Assessment

Model Foundation

The research was conducted on the first and second floor of the Building No.2 in the Teknikparken (where the FPX organization located). The construction of the 3D model and the multi-level network was based on the 2D architectural plan. Even tiny features had to be built precisely and the feature classes connected correctly to avoid deleterious routes. Furthermore, the attribute data input was time consuming. Software upgrades would reduce the amount of manual labor required to construct the model.

Digitization Limitation

The coordinates of each office’s centre cannot be obtained by GNSS. Route selection and calculations were consequently generated by the distance value of each route segment. The calculations would be more reliable if the real time coordinates of each point node were used. In addition, land survey mistakes may reduce the reliability of the analysis. These technical mistakes have to been avoided as much as possible during the research process.
3D model creation

Google SketchUp was used to provide a visible rendition of the building, routes, and thus model. This step allows users to literally “see” what the algorithm will analyze and the paths occupants will take. However, the initial 3D modeling data generated by Google SketchUp may be redundant. Translating data from one application to another can affect the data quality remarkably. A large amount of 3D data was also converted to SHP (shapefile) files and the resulting models moved several times between ArcScene and ArcMap. Better software integration could eliminate these unnecessary transitions.

Data processing

The 3D network analysis seemed to be unproblematic; however, extreme care was needed to do the data processing and 3D modeling. There are many essential parts including database establishment, attribute connection, data input, and route solving. The z value in the 3D network analysis was indispensable. All the feature classes had to be assigned by height in order to be rendered in 3D stereo views. Care was taken to keep manual mistakes to a minimum.

Facility analysis

Facility analysis must be considered. The goal of the study was to increase the ability of building occupants, fire fighters, and property keepers to plan for emergencies. People in emergency situations may turn too anxious and upset to choose the right the escape route (Olsson, 1996). Route planning should thus be supplemented by facilities like guide speakers, smoke sensors and exit indicators as Andersson and Meriä maintain (2011).

4.4 Future Development

While Dijkstra’s search algorithm has been used widely in 2D network analysis, it is
obvious that 3D network analysis requires more efficient and intelligent search algorithms. The methods for analyzing 3D systems must also mature. 3D methods can show buildings in extraordinary detail with stereo vision (Hyojoo & Kim, 2010). At present, CAD (Computer Aided Design) and BIM (Building Information Modeling) are utilized widely. However, GIS has not been combined with these two kinds of technology. 3D data storage problem and the lack of the 3D system platform are also the unsolved issues (Li & He, 2008). Parker (2008, November 19) argues that “It’s a requirement that CAD, BIM, GIS, visualization and collaboration come together now.”

Information about the building’s elevator feature was included in the FloorTransitions variable. Nevertheless, the availability of wheelchairs and their ease of movement were not taken into account. Researchers should pay more attention to this element to the disabled or those with special in future work.

In addition, more factors should be taken into consideration, such as the age, and education of occupants, and path width, and route design. In the future work, more internal and external aspects can be considered to make the model more reliable.

5. Conclusion

This paper presents an elementary 3D network analysis model which provides the integrated information for emergency management and planning. The model was tested by comparing the software 3D network analysis results and real time simulation experiments. The final results indicate that the 3D model provides accurate assessments for emergency management, precise data collection, robust database design and a detailed digital model.

The simulation experiments were conducted for four different scenarios. The results indicate that the network analysis algorithm’s default speed may not provide the best estimates for 3D evacuation analysis due to external factors. The difference in the
time for the selected routes is greater for the model than for the experimental scenario. The network model only takes distance into account while the scenarios are affected by human and building factors. For example, congestion can be a serious problem during evacuations. It deserves more attention in future studies. The reliability of the 3D model was much better for the other scenarios, indicating that 3D modelling can provide accurate and efficient evacuation routes identification.
References


Ying, S., Li, L., & Guo, R. (2011). *Building 3D cadastral system based on 2D survey plans with SketchUp* Wuhan University, co-published with Springer.

Appendix A.

The Office Owner Name Table can be referenced when the user want to select the office by attribute *Name* in ArcGIS.

<table>
<thead>
<tr>
<th>Office number</th>
<th>Office Owner Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Johan P. Bång</td>
</tr>
<tr>
<td>2</td>
<td>Emilie Hildebrand</td>
</tr>
<tr>
<td>3</td>
<td>Martin Snygg</td>
</tr>
<tr>
<td>4</td>
<td>Therese Ohman</td>
</tr>
<tr>
<td>5</td>
<td>Lars Palm</td>
</tr>
<tr>
<td>6</td>
<td>Nils Muhren</td>
</tr>
<tr>
<td>7</td>
<td>Jessika Nilsson</td>
</tr>
<tr>
<td>8</td>
<td>Xin He</td>
</tr>
<tr>
<td>9</td>
<td>Solgerd Tanzilli</td>
</tr>
<tr>
<td>10</td>
<td>Small meeting room 1</td>
</tr>
<tr>
<td>11</td>
<td>Machine room</td>
</tr>
<tr>
<td>12</td>
<td>W.C.</td>
</tr>
<tr>
<td>13</td>
<td>Big conference room</td>
</tr>
<tr>
<td>14</td>
<td>Zhuhai Hi-Tech Zone</td>
</tr>
<tr>
<td>15</td>
<td>Roland Norgren</td>
</tr>
<tr>
<td>16</td>
<td>Jiaman Tang</td>
</tr>
<tr>
<td>17</td>
<td>Lars Brandhammar</td>
</tr>
<tr>
<td>18</td>
<td>Small meeting room 2</td>
</tr>
</tbody>
</table>
Appendix B.

3D models

(Both still image and operable pdf 3D model are displayed below for each model. Open in Adobe Reader, click the pictures below on each page to active them. Then they can be manipulated by mouse.)

1. Plan 1
2. Plan 2
3. Teknikparken Overview
4. 3D Network Analysis Model (Pink - Plan 2, Blue - Plan 1)