LSGI4391 Individual Project

GIS for Indoor Fire Evacuation System

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Abstract

This study develops a GIS-based Indoor Fire Evacuation System (IFES) with two improvements on current studies: the network evacuation model with emphasis on behavioural rules, and the multi-stage fire risk assessment. The classical network data structure is modified mainly to simulate three essential evacuation behaviours: exit selection based on evacuees' knowledge, location of fire hazards and people's visibility; repulsion and friction; and queuing. The multi-stage risk assessment is realized by interactive overlay of Available Safe Escape Time (ASET) and Required Safe Escape Time (RSET) at each location and instant handling of unsafe evacuees. Quantitative analyses show that both improvements are much meaningful to the reliability of the IFES, since the absence of either of them can lead to significant discrepancies in simulation results, particularly the risk assessment. Thus they are expected to enhance the accuracy of indoor fire evacuation simulation and support better decision in building fire safety analysis. A functionality test also demonstrates the usability of the integrated and automated system, especially for non-technical users, which can expand economic value of this system and help to make Geo-IT more accessible to the public.

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1 Introduction

Indoor fire safety has long been a significant topic in Hong Kong. About 35,000 fire calls have been received by Fire Service Department per year on average since 2005, and more than 80% of them are building fire calls. (“Statistical Figure”, 2010) Hong Kong is only a representative of numerous large cities suffering from frequent building fire incidents. With the rapid pace of urbanization all over the world, new and renewed constructions present pressing needs for effective Indoor Fire Evacuation Systems (IFES) for evaluating building design and occupant allocation in the view of fire protection and assessing fire risks.

Great efforts have been made on indoor fire evacuation studies by institutions worldwide, like Key Laboratory of Fire Science in University of Science and Technology of China and National Institute of Standards and Technology in the United States. (Xu et al., 2009). An IFES typically requires two basic modules: the evacuation model to simulate human movements under fire threats, and the fire model to reconstruct the spreading of fire hazards. The two modules are integrated onto a common platform to derive simulation results like the evacuee safety assessment, and to present the results in a way comprehensible to technical professionals as well as non-professional users, preferably including visualizations.

Recent IFES studies have shown a promising trend to utilize geographic information system (GIS). With strong functions to handle spatial information, GIS is a highly capable integration platform for various modules of the IFES, since IFES essentially concerns the spatial information about positions of evacuees and fire hazards and interactions based on their relationship of locations. The visualization and decision support techniques in GIS also add to its superiority to be applied in IFES studies.

Despite rapid development and fruitful accomplishments, current IFES still calls for improvements. Some issues concern individual modules in the system. For instance, network is a classical data structure for evacuation modelling, often criticized for insufficient consideration of behavioural rules which are critical to the accuracy of simulation. Cellular automata (CA) is a popular data structure that can realistically depict human behaviours, but is difficult to be examined against real-world fire evacuation data for validation of its accuracy. It is desirable to develop a model that combines the ease to be examined of network models and the high ability to simulate human behaviours of CA models. Other issues are about GIS functionalities. An example is the common practice to assess fire risk by only the total required and available evacuation times which is suspected too coarse to produce accurate risk predictions, even if a more precise multi-stage risk assessment has the potential to be realized via GIS dynamic overlay functions.

This study presents a GIS-based IFES primarily with two improvements regarding the state of art about IFES studies: the network evacuation model with emphasis on behavioural rules, referring to the implementation of these rules in CA models, and the multi-stage fire risk assessment which better utilizes the dynamic overlay functions in GIS. Quantitative analyses are made to demonstrate the enhancement in reliability of the IFES by these improvements. The system is also integrated and automated on the Visual Basic platform to ease its use especially by non-professional users.

This report is divided into 6 chapters:

- Chapter 1 is the current part and the introduction;
- Chapter 2 is the review and a analysis of previous work on evacuation modelling, fire risk assessment and the application of GIS in fire evacuation studies;
- Chapter 3 puts forward the objective and significance of this study;
- Chapter 4 describes the methodologies to construction the IFES, which comprise data collection, data representation and integration in GIS, network evacuation model construction, fire model construction, overlay analysis for fire risk assessment, output generation, visualization, and system automation;
- Chapter 5 presents the results of IFES development in the form of a system functionality test, as well as analyses on essentialities of various system functions;
- Chapter 6 concludes this report by the overview evaluation on the study, limitations of the study and recommendations for further development.

2 Review and analysis of related work

2.1 Indoor evacuation dynamics

Modern studies on indoor evacuation dynamics have had a history of four decades, and a variety of evacuation models have been developed. Some models deal with the evacuation only, while the others focus on fire evacuation and include fire propagation in the model, so that the interaction between evacuees and the fire can be handled and evacuation scenes become more realistic. The following is some common model types which are classified by their data structures:

(1) Network model: this model divides the physical evacuation environment into nodes representing building components like rooms and stairways, and arcs representing passageways between the components. Evacuees are treated as flows passing the nodes and arcs, so the model is also called flow-based model. Building geometry is usually the core consideration for this model type.

(2) Force-based model: this model simulates people movements and interactions by physical forces and represents evacuation rules by mechanical formulas. Social force model (Helbing and Mulnár, 1995) is the representative of models in this category.

(3) Cellular automata (CA) model: this model divides the evacuation environment into grid of cells. A cell can be occupied by building structures or obstructions, an evacuee, or nothing. Evacuee movements are recursively calculated according to

a set of rules, and evacuee location at each time step is the basis for calculation at the next step.

(4) Multi-agent model: this model emphasizes individual differences among the evacuees. The evacuees are depicted by their physical and psychological attributes, like age, gender, having difficulty in walking or not and familiarity to the environment, and values of these attributes will influence the results of evacuation simulation.

An evacuation model can combine the features of multiple model types, and several of such cases are to be covered in the following discussion. Regarding to the concern of this project, only studies about network models and CA models will be further reviewed.

Network model is the most classical type of model and has been used since the earliest stage of study. (The Confederation of Fire Protection Associations in Europe (CFPA E), 2009) Kisko et al. in The University of Florida developed EVACNET network evacuation model in 1983, and its enhanced versions EVACNET+ in 1984 and EVACNET4 in 1998 (Kisko et al., 1998). The EVACNET series produces optimal evacuation plans from inputs of building geometry and evacuee allocation, and can identify bottlenecks in evacuation routes. However, it does not describe human behaviours under emergent evacuation circumstances. Other network systems like WayOut (Shestopal, 2003) and Takahashi's Fluid (Kuligowski, 2004) are also primarily based on building geometry and do not account for human behaviours.

Fahy (1995) in The National Fire Protection Association, US designed EXIT89, a partial behavioural network model in terms that it adopts the multi-agent concept. The model allows variable evacuee response times, assigns different body volumes for Americans, Austrians and Soviets, and introduces disabled people. Smoke blockages which can trap the evacuees and change their evacuation routes are also defined in the model.

EXITT developed by National Institute of Standard and Technology (NIST) considers more human behavioural factors: the evacuees act as family groups, and their first reactions to fire are corresponding to their roles in the family. Adult males investigate the fire, adult females go to their children and children stay and wait for instructions. Also, moving speed of people is affected by smoke density. (Bukowski and Peacock, 1989)

Network model has the advantage of small computation loads, yet this is diminishing as the capacity of modern computers multiplies. Another strength is the straightforward simulation parameter settings and easy backtracking of parameter errors: the parameters generally have clear physical meanings, such as speed, moving direction and time delay. When the simulation result is examined against data from real world fire incidents, the discrepancies can be analyzed by varying parameter values and see if the result is improved, until the parameter settings are considered appropriate. Then the settings can be projected to similar scenarios for evacuation simulation when real word data is unavailable.

The critical deficiency of network model is the less detailed description of evacuation scenes, particularly the insufficient applications of behavioural rules. Although EXIT89 and EXITT include behavioural modules, they still produce evacuations along either optimal routes or user-defined routes, rather than automatically calculate most probable routes chosen by people with regard to behavioural rules. In EXITT, the optimal routes are more than “shortest” or “fastest”, with smoke density taken into consideration, yet the route searching algorithm aims at least cost after all, or “the wisest choice” of the evacuees. However, data in reality shows that people in fire can hardly be assumed to make the wisest decision, and it is commonly believed that the lack of behavioural rules will lead to inaccurate simulation results, usually underestimations on evacuation time and fire risks. (Yang et al., 2007; Yuan and Tan, 2007; CFPA E, 2009)

A typical CA model is EGRESS designed by Ketchell et al. (1993) in AEA Technology, UK. It represents the building environment in a hexagonal cell grid and calculates people movement in discrete time steps. It is able to support simulations with thousands of evacuees and in several squared kilometres area, thus is suitable for simulations in public places. The claimed accuracy of evacuation time against real-world data is ±20% for general building structures.

Song et al. (2006) in University of Science and Technology of China developed CAFE model where force essentials are adopted into CA data structures to formulate people movements. People movements are decomposed into three basic forces: attraction, repulsion and friction. The simulation results demonstrate the ability of this model to depict subtle behavioural phenomena in evacuation. For instance, the evacuation speed will go down when people congest and intend to move fast.

Another phenomenon is the irregular evacuee outflows from crowded exits, or that the time headway between two evacuees leaving the exit is far from uniform, particularly when people are panic and desire for a high evacuation speed.

Yuan and Tan (2007) in Nanyang Technological University, Singapore modified CA model and implemented comprehensive behavioural rules in exit selection among multiple exits, according to location relationship between people and the exits, crowdedness of the exits, people's familiarity to the environment, grouping effect, and so on. The model formulates exit selection and people movement with probability functions and can precisely assess the goodness of indoor exit design in terms of evacuation efficiency.

CA models enjoy a major advantage of capacities on realistic depiction of evacuation behaviours, which should be essential for accurate simulation. However, this ability to make precise simulation can not ensure the accuracy of simulation, unless the results are validated against real-world fire evacuation data. Unfortunately, CA models usually rely on complicated mathematical processing and involve a large number of parameters: a single people moving speed or moving direction can be controlled by several or even more than ten parameters. Moreover, many parameters may not have intuitive physical meanings, so their values are difficult to estimate, and sometimes are just assigned convenient numbers like 0 or 1. When tested by real world measured evacuation conditions, even discrepancies between the measured and simulated evacuations are identified, the error tracing and adjustment of parameter values will be much more difficult than in network models, since the number of combinations of the many parameters is immense, and it is almost impossible to exhaustively test these combinations and find the adjustment of which will best improve the simulation accuracy. This leaves many quantitative analyses in CA model unconvincing despite their merit in implementing behavioural rules.

2.2 Fire risk assessment

The fire risk assessment is typically done by comparing the Available Safe Escape Time (ASET) by which fire hazards reach thresholds of human tolerance, and the Required Safe Escape Time (RSET) by which people are able to move to safer places. Very often, only the total times are compared, that is, the evacuees are considered safe if ASET > RSET at safety exits. This can give overoptimistic prediction on evacuee safety by ignoring the possibility that people reach an intermediate location in evacuation later then the fire hazard, even they would reach the exits earlier than ASET if not caught in fire halfway. Figure 2.1 illustrates such a situation: suppose that it takes 2 minutes for the fire to reach location A in the evacuation route and 8 minutes from A to the safety exit B, and people need 4 minutes to A and 3 minutes from A to B. People should in fact caught by fire before passing A, but they will be predicted safe if only the total evacuation time is considered, since people are supposed to get to B at t=7min while the fire gets to B at t=10min. Furthermore, unsafe people behave differently from the safe ones: if injured and can not move further, they will not get to the exit and make it more crowded as the others do, but the others' ways may be obstructed by the injuries. (Dirk et al., 2000) Errors will be generated if people under risk halfway are not indentified or processed differently from safe evacuees immediately after the risks occur.

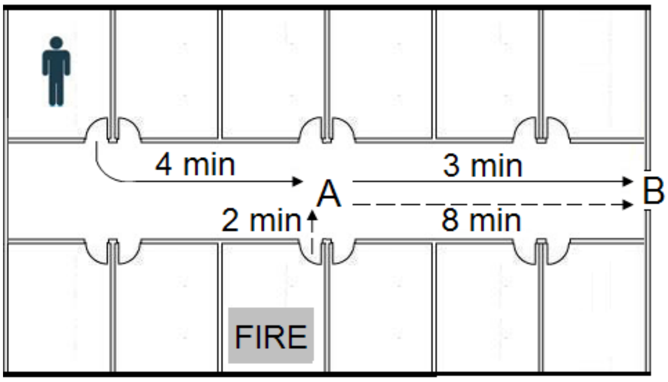


Figure 2.1 A case where the evacuee should be caught in fire halfway. The plain lines represent people movements and the dashed lines represent fire propagation.

For an IFES where evacuation and fire modules are merely overlaid at the end of simulation rather than dynamically integrated, the risk assessment can either be single-stage, or at best compare ASET and RSET at each node but not include instant handling of unsafe evacuees. Even those models which include interactions between people and fire may not deal with risk assessment. Only a few systems output comprehensive risk assessments, such as CRISP developed by Fraser-Mitchell in Fire & Risk Sciences Projects, BRE Group, UK, and ASERI by Schneider, Integrated Safety Technology Limited, Germany. Internal mechanisms of these commercial software is hardly accessible, thus it is unclear if their risk assessments compare ASET and RSET at each location and instantly handle unsafe evacuees. Yet the expected output from a multi-stage interactive risk assessment, the location and time of fire risks based on individual events or probability distributions, can not be obtained. CRISP provides percentage of people under risks in each room, but room is not the basic spatial unit in that model, so the result is not as detail as a multi-stage dynamic risk assessment can be. ASERI outputs RSET of each room, but ASET of each location is not provided. (Hanea, 2009)

2.3 GIS applications in fire evacuation studies

GIS has been increasingly involved in fire evacuation studies since the 1990s. It can be used in either the evacuation module or the fire module. Cova and Church (1997) in University of California, Santa Barbara presented a GIS-based method to assess evacuation vulnerability (transportation difficulties in evacuation) at neighbourhood level. The method implements critical cluster model to estimate the worst situation of evacuation for each location and produces an evacuation vulnerability map. The study also suggested a scheme to overlay hazard maps and evacuation vulnerability maps in GIS for risk assessment of hazards such as urban firestorms. Fire behaviour simulations have also been handled in GIS: Vakalis et al. (2004) used GIS to estimate fire spread with fuzzy system/neural network method, and Yassemi et al. (2007) designed a GIS model with CA data structure to characterize forest fire behaviours.

GIS can also be used as the integration platform of modules in fire evacuation systems. Kwan and Lee (2003) tested an integrated three-dimensional network fire evacuation model supported by a GIS database of Ohio, US and mobile services. They found that the system had the potential to significantly reduce the response delay of evacuation in multi-floor buildings. Lo et al. in City University of Hong Kong put forward a platform using GIS to integrate existing evacuation systems SGEM and GIS-SimQue for large scale evacuation under fire and other emergencies (Liu and Lo, 2009; Zhan and Lo, 2008). ESRI also reported applications of its GIS products for fire evacuation solutions, like using tapestry segmentation to identify people with special needs in evacuation (ESRI, 2009), and employing ArcGIS Network Analyst to facilitate planning (ESRI, 2008) as well as real-time reaction decision making (Price, 2011) of wildfire evacuation.

While GIS has been extensively applied in fire evacuation studies, most applications are targeted at large-scale evacuation where individual buildings or floors are treated as single locations while the internal structures are not represented (Zou et al., 2005). Actually, GIS has great potential in applications to micro-scale indoor fire evacuation studies due to its strong capability in spatial data handling. For instance, its topology structure is highly suitable for evacuation route searching; latest advances in three-dimensional GIS show good prospect in handling the usually difficult data representation in multi-storey buildings where the same horizontal location is associated with multiple data items in different heights.

3 Project objective and significance

Based on the review and analysis presented in Chapter 2, the objective of this study is to develop a GIS-based IFES with two major improvements: the network evacuation model with emphasis on behavioural rules, and the multi-stage interactive fire risk assessment.

The network data structure will be modified to adopt a series of behavioural rules that are frequently implemented in CA models, so that the evacuation scene can be better depicted, the deficiency of network models from the lack of behavioural rules reduced, and the difficulty in CA to be tested and adjusted by real-world data due to model complexity avoided.

The multi-stage dynamic risk assessment will compare ASET and RSET at each location on evacuation route, and regard the evacuees as safe only if they are safe at all locations, otherwise immediately apply different behavioural rules to unsafe evacuees. This applies the GIS function of dynamic spatial overlay and is an exploration to use specific GIS techniques in scientific studies.

To ease the use of this system especially by non-professional users, the system will be integrated onto a single graphical user interface, with simple user inputs, wholly automated internal data communication and processing, and comprehensible outputs and visualizations.

Both the improvements are expected to increase the reliability in RSET estimation and fire risk assessment, hence the fire evacuation analysis can guide and judge the fire protection design of buildings more effectively. This is the scientific significance of this project. The integrated and automated system can lower the requirement for users' expertise, expand the potential market of this system and reduce costs of user training. This is the economic significance of this project.

4 Methodologies for GIS-based IFES construction

4.1 Data collection

The study area of this project is 7/F, HJ wing in the campus of The Hong Kong Polytechnic University. It is the office area of The Department of Land Surveying and Geo-Informatics and accommodates tens of staff members. The area is about 20m in width and 50m in length, within which there are 28 offices, 1 meeting room and 1 printing room, guarded by two fire-proof exits on the northwest and southeast (referred to as "north exit" and "south exit" later). Most offices are for 1 or 2 staff members only and are no wider than 3m, and rooms are linked by 2m wide long corridors. This building geometry is appropriate for network structure, since the dimensions of rooms and corridors limit the evacuation route near to their centrelines where the network links can be located (Figure 4.1). A wet-pipe pendent-head sprinkler system covers the whole area.

Four types of data are required for this study:

(1) Two-dimensional building geometry: dimensions of rooms and corridors, locations of doors, and so on. They are used to construct the evacuation network and environment in the fire model. The primarily source of this type of data is the digital floor plan covering the study area from Campus Development Office, The Hong Kong Polytechnic University. The floor plan is of drawing number AR/07F/FGHJ and is in .dwg format. It has a scale of 1:100 and a precision level in centimetres, and provides much comprehensive planar building geometry.

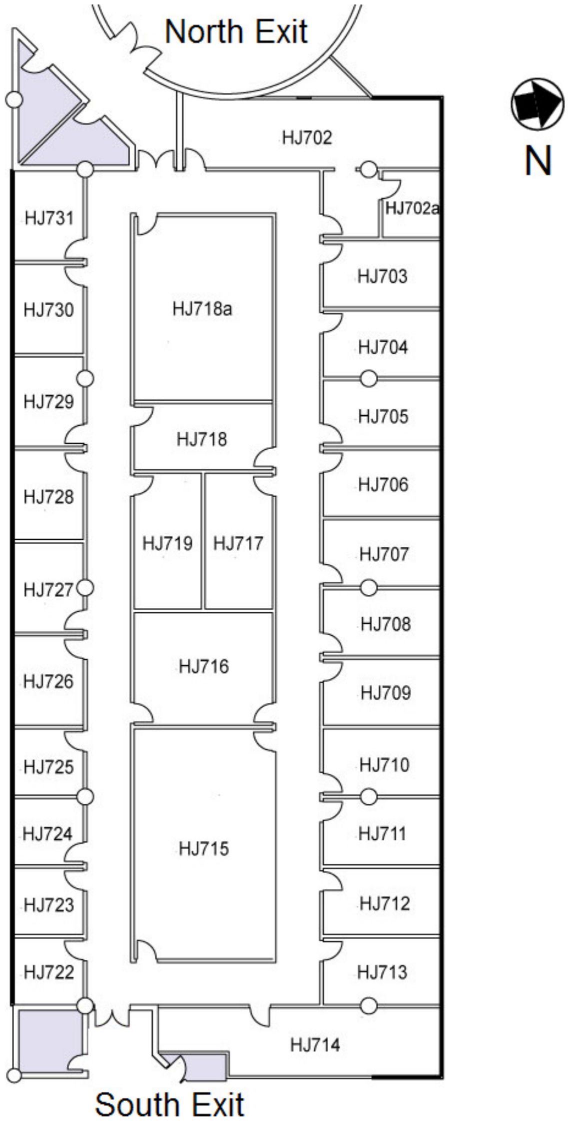


Figure 4.1 The study area

The information on the floor plan is validated by field survey with a pocket steel tape of millimetre precision level, and some mistakes and inaccuracies are identified and corrected. For example, the doors are 76cm wide on the plan, while their actual width is 90cm, and some doors open in wrong directions on the plan. The geometry on the plan is considered true to scale if the difference between field measurements and the plan is no more than 1 to 2 centimetres per meter, and hence the data quality should be sufficient for the 50cm geometry precision in the evacuation model and the 20cm×20cm×50cm grid cells for fire calculation.

(2) Height information of the corridors, doors and vents in the top part of walls between the offices and corridors. The height information is only used to construct the fire model geometry, while the evacuation model is planar and requires no height. The heights are manually measured in field survey with the pocket tape as mentioned. 3 to 5 measurements are taken in different parts of the building for each height and the average is taken. Regarding to precision of the pocket tape, random measurements errors are unlikely up to centimetre level, and would be negligible when the building geometry is resampled into cells of the fire model with 50cm resolution in Z dimension.

(3) Other details like sprinklers and surface patterns. The sprinkler system covering the study area is included in the fire model, since it can significantly slow down fire propagation and affect the fire simulation result. The sprinklers are surveyed in field because map data about them can not be found. All the sprinklers are located in the centre of 50cm×50cm ceiling bricks, so their locations are recorded by bricks and then translated into coordinates. This may causes coordinate errors of up to half the

brick size, or 25cm, since the locations of ceiling bricks shift a little in different rooms. This is slightly over the 20cm accuracy required by spatial units in the fire model, but seems acceptable considering the difficulty to manually measure the shifts of ceiling bricks in each room.

Building surfaces like doors and walls have their outlooks photographed by a personal digital camera. The photos are used to make surface patterns for fire model visualization in later stages.

(4) Modelling parameters such as human walking speed, sprinkler configurations and typical intensity of office fires. Values of these parameters are referenced from relevant literatures, and the value and reliability of each parameter will be covered when they are concerned later in this study.

4.2 GIS-based integration platform and data representation

Figure 4.2 illustrates the schema of the GIS-based integration platform used in this study which combines a GIS database, the evacuation and fire computation modules, and the user interface. Data representation in the GIS database is also shown in the figure.

In current stage the study does not utilize any commercial GIS software or geospatial databases. The spatial data for the study area are relatively simple and can be well represented with a normal relational database, hence a geospatial database is not used,

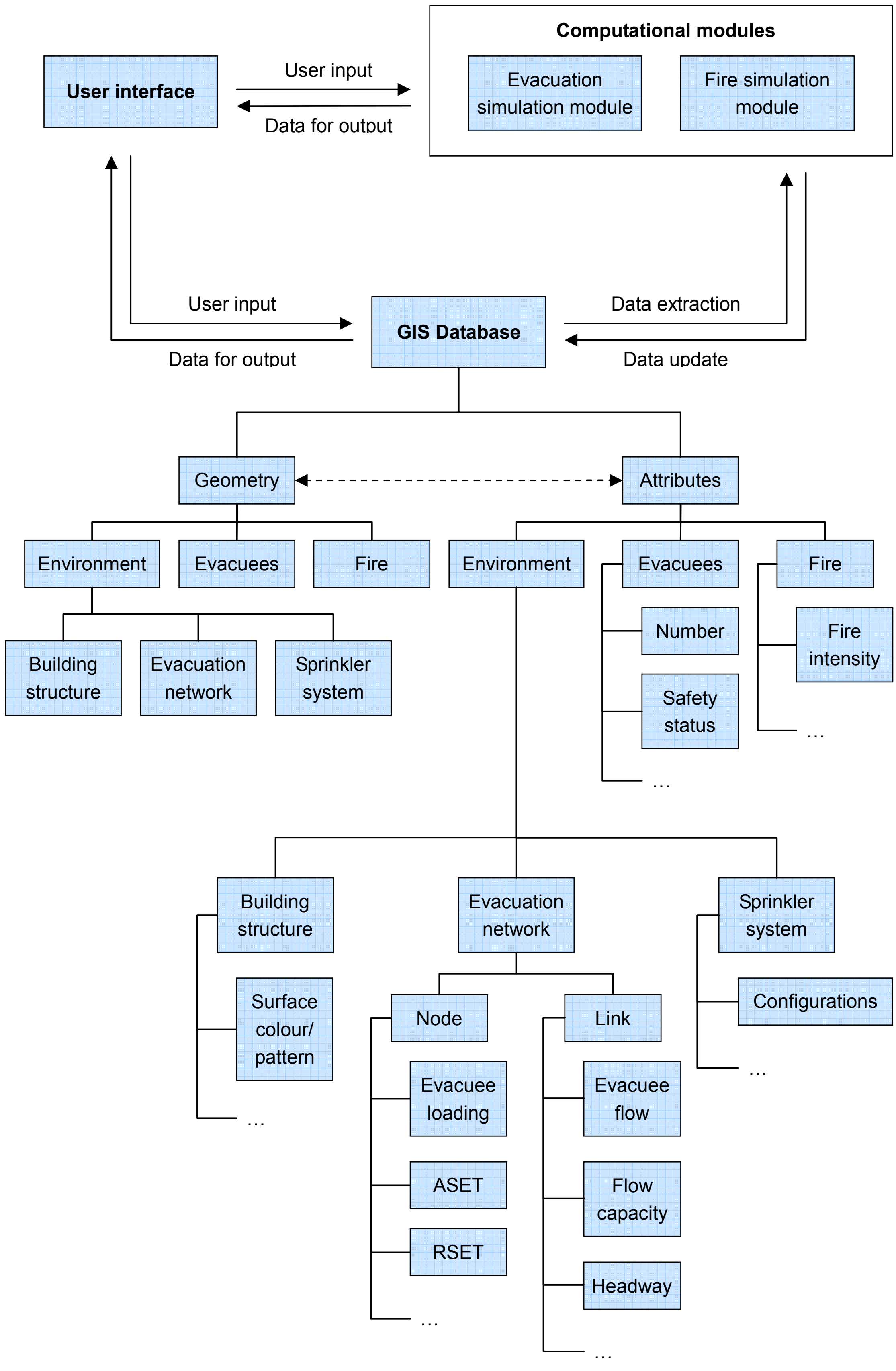


Figure 4.2 Schema of the GIS-based integration platform

so that users can avoid the cost and inconvenience to install GIS software in order to use the system. Nevertheless, GIS methods and functions are dominating in data representation and communication on system design and implementation stages.

A GIS database includes the spatial data component and the attribute data component. In this study, spatial data are represented by coordinate lists and stored together with non-spatial attributes as the geospatial database is not used. As the essential spatial information in GIS, topology in the network evacuation model is defined by referencing keys in text data tables. The spatial overlay for fire risk assessment is processed by searching for locations with the same coordinates.

The database comprises three kinds of spatial entities: the evacuation environment, including building body, evacuation network node and link, and other details like sprinkler; the evacuee group; and the fire hazards. The entities used in the evacuation model are node, link and evacuee. Their static attributes which are constant in the simulation are stored in text data files, and dynamic attributes which are to be updated in the simulation are generated in the evacuation computation program. Although the database is not geospatial, an object-oriented approach is used to integrate the spatial and non-spatial, static and dynamic data: each entity is defined by a class of instances, and each instance is treated as an object. Data about building bodies, details like the sprinklers and fire hazards are almost only used in the fire module, hence they are directly recorded in the fire simulation input file.

Figure 4.2 also suggests the data flows between the GIS database, the computational modules and the user interface. The data flows only provides a general idea of the communication between components on this platform. At the last section of this chapter, after the individual data items are explained, a more specific description about how these components communicate with each other will be presented.

If the system is adapted to more complicated spatial data, or in commercial use which frequently requires customization to different building environments, the geospatial database may be a must. For a project area which is many times as large as the current study area, it will be too labour consuming to construct the evacuation network manually. Instead, the network nodes should be generated by applying centre locating functions in off-the-shelf GIS software to building structures, and the node-link topology construction needs automatic topology building functions in GIS software. WebGIS can be used to transmit user input from client computers through the Internet to project servers. The servers do all the data handling and computation, and send the fire evacuation simulation result back to the clients for output and visualization. In this case the clients will not need to install any infrastructures in their local machines.

4.3 Network evacuation model

The primary output of the evacuation model is RSET of each location in the study area. It should be noticed that the evacuation model in this study do not really handle the whole RSET, which includes the time for fire detection and alarming, for the evacuees to response and start moving, and for them to travel to a safer place. The model in this study only calculates the travel time, while the time before the evacuees start to move is subject to user input. Although the setting of this pre-movement time can be crucial for fire risk assessment (CFPA E, 2009), this study do not work on this part. The pre-movement time is primarily a socio-psychological topic, not much related to spatial domain, and is not very meaningful to be addressed by GIS studies.

The evacuation model is implemented on Visual Basic 2005 platform. This object-oriented programming language is selected because of the need of defining object classes as explained in Section 4.2, and the capability of this language to handle two-dimensional geometric data and graphics for evacuation computation and visualizations.

4.3.1 Evacuation rules with emphasis on human behaviours

The general evacuation rules which are considered in this project are listed as follows. Most of them concern human behaviours in emergencies which are revealed in socio-psychological researches. These rules are about how people decide their evacuation routes, select an exit as the destination in an area with multiple exits, and how the evacuation time of the evacuees is estimated.

(1) *Attraction of exits:* people try to move out of the dangerous place as soon as possible, and to approach the safety exits (Yang et al., 2007; Yuan and Tan, 2007). Indeed, beginning evacuation may not be the first reaction of people in fire. Yet according to researches concerning first behaviours of the evacuees (Bryan, 1977; Lo, 1996), after excluding behaviours that rarely take place in offices, like

"getting dressed", "gathering the family" and "caring the pets", most evacuees either first leave the building, or inform others. In the project area, informing others can be done by simply calling out in the corridors due to high connectivity of the rooms to the corridors, and will not delay the evacuation of informers. Hence moving towards the exits could be assumed the first reaction of evacuees.

(2) *Nearest exit / unadventurous effect:* when people are familiar with the evacuation environment, they are likely to choose the nearest exits among multiple ones. On the contrary, evacuees unfamiliar with the environment are likely to select the exit from which they entered the building to avoid adventurous exploration of new exits (Yang et al., 2007; Yuan and Tan, 2007).

(3) *Herding:* people are likely to follow each other in choosing moving direction, and a group of evacuees is highly possible to select the same exit (Yang et al., 2007; Yuan and Tan, 2007).

(4) *The trend to overlook alternative exits under the stress of escape* (Keating, 1982; Dirk et al., 2000).

(5) *Inertial effect:* people would rather keep than change their targeted exit and moving direction (Yuan and Tan, 2007).

(6) *Repulsion:* people tend to avoid contacting other people and walls, which leads to deceleration, moving direction adjustment and slower evacuation (Dirk et al., 2000; Song et al., 2006).

(7) *Friction:* physical interaction between people will reduce moving speed (Dirk et al., 2000; Song et al., 2006).

(8) *Queuing / congesting:* people queue at doors and exits when they are more imperturbable and familiar with the environment, and congest when they are less. Congestion will slow down the evacuation process and may cause injuries from collision of evacuees (Dirk et al., 2000; Song et al., 2006; Yang et al., 2007; Yuan and Tan, 2007).

There are two major considerations to select the behavioural rules as above. One consideration is that since this study aims to approach CA models' performance with network data structure in behaviour simulation, it should include those behavioural rules that are usually adopted in CA models. Hence the rules are selected based on their frequent implementations in existing evacuation models, particularly in CA models. Rules which frequently occur in evacuation study literatures also enjoy higher confidence to their authorities and priorities to be adopted. Particularly, a large part of the rules, namely rules (1) – (5), are about exit and route selection. The emphasis on these rule results from the finding in literature review that even many network models consider behavioural factors, they may just apply the rules to moving speed and route cost calculation, while the route/exit selection is still based on optimal paths, like EXIT89 and EXITT illustrated in Chapter 2. On the other hand, studies show that people in emergencies do not quite follow the most efficient evacuation routes. Thus it is desirable to establish a detailed simulation of route/exit selection behaviours and see to what extent people's choice are similar to optimal paths, such as the attraction of the nearest exits, and to what extent deviant from optimal paths, such as herding and the trend to overlook alternative exits.

The other consideration is that the typical functionalities in existing network models should be preserved. Repulsion and friction are often adopted in CA models to adjust people movements, and correspondingly they are modelled in network models by assigning variable moving speeds to evacuees. The situation is similar for queuing/ congesting rules which are implemented in network models by flow capacity of doors, or the maximum number of people that can pass the doors in unit time. Many network systems model time delays for people to pass doors by either constraining the moving speed or giving door flow capacity, that is, simulate only either repulsion and friction or queuing/congesting, while this study follows the common case in CA models to simulate both sets of rules by rules (6) – (9). A qualitative analysis will be conducted in Section 5.2.2 to confirm the necessity of this improvement.

The rules are then applied to three processes in the evacuation modelling: the selection of exits by the evacuees, the evacuees' movements in rooms and corridors, and their behaviours at doors and exits.

(1) Selection of exits

People in the study area are most likely staff of the department, or visitors like students and outside scholars. Hence they should be either familiar with the environment (staff) or accompanied by people familiar with the environment (visitors). This is an essential premise for applying the behavioural rules.

According to the rule of nearest exit / unadventurous effect, the evacuees will select the nearer exits since they are familiar with the study. Each location in the area is associated with the nearer exit, either the north one or the south one, as the initial selection of people at that location. Evacuees starting from the same location are handled as an evacuee group, and each group is regarded as knowing the initial exit selection.

Based on the attraction of exits, the evacuees will avoid moving in the direction of fire and smoke. To simulate this behaviour, each evacuee group is given a chance to change their exit selection when firstly entering the corridors. If fire or smoke approaches from the way to their initial selection of exit, the exit will be considered dangerous and the alternative one will be chosen. If both exits are dangerous, the group will remain the initial selection. Flames should weight over smoke, as the former indicates the direct fire source. If flames are observed, the exit in the opposite direction will be selected regardless of the situation of smoke.

By the rule of herding, members of each evacuee group, in most cases people in each room, will choose the same exit.

The trend to overlook alternative exits implies that the evacuees will also overlook uncommon intermediate exiting points of building components, like the doors of other rooms. Thus the evacuees are likely to move in only corridors and ignore alternative routes to pass through another room with multiple entrances (Figure 4.3) .

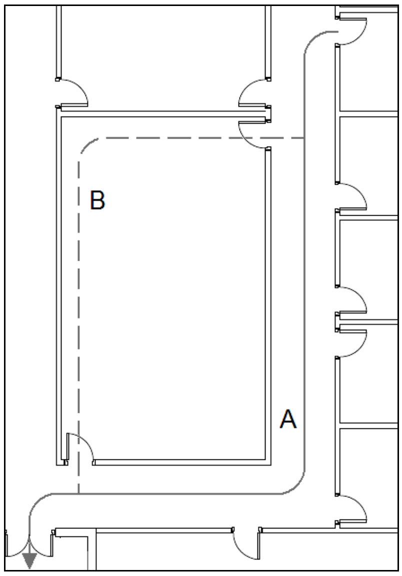


Figure 4.3 The trend to overlook alternative exiting points. Evacuees are supposed to take only route A in the corridor and ignore route B through the room.

By inertial effect, once the evacuees select an exit according to the rules above, they are supposed to stick to the exit, and will not change the route even if smoke comes from the way to that exit later.

(2) Evacuee movements

The repulsion rule suggests that people will avoid contacting walls when moving in rooms and corridors. Since the building components in study area are generally narrow, as mentioned in Section 4.1, there will be little space left beside the centrelines of building components after the space close to walls is peeled away. Hence it would be reasonable to approximate the evacuation routes with these centrelines.

Due to repulsion among evacuees and friction, people's moving speed will vary with the density of evacuees in surrounding area. Each time a evacuee group going to a new location on the evacuation route, its moving speed will be updated dynamically based on people density at their current and the next location.

(3) Behaviours at doors and exits

As stated in the behaviour rule (8), whether people tend to queue or congest at doors depends on their imperturbability and familiarity to the environment. In this study, people are supposed to queue rather than congest. One reason for this assumption is their familiarity with the environment as has been mentioned. Another reason is that people are less panic at the early stage of evacuation (Lo et al., 2001). this is exactly the case of the relatively small study area, where people starting evacuation from the area will not need to go far to leave it.

4.3.2 Network data structure

As mentioned earlier in the study, the three entities in the network evacuation model are node, link and evacuee group. Each node represents a building component: a room, a corridor segment, or a point right outside the two exits. Each link represents a passageway between the nodes, which may be a door or a part of the corridor centreline. Each evacuee group is the collection of evacuees with the same initial position (node). The node-link network in the study area is shown in Figure 4.4.

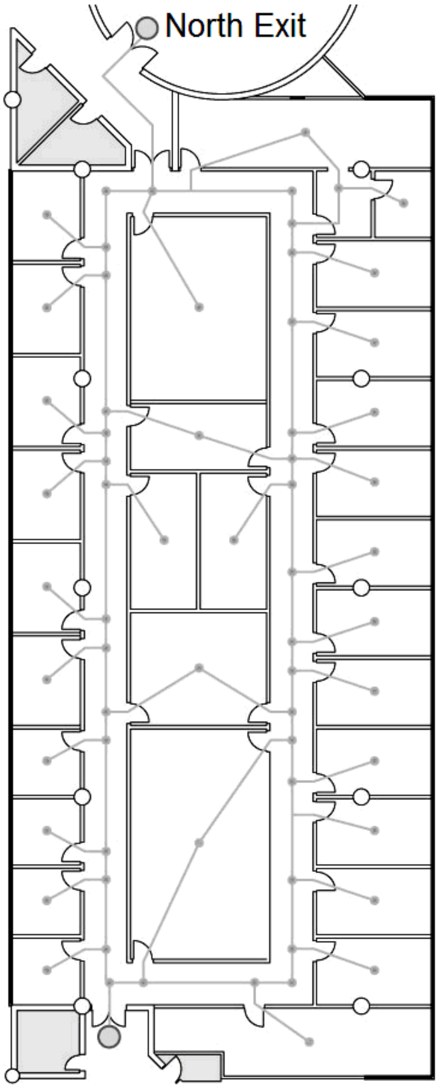


Figure 4.4 Node-link network in the study area

One data table is defined for each entity in the evacuation model, and data specifications of the three tables are listed in Table 4.1 to Table 4.3. The EVACNET4 network model which has been reviewed in Chapter2 is referenced in developing the part of data structure that is generally common in classical network evacuation models. EVACNET4 does not employ behavioural rules or dynamic moving speed computation, and this study makes significant expansions on data structure to adopt these functionalities, so as to make them the major improvements on classical network evacuation models.

Table 4.1 Data specification: node table

Attribute	Data Type	Description
ID	Integer	Identification key of the node.
Name	Text	Displayed name of the node, for simulation output.
type	Enumerator	Type of the node; "R" for rooms, "C" for nodes in corridors, and "E" for exits.
nextLinkN, nextLinkS	Integer	ID of the next links towards the north and south exits, defining network topology. The geometry of the network ensures the uniqueness of such links.
X,Y	Numerical	Coordinates of the node.
area	Numerical	Area of the node, defined as the space between the midpoints of nextLinkN and nextLinkS of the node.
content	Integer	Number of evacuees at the node.
destination	Boolean	The initial selection of exit for people starting evacuation from this node, with the mere consideration of nearer exits. "True" for the north exit and "False" for the south exit.
smokeObsN, smokeObsS	Integer	ID of the nodes serving as smoke observation points from this node, for judging the evacuees perception of "dangerous exit" in exit selection. Only applicable for nodes in the corridors and is generally the four corridor corners. (Detailed explanation will come in implementation methodology later.)
smokeTime	Numerical	Time when the visibility at this node gets below 10m due to smoke concentration. Also functions in exit selection. Only applicable for nodes in the corridors.
availableTime	Numerical	Time available for people to evacuate to this node, i.e., ASET at this node from the fire model. Only applicable for nodes in the corridors.

Table 4.2 Data specification: link table

Attribute	Data Type	Description
ID	Text	Identification key of the link.
type	Enumerator	Type of the link. “D” for links representing doors and “C” for links representing corridors.
end1, end2	Text	ID of nodes at the ends of the link，defining network topology.
length	Numerical	Length of the link, for calculating the time to pass it.
headway	Numerical	Headway between two individuals passing the link, for calculating the time to pass the link. Only applicable for links of type “door”.
flow	Numerical	Number of evacuees at a link. Only applicable for links of type “door” for calculating queuing time.

Table 4.3 Data specification: evacuee group table

Attribute	Data Type	Description
ID	Integer	Identification key of the evacuee group.
origin	Integer	The ID of the node from which the group begins to evacuate.
location	Integer	Current location (node) of the safe members in the group. The initial value is the origin of the group.
destination	Boolean	The group’s selection of evacuating exit; the initial value is the destination of the origin node.
destSelected	Boolean	Whether the group has selected the exit based on the sight to fire.
noOfEvacuee	Numerical	Total number of evacuees in the group.
noOfSafe	Numerical	Number of safe evacuees in the group. The initial value is noOfEvacuee of the group.
caughtNo, caughtLocation, caughtTime	Numerical Array	Information of evacuees caught in the fire: the number of caught evacuees, the location where they are caught and the time when they are caught.
evacuationTime	Numerical	Time for the group to evacuate from the beginning of the evacuation. The initial value is time for the group to get informed of the fire and start to evacuate.
route	Integer Array	List of IDs for the nodes passed by the group.
finished	Boolean	Whether the evacuation simulation for the group is finished.

4.3.3 Algorithms for evacuation simulation

The logic flow of the evacuation simulation process is shown in Figure 4.5. Procedure (1) ~ (4) noted in the figure are the major evacuation rule implementations and will be discussed in detail.

It can be indicated from the figure that the simulation is divided into time steps. An evacuee group is considered to be “finished processing” when it reaches an exit, or all its member are caught in fire. Every “unfinished” group is scanned at each time step, and if its cumulate evacuation time until the last movement is equal to current time, the next movement of this group will be searched, and time consumption of that movement will be calculated by dynamic moving speed based on evacuee density and queuing time delay, giving RSET of the group at the next node. Then the RSET is overlaid with ASET from the fire model, and safety status of the group is determined. The simulation terminates when all the groups are finished processing.

The time step used in this study is 0.5s, and the spatial precision is 0.5m. This is comparable with typical settings in CA evacuation models with cell size of around 0.4m×0.4m to represent average space taken by one person, and temporal precision as the time to move from a cell to an adjacent one, or sometimes rounded to 0.5m and 0.5s.

(1) Exit selection

As has been mentioned, the exit selection is affected by both fire flames and smoke.

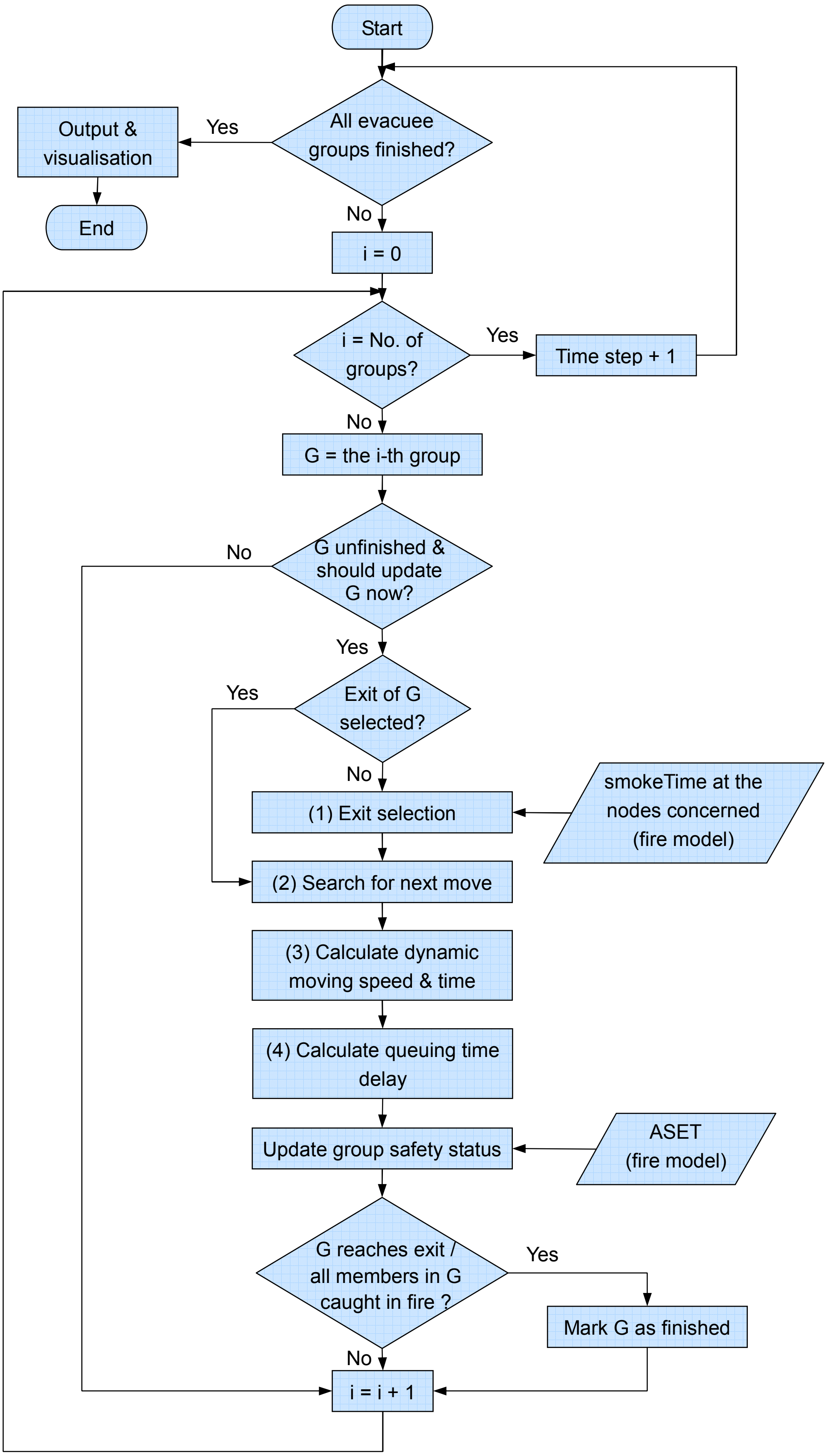


Figure 4.5 Logic flow of evacuation simulation

Firstly, the system will judge by coordinates of the fire source whether the fire occurs in corridors or in rooms. In the former case, the evacuees may be able to observe flames. Then the viewshed of each node in the corridors, or the visible area from this node, is calculated. As shown in Figure 4.6, at node *(x, y)*, people's sight is bounded by two of the four corridor corners, (x_1, y_1) and (x_2, y_2). Then the formula of l_1 is computed by *(x, y)* and (x_1, y_1), the formula of l_2 by *(x, y)* and (x_2, y_2), and the viewshed highlighted can be determined. If the fired area overlays the viewshed, evacuees at that node will select the exit in opposite direction to the fire, and smoke observing for determining exit safety will not be processed.

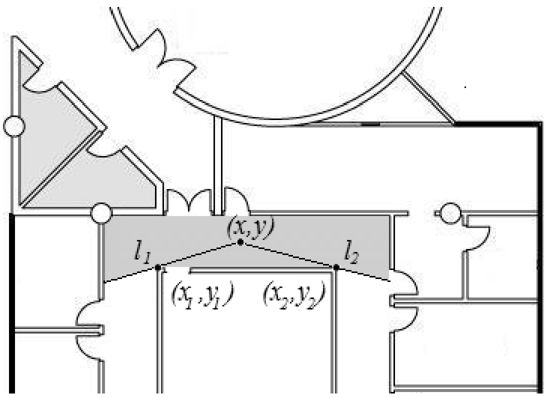


Figure 4.6 Viewshed calculation for nodes in the corridors

If the fire ignites in rooms or behind the corner in corridors, the evacuees could still identify the direction of fire source from approaching smoke to avoid running into danger. However, whether people can distinguish the coming direction of smoke depends on the visibility at their locations.

A widely accepted criterion for human tolerance to smoke hazard in fire is corresponding to visibility = 10m suggested by Rasbash (1975), under which the evacuees will not be able to search moving directions. This criterion is not used if the evacuees are familiar with the environment like this study, since they do not need to explore new routes and still know where to go under such low visibility. Yet since under this visibility people's sight is hindered so much that the moving direction can not be found, the evacuees should perceive the danger when the coming smoke can cause that low visibility, and select the exit in the opposite direction. However, if the location of the evacuees themselves is of this low visibility as well, they will not be able to observe denser smoke behind, and unable to discriminate the coming direction of smoke. If the visibility on both sides in the corridor is below the 10m threshold, the evacuees can not tell where the smoke comes from either. One can identify the propagating direction of smoke only when the visibility at its position is over 10m, and the visibility between its position and corridor corner to one exit, or the "smoke observing point", is also over 10m, while somewhere between its location and the "smoke observing point" for the other exit has a visibility below 10m. The "smoke observing points" for the two exits are defined as `smokeObsN` and `smokeObsS` attributes for the location (node) of the evacuees (Table 4.1).

The fire model can calculate the `smokeTime` attribute of each node by which visibility drops below 10m at the node. Then `smokeTime` is compared to the "entering time", or the time when the first member of an evacuee group enters the corridors. If `smokeTime` at the group's location is more than the "entering time", the group will get enough visibility to select an exit. Then if the `smokeTime` at each node from its location to, for example `smokeObsS`, is more than the "entering time", while the `smokeTime` at certain nodes from its location to `smokeObsN` is less than the "entering time", the south exit will be selected.

To get the time when the first member of an evacuee group enters the corridors, exit selection is actually performed during queuing time calculation (process(4) in Figure 4.5) on passing the door to the corridors, after the queuing time delay for the first member is added. Queuing time delay for other members will be updated when the exit selection is finished. Still, exit selection is placed in the flowchart before process (4) and as the first process to simplify the logic flow.

The following pseudocode describes the logic of exit selecting rules in computer implementation. The entities' attribute names for the pseudocodes here and later in this study are coherent with data specifications in Table 4.1 to Table 4.3.

```
'Consider evacuation group G
currentNode = G.location
If currentNode.type = "C" And G.destSelected = False
'Select exit only once when G firstly enters the corridor

    North exit is safe
    South exit is safe

    'Flame observation
    If fire.location is in the corridors
        If currentNode is in the viewshed of fire.location
            If currentNode.Y < fire.Y 'the fire is in the north
                G.destination = south exit
            Else
                G.destination = north exit

    Else
    'smoke observation
        If currentNode.smokeTime > currentTime
        'G is able to select the exit
            For each node N from currentNode to currentNode.smokeObsN
                If N.smokeTime ≤ currentTime
                'somewhere to the north exit has dense smoke
                North exit is dangerous
                Exit for
            'Similar for the south exit
```

```
        If north exit is dangerous and south exit is safe
            G.destination = south exit
        Else if south exit is dangerous and north exit is safe
            G.destination = north exit
        'Else G.destination remains the nearer exit

    G.destSelected = True
    'Mark G as "exit selected" so that exit will not be selected again
```

(2) Evacuation route searching

After exit selection of an evacuee group, the list of links and nodes on the way towards the selected exit will be searched using network topology:

```
consider evacuee group G
currentNode = G.location

If G.destination = north exit
    nextLink = currentNode.linkN
Else
    nextLink = currentNode.linkS

If currentNode = nextLink.end1
    nextNode = nextLink.end2
Else
    nextNode = nextLink.end1
```

(3) Dynamic moving speed calculation

In CA model, repulsion and friction can be simulated by manipulating formulas to update the evacuees' location, so as to make them move slower or change direction when getting close to other people or obstructions. Queuing can be simulated by assigning a location randomly to one evacuee when several evacuees target at the same location, and letting the others wait until the next time step (Yuan and Tan, 2007).

The basic idea of repulsion and friction can be expressed as “people move slower towards the exit when they are close to each other”. Hence these two behavioural rules are implemented by varying evacuees’ moving speed according to their density at the link which they are going to pass. This density is the summed number of evacuees at ending nodes of the link divided by the summed area of the nodes. People moving speeds at different density levels are set by the suggestion of The CFPA E (2009):

$$S = \begin{cases} 1.2, D \le 0.54 \\ 1.4 - 0.266 \times 1.4D, 0.54 < D < 3.8 \\ 0, D > 3.8 \end{cases} \qquad \text{(Equation 4.1)}$$

Where S is evacuee moving speed in m/s

D is evacuee density in person/m^2

The suggested speed is claimed to be from international studies and reflect the average physical ability of human beings. Since Asians dominate the study area, this standard should be more suitable than most other widely accepted standards based on configurations of westerners. A standard specially for Asians would be preferred if it was found.

EVACNET4 also suggests moving speed parameters according to U.S. official Pedestrian Planning Procedures Manual (Kisko et al., 1998), but the software requires user input to set a constant speed for each link. The users have to estimate the evacuee density at each location of the network, which is often difficult and unguaranteed to be accurate. Moreover, model of constant moving speed can deviate a lot from reality when evacuee density varies a lot on the links, and generate errors in travel time calculation. Thus the dynamic moving speed estimation is likely a significant improvement, and its effect will be examined by quantitative analysis in next chapter.

After obtaining the real-time moving speed, time consumption for the evacuee group to travel to the next node is computed, and total RSET of this group is accumulated for calculating RSET on the next step. The following pseudocode shows the process from moving speed computation to time updating.

```
Consider evacuee group G at currentNode and is passing nextLink
nextNode is the other end of nextLink

evacueeDensity = (currentNode.content + nextNode.content) /
                 (currentNode.area + nextNode.area)
If evacueeDensity < 0.54
    speed = 1.2
Else
    speed = 1.4 - 0.266 * 1.4 * evacueeDensity
 'modify the lowest speed from 0 to 0.01 to avoid overflow error
If speed < 0.01
    speed = 0.01

'update evacuation time
G.lastMoving = nextLink.length / speed
G.evacuationTime = G.evacuationTime + G.lastMoving
```

(4) Simulation of queuing at doors and exits

Apart from moving along network links, another source of time consumption in the evacuation is queuing at doors and exits. In classical network evacuation models like EVACNET4, queuing is often dealt with the concept of flow capacity, or the number of people that can pass the door per unit time. The queuing time delay is decided by flow capacity of the door and number of people in the queue.

In this study an algorithm similar to the classical method is used to simulate queuing. Instead of flow capacity, this study employs the headway between two individuals passing the door, which is the reciprocal of flow capacity. Queuing time is equal to headway multiplied by number of people in the queue. By the recommendation of Fruin (1971), the headway of office doors which revolve in one direction is 2 seconds, and that of the free-swinging exits is 1.5 seconds. The number of evacuees in the queue counts not only the evacuee group under concern, but also other groups at the door when the group under concern enters the queue. The total number of evacuees in the queue is recorded by the "flow" attribute of the door link.

If a group enters the queue at a door when other groups are queuing there, the increased flow at the door will also prolong the queuing time of the groups arriving at the door earlier. Hence after computing the queuing time of the group under concern, all the other groups at the same door link are identified and the prolonged queuing time added to their RSET.

```
Consider evacuee group G at currentNode and is passing nextLink
If nextLink.type = "D"
    ' compute the queuing time of G
    nextLink.flow = nextLink.flow + G.noOfSafe
    G.lastMoving = nextLink.flow * nextLink.headway
    G.evacuationTime = G.evacuationTime + G.lastMoving

'identify other groups at nextLink and add the prolonged queuing time
If nextLink.flow > G.noOfSafe
'flow is not zero before G comes, i.e., there are other groups
    For each evacuee group G'
       If G'.location = G.location And Not (G'= G) And G'.finished = False
           G'.lastMoving = (nextLink.flow -G.noOfSafe) * nextLink.headway
           G'.evacuationTime = G'.evacuationTime + G'.lastMoving
```

At the end of every time step, the flow that has passed the door in the time step is reduced from the flow of the door, so as to retain the accuracy of flow values and queuing time estimation:

```
For each link L in the network
    If L.flow > 0
        L.flow = L.flow - 0.5 / L.headway  '0.5 is the time step length
```

4.3.4 Summary of improvements on network evacuation model

In this study, the network evacuation model mainly simulates three events: the exit selection by evacuees, people movement in corridors, and queuing at doors and exits. This model contributes two improvements to current development of network evacuation models:

(1) Behavioural rules are applied in a relatively systematic approach, especially the depiction of exit selection in detail with multiple factors. The exit selection is neither decided by shortest routes nor unconditional avoidance of hazards; rather, the evacuees' ability to recognize the source of hazards depends on the visibility at their location when they select exits, and the selection considers both the nearer exits and the conditional avoidance of hazards.

(2) People moving speed is dynamically computed by evacuee density at each location. Particularly, time delays of the evacuees at doors are modelled by friction and repulsion factors as well as queuing factors.

4.4 Fire model with adoption of FDS

This study emphasizes evacuation modelling and fire risk assessment rather than fire behaviours, therefore it employs an existing model for fire and smoke simulation instead of developing an original one, and extracts results from the fire model as input of overlay analysis with the evacuation model for fire risk assessment.

Fire behaviours can be modelled by empirical formulas as well as computer simulations. The empirical formula approach predicts fire propagation by formulas about the relationship between temperature and time. The temperature is assumed uniform in the fired compartment or radially diminishing from the fire source, and fire behaviours other than temperature are rarely modelled. Examples of empirical formulas for fire modelling are BSEN1991-1-2 and PD7974-1.

The common fire model types in computer simulations include zone model and field model. Zone models divide the physical environment into multiple horizontal layers, and predict heat and probably smoke properties in each layer. However, the division of physical environment in horizontal directions are not more precise than empirical formulas. Some models of this type are CCFM, CFAST and Ozone.

Field models, or Computational Fluid Dynamics (CFD) models, divide the space into cell grids and produce heat, smoke and other physical properties for each cell based on CFD formulas. CFD models have the advantage of much higher precision than empirical formulas and zone models, while the disadvantage of computational complications and long processing time. Typical CFD models are FDS, SOFIE and

SMARTFIRE. (Bailey, 2005; Combustion Science & Engineering, Inc., 2008)

Building geometry in the study area comprises many compartments with wall obstructions, which can not be properly handled with the relatively coarse division of space by empirical formulas and zone models. Also, both temperature and smoke density factors are needed for behavioural rules implementation, while empirical formulas and many zone models do not handle the smoke. Hence the field model is the only appropriate choice for this study.

Among the variety of field models, Fire Dynamics Simulator (FDS) is selected under the consideration of authority, availability and freshness. Developed by NIST, U. S. Department of Commerce, this software is highly recognized and widely used in scientific studies and real-world applications (McGrattan et al., 2007). It is free of charge and can be acquired by the public from NIST website. The version of FDS used in this study is the latest version 5.5 released in October 2010.

FDS is a Fortran-styled program reading user input from text files, performing numerical computation and generating user-specified output files. For this study, the major inputs are calculation units, building environment and fire initialization. The primary outputs are ASET at each node in corridors when fire hazards reach human tolerance and the `smokeTime` attribute of these nodes, as discussed in Section 4.2.

4.4.1 Inputs: units, building environment and fire initialization

The input file for FDS is of the format .fds exclusive for this software. It can be opened as text file in programs like Notepad for editing user input, or opened by FDS for calculating the fire simulation. In the .fds file, input parameters are specified with records formatted by *namelists*, and a collection of namelists performing a function is referred to as a *namelist group*.

FDS places the simulation environment in cell meshes and performs calculation at each time step. A cell mesh is defined by MESH namelist group. The attribute `IJK` in the group defines the number of cells in x, y and z direction in the mesh, and attribute `XB` with parameters `X1, X2, Y1, Y2, Z1, Z2` specifies the extent of the mesh in metres. The cell size, as spatial calculation unit of the model, is equal to the division of mesh extent and number of cell. the current cell size used in 0.2m×0.2m×0.5m. Actually 0.5m×0.5m×0.5m cell size is more compatible with the evacuation model, but the resultant RSET can be different by tens of seconds using 0.2m and 0.5m horizontal cell size, and developers of the software indicated that this means the coarser resolution is not enough. Also, building structures in this area cannot be displayed normally with a horizontal cell size over 0.2m in the visualization software which is bound with FDS. (The visualization software will be discussed later in methodologies.) Time step is set by attribute `DT` in `TIME` namelist group, and the value is 0.5s to match the evacuation model. Another attribute `T_END` in the group defines the time length of fire simulation.

Building environment in the fire model includes building geometry, surface appearances and the sprinkler system. The building geometry is represented as obstructions by the `OBST` namelist group. An obstruction also has attribute `XB` with parameters `X1, X2, Y1, Y2, Z1, Z2` as a rectangular block orienting along coordinate axes of the simulation space, taking the room between (X1, Y1, Z1) and (X2, Y2, Z2). Most walls in the study area can be defined by a series of connected obstructions. For rectangular building structures orienting in other directions and non-rectangular building structures, thin rectangular slices are used to approximate their shapes (Figure 4.7). For doors and windows in the walls between the offices and the corridors, `HOLE` namelist group is used to hollow rectangular holes in the walls, and new obstructions are created as door planks and windows.

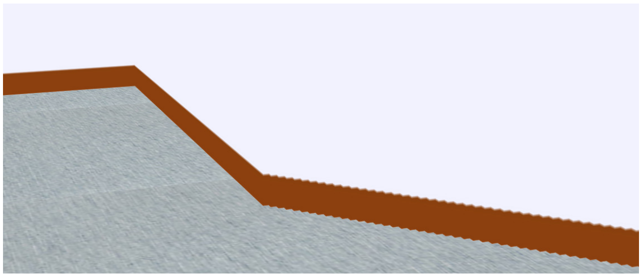


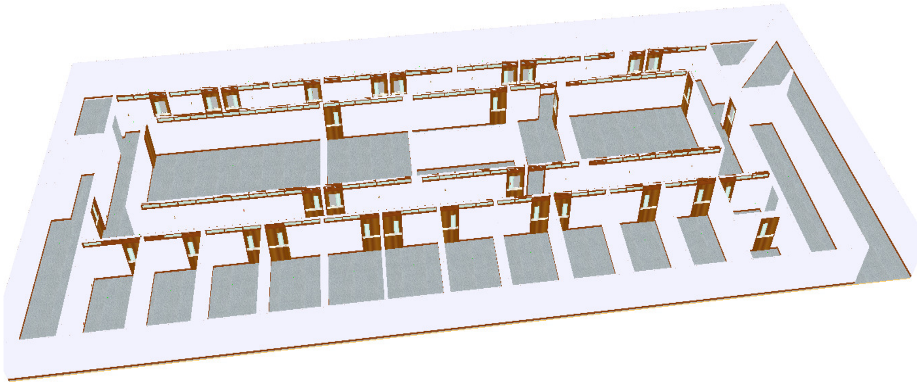
Figure 4.7 A wall not orienting along coordinate axes defined as approximating rectangular slices in FDS, visualized by Smokeview. In this very close view, slice serrations can be seen, yet during normal navigations it is beyond the discrimination of human eyes.

Surface appearances of the walls, floor, ceiling, doors and windows are set in the `SURF` namelist group, with the `RGB` attribute for assigning pure colours and the `TEXTURE_MAP` attribute for painting textures. Although much labour is required in building geometry and surface outlook definition, and some work are purely for visualization purpose, the effort to construct the clear and pleasant-looking visualization is worthwhile, regarding the need to enhance usability of the system particularly for the non-professionals. For instance, different patterns are made with graphic editing software for each door according to their real appearances, because trail runs of the visualization shows that depictions of doors, especially room numbers on them, are important for users to discriminate the very alike office rooms in corridor view.

For the sprinkler system, the exact configurations of the device in the study area are unavailable, hence default settings in FDS are generally followed, like the 74°C threshold temperature to activate the sprinklers. Water discharge rate of the sprinklers does not have a default value, and 83 L/min for standard sprinklers are used (Schroll, 2002). Sprinkler configurations are defined in `PROP` namelist group, and each sprinkler is located on the ceiling by a `DEVC` namelist formatted record, with definition of coordinates and appearance.

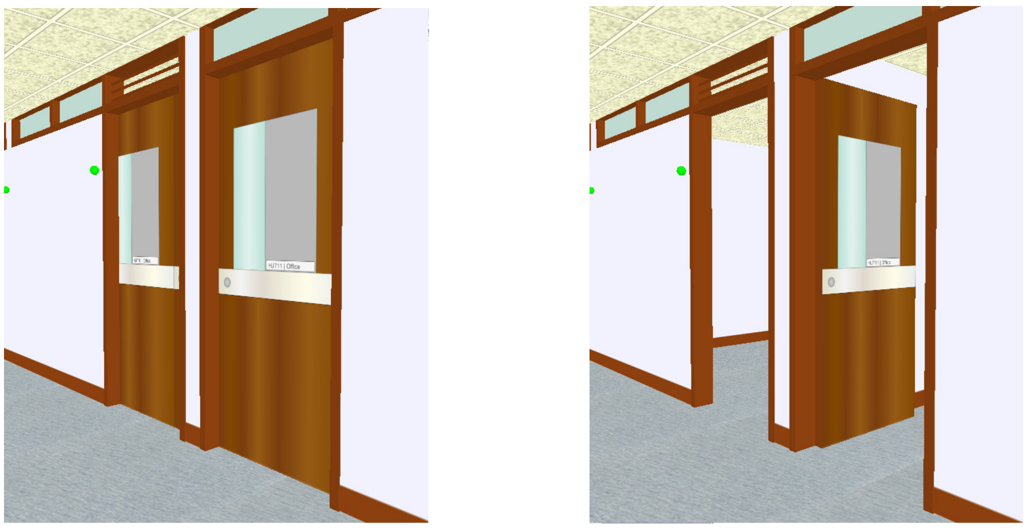
The door opening events are also included in the model. Office doors in study area are normally closed and not self-closing, and it is reasonable to assume that people leave the doors open in emergent evacuation. This may affect ASET by increasing much room to accommodate heat and smoke and thus should be modelled. By defining a timer in a `DEVC` record with the door opening time, and associating the timer into the `OBST` record for the door, this door can be removed at the designated time, and another obstruction is created where an open door should be. To determine the door opening time, the evacuation model is partially run and terminates after all the evacuee groups have started to pass doors, and the time for each group to pass the door is extracted and used as the door opening time.

Figure 4.8 shows the fire simulation environment modelled with the described methodology and visualized in Smokeview.



(a)

(b)



(c)

Figure 4.8 Simulation environment modelled in FDS, visualized by Smokeview

(a) Overview of study area

(b) Corridor view: surface patterns, doors, windows, vents, sprinklers and fire hazard detectors (the green balls)

(c) Closed and open doors dynamically controlled by `DEVC`

There are many approaches to initialize a fire in FDS, and a simple approach giving heat release rate per unit area (HRRPUA, in kW/m^2) is used. This HRRPUA is set by `HRRPUA` attribute in a `SURF` namelist formatted record. The location and extent of fire is set by `XB` attribute under `VENT` namelist group.

Apart from the inputs covered above, many other settings of the simulation environment is left as system defaults, such as surface materials and physical conditions. The default surface is 20°C adiabatic non-combustible in FDS. Most surface materials in study area are synthetic, thus their thermal properties are highly variable and hardly known without survey by fire service professionals. Besides, the materials are generally non-combustible and unlikely to emit much poisonous gases shortly afterward the fire. Even the carpet made of synthetic fibre could melt when heated and thus flame retardant. Usually the fire simulation ends in several minutes, and the default surface would make no significant difference within that time compared to the real material. The default physical conditions, like temperature and gas mixture, simulates a mild climate similar to the study area. These default settings are retained considering that fire behaviour is not the focus of this study.

4.4.2 Outputs: ASET and smoke observing time

The core output of the fire simulation is ASET at each location when fire hazard reaches the limit of human tolerance. This study employs two criteria of fire hazard assessment: heat hazard as flue-gas temperature and smoke hazard as visibility, and their values are given in Table 4.4. Due to the difficulty to simulate many of the fire hazards that cause human injuries, flue-gas temperature is used as the single parameter for risk assessment in many countries (Yang et al., 2010). However, the smoke hazard is even severer, causing 85% of fire injuries (Department of Emergency Services, Queensland Government, 2009?), hence should be included in the fire model.

Table 4.4 Fire hazard thresholds

Hazard	**Threshold for human tolerance**
Heat: flue-gas temperature	110~120℃ at height of human eyes (Yang et al., 2010)
Smoke: visibility	4m for people familiar with the evacuation route (Jin, 1981)

Recorders of fire hazards are also defined by `DEVC` records with coordinates defined by `XYZ` attribute. (x, y) of the recorders are the same with the nodes in evacuation model and the z coordinate is 1.5m to present the height of human eyes under the spatial resolution of the fire model. The recorders are shown as green balls in Smokeview visualization (Figure 4.8).

The `QUANTITY` attribute in a `DEVC` record specifies the type of physical amount to be measured for fire hazards, and a recorder is activated when that quality at its location excess the value in the `SETPOINT` attribute.

Since the range of unsafe visibility is that below the threshold, and FDS provides no mechanism to activate a recorder when the physical amount it measures is below a certain value, the light extinction coefficient K indicating light obscuration is used for substitution, where

$$K = 3 / \text{visibility} \qquad \text{(Equation 4.2)}$$

For light reflecting signs. The K value for 4m visibility is 0.75. Recorders for the `smokeTime` attribute are defined in a similar way, but the K value is 0.3 corresponding to the 10m visibility.

At the end of fire simulation, activating times of the devices are written to FDS output file (.out) and ready for extraction. The activating time for either heat hazard or smoke hazard, whichever is earlier, is used as ASET at each node.

4.5 Overlay analysis for fire risk assessment based on GIS

As stated in Chapter 2, a common criteria for the evacuee safety in fire risk assessment is that ASET is longer than RSET, that is, the evacuees are considered safe when

$$ASET > RSET \text{ at exit(s)} \qquad \text{(Equation 4.3)}$$

For multi-stage fire risk assessment in this study, ASET and RSET are calculated not only for the exits, but for each node in the network. Evacuees are judged as safe only if

$$ASET > RSET \text{ at each node on evacuation route} \qquad \text{(Equation 4.4)}$$

Otherwise, the evacuees are regarded to be under fire risks on the way to the node where Equation 4.4 is not fulfilled from their last location. ASET and RSET are recorded in the `availableTime` attribute of `node` entity and the `evacuationTime` attribute of `evacueeGroup` Entity, respectively (Table 4.1 and Table 4.3).

Members in an evacuee group actually have slightly different RSET values due to queuing, and the `availableTime` attribute records only RSET of the last evacuee. Hence it is possible that some group members are barely able to pass the corridors or doors, while the others falling behind are caught in fire. The number of caught evacuees, N_{caught}, is determined by

$$N_{caught} = \begin{matrix} (RSET - ASET)N_{safe} / T_{last}, or \\ N_{safe}, \ Whichever \ is \ smaller \end{matrix} \qquad \text{(Equation 4.5)}$$

Where

N_{safe} is the number of safe evacuees remained in the group

T_{last} is the time consumption of the group to pass the last link

By determining N_{caught}, N_{safe} of the group can be updated. This is important not only for obtaining the final number of safe evacuees, but for RSET estimation of this group and probably other groups. For one thing, RSET of the group is longer than ASET at the current node, but time delays of the unsafe members are also counted in this RSET. If there are still safe members in the group, at the next movement its RSET should only include the safe evacuees, and the difference is exactly the time consumed by unsafe evacuees, which is proportional to the number of these unsafe evacuees. This difference is corrected in RSET of this group, so that RSET computation in later movements will not be affected. For another thing, the reduce of safe group members will decrease the queuing time of this group and other groups queuing together with the group at doors or exits.

The number of unsafe evacuees and the time and location of the fire risk are recorded in the `caughtNo, caughtTime, caughtLocation` attributes of the evacuee group. If all the member in a group are under risk, the group will be stopped processing.

The pseudocode for fire risk assessment is shown as follows.

```
'consider evacuee group G on the way to currentNode
'caughtNo is the number of caught evacuees
'caughtTime is the time when the evacuees are caught
'caughtLocation is the node on the way to which the evacuees are caught

'if not ASET > RSET, determine no. of unsafe evacuees
If Not currentNode.availableTime > G.evacuationTime
   timeDifference = currentNode.availableTime > G.evacuationTime
   caughtNo = G.noOfSafe * timeDifference / G.lastMoving round up to integer
   If G.caughtNo(tmpBound + 1) > G.noOfSafe
      G.caughtNo(tmpBound + 1) = G.noOfSafe

   'update caughtLocation
   caughtLocation = G.location

   'correct time overestimation by unsafe evacuees and update caughtTime
   G.evacuationTime = G.evacuationTime - (caughtNo / G.noOfSafe)
                    * G.lastMoving
   G.lastMoving = G.lastMoving - (caughtNo / G.noOfSafe) * G.lastMoving
   caughtTime = G.evacuationTime

   'update number of safe evacuees
   G.noOfSafe = G.noOfSafe - caughtNo
   If G.noOfSafe = 0
      G.finished = True
```

4.6 Simulation output and visualization

Outputs of the system include a text report, two-dimensional static visualization and three-dimensional animated visualization.

The text report and the two-dimensional visualization are generated in Visual Basic Express 2005 like the implementation of the evacuation model. The report provides a comprehensive simulation result including three parts:

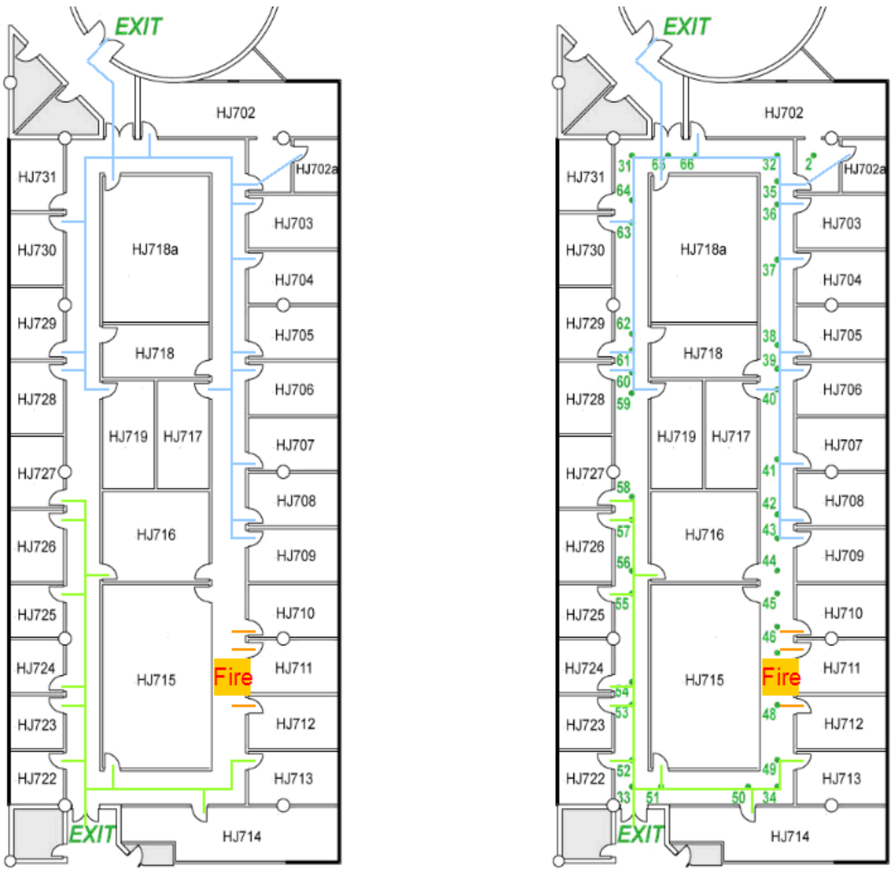
- Simulation summary: the total number of evacuee groups, evacuees, and safe evacuees, and total evacuation time;
- Simulation result by group: origin, total number of evacuees, number of safe evacuees, selection of exit, and evacuation time of each group. The exit selection is annotated "-" when the whole group is under fire risk immediately after entering the corridors and has no time to select an exit. For the groups whose members are all caught by fire, the evacuation time is the time when the last member is caught.
- Fire risk diagnosis: the number of evacuees involved, the location, and the time of each fire risk. One group may encounter multiple fire risks (Figure 4.9).

```
FireEVA v1.0 Evacuation Simulation Report

No. of evacuee groups: 29
Total No. of evacuee(s): 74
Total No. of safe evacuee(s): 71
total evacuation time: 188s

Group   Start Location   Evacuee(s)       Safe Evacuee(s) Exit     Evacuation Time
1       HJ702            4                4               N        173
...

  Fire risk assessment
  Group   No. of evacuee(s) under risk    Location        Time
  6       1                               39              30
  ...
  17      4                               39              72
```

Figure 4.9 Sample text report of the simulation

The two-dimensional visualization represents the location and extent of the fire source, the evacuation routes of each evacuee group and the fire risks on the floor plan of the study area. Routes towards different exits are painted in different colours for discrimination. Locations of the fire risks are marked by red crosses (Figure 4.10).

These graphics are painted by Visual Basic drawing functions and the data required are coordinates of the fire, routes and locations of fire risks, which are recorded in the `route` attribute of the `evacuee group` entity in evacuation simulation. Since the text report uses node numbers to represent locations of fire risks, there is also an option to toggle the display of node locations and numbering on the floor plan, so that the users may understand what location these numbers represent (Figure 4.10(b)).



(a) (b)

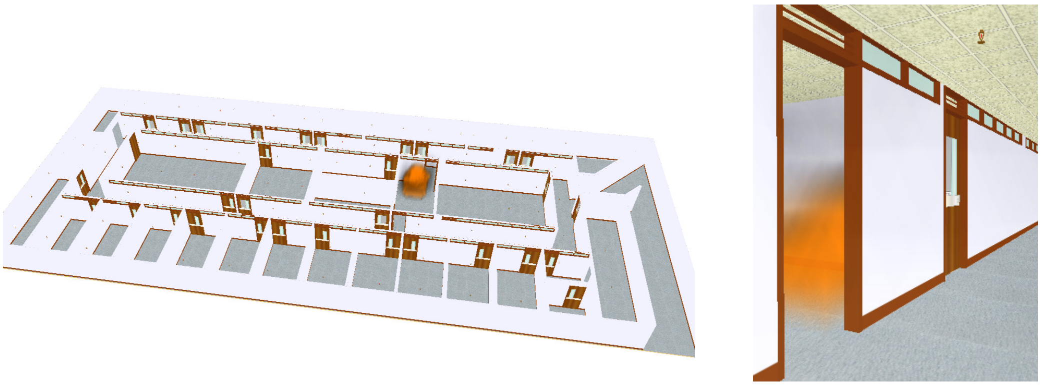
Figure 4.10 Two-dimensional Visualization: floor plan, fire location and evacuation routes. The blue routes are towards the north exit, the green routes are toward the south exit, and the orange routes are for evacuee groups caught in fire immediately after entering the corridor.

The three-dimensional visualization is realized on Smokeview platform as mentioned previously. Smokeview is the visualization software exclusively for FDS and is also developed by NIST. It is chosen as the three-dimensional visualization tool because of its data integration with FDS, as well as its ability to animate fire and smoke which is rare among three-dimensional visualization software.

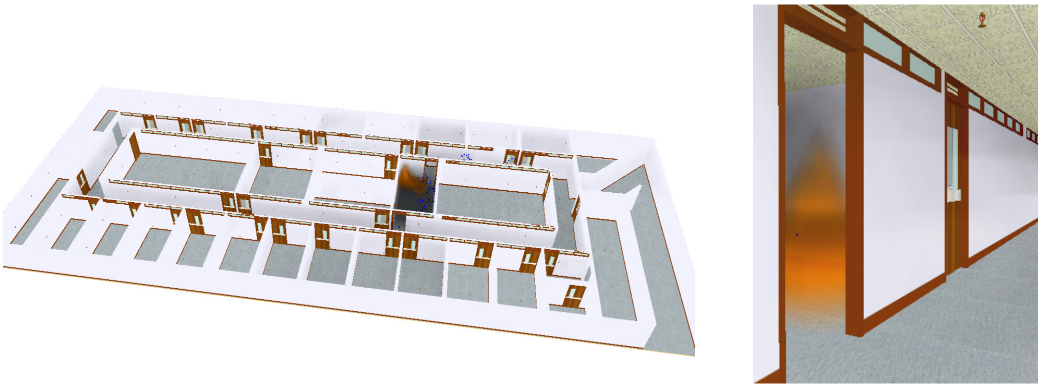
Once FDS finishes a fire calculation, the corresponding Smokeview visualization is automatically generated as a .smv file. The items shown in the visualization are building environments defined in the fire model as described in Section 3.4.1, and the animation of fire flames, smoke and water spray from sprinklers, showing the propagation of heat and smoke hazard and functioning of the sprinkler system.

The three-dimensional visualization does not directly show evacuation information, but it can facilitate the understanding of fire behaviours and the simulation result. For instance, in the text report some evacuees may be predicted under the smoke risk at a node and a specific time, and the users can easily comprehend this when they see dense smoke in the .smv visualization at the predicted time and location.

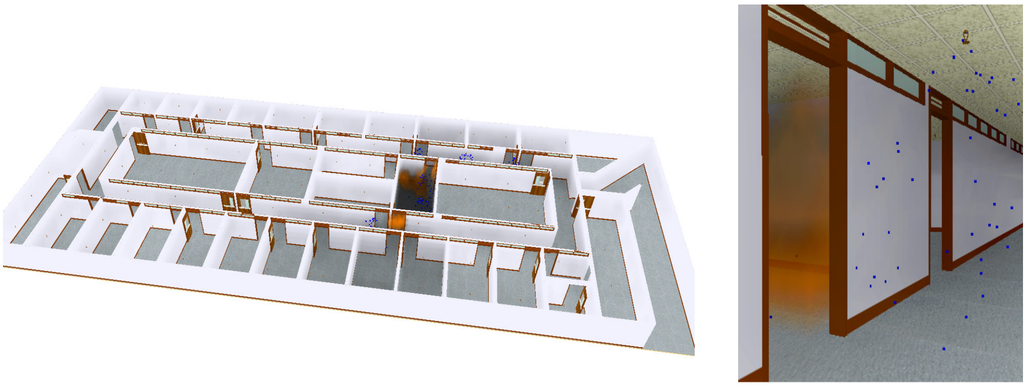
Figure 4.11 illustrates the Smokeview visualization and shows its features such as dynamic door opening, animating fire, smoke and water spray, and various viewing angles inside and outside the building to observe the fire scene.



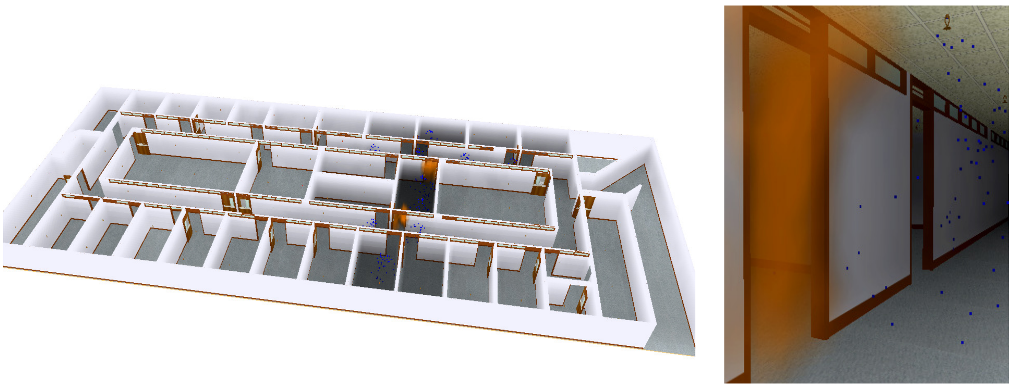
Time = 5s



Time = 60s



Time = 120s



Time = 300s

Figure 4.11 Three-dimensional Visualization: snapshots of fire scene animation in Smoke view. The left figure of each time point is overall view, and the right figure is corridor view.

4.7 Data communication and system automation

The relationships and interactions among the evacuation simulation module, the fire simulation module and the fire risk assessment have been described in this chapter when these three components were discussed individually. Figure 4.12 summarizes the data communication among these components.

The system automation mainly target at realizing all the functionalities though a single Visual Basic .exe user interface, with only simple user operations like figure input and button pressing, and encapsulating the users from all internal algorithms and implementations. This calls for substantial work which largely uses computing rather than GIS techniques, but is essential for guiding users for necessary data to perform geo-informational functions and utilize the outputs of simulation result. on the other hand, detailed methodologies to implement the automation are not going to be introduced here, since they are not very relevant to geo-informatics. Only the functions that have been realized are described, which can be divided into three categories:

(1) Input and output handling: inputs and outputs are translated to items labelled by non-technical words. The user input is generally figure input into textboxes, except the fire location input interactively by figures and graphics. The users can either keying in the location and extent of the fire and see the drawing of the fired surface on the floor plan, or draw the fired surface on the plan and see the fire location and extent defined by the drawing. It is suggested to roughly draw the fired surface on the plan and then adjust figures in the textboxes, most probably

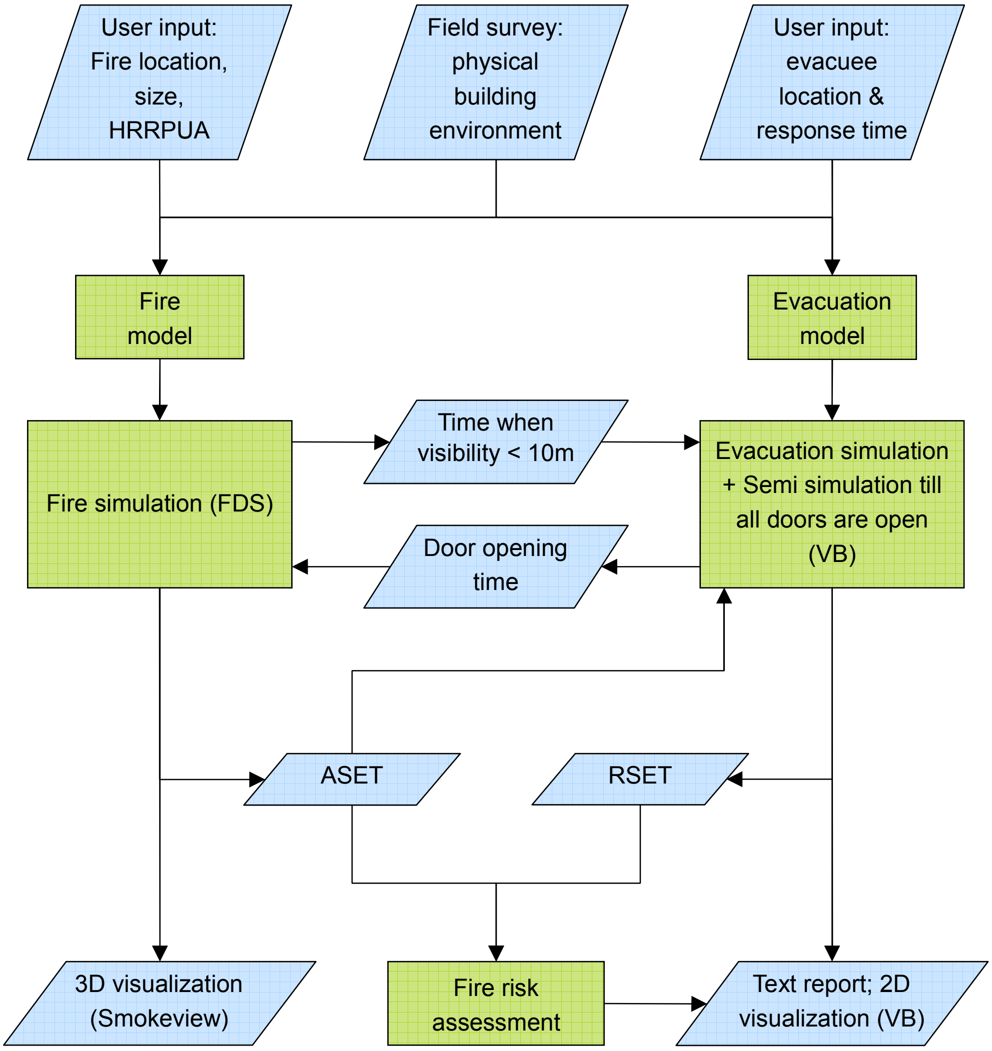


Figure 4.12 Data communication in the IFES

to rounded numbers. This method allows the users to input fire location without frequently referring to building coordinates, and reduces chances of unreasonable inputs like a fire across a wall, half inside a room and half in the corridor, since the figures and graphics for fire location are synchronized (Figure 4.13).

Default settings for all the inputs can be automatically filled into the input fields once the options to use the defaults are checked (Figure 4.13 and Figure 4.14).

(2) Data communication: this is performed by various data handling functions in Visual Basic language. Predefined data for the fire and evacuation model, like the node and link tables and the building environment in the fire model, are stored in text files (.txt) and .csv files. These files are read together with user input to complete the attributes of objects used in the program, and to write the FDS input file (.fds). This work are also involved in intermediate processes, such as passing door opening times, ASET and RSET among the models and the overlay analysis module, and coordinate transformations.

(3) User support: automatic launching FDS and Smokeview, scripting to control the proper display options on loading the .smv visualization, exporting the text simulation report to text files, and so on.

Figure 4.13 to Figure 4.15 provide comprehensive pictures on functionalities and user operations in the system.

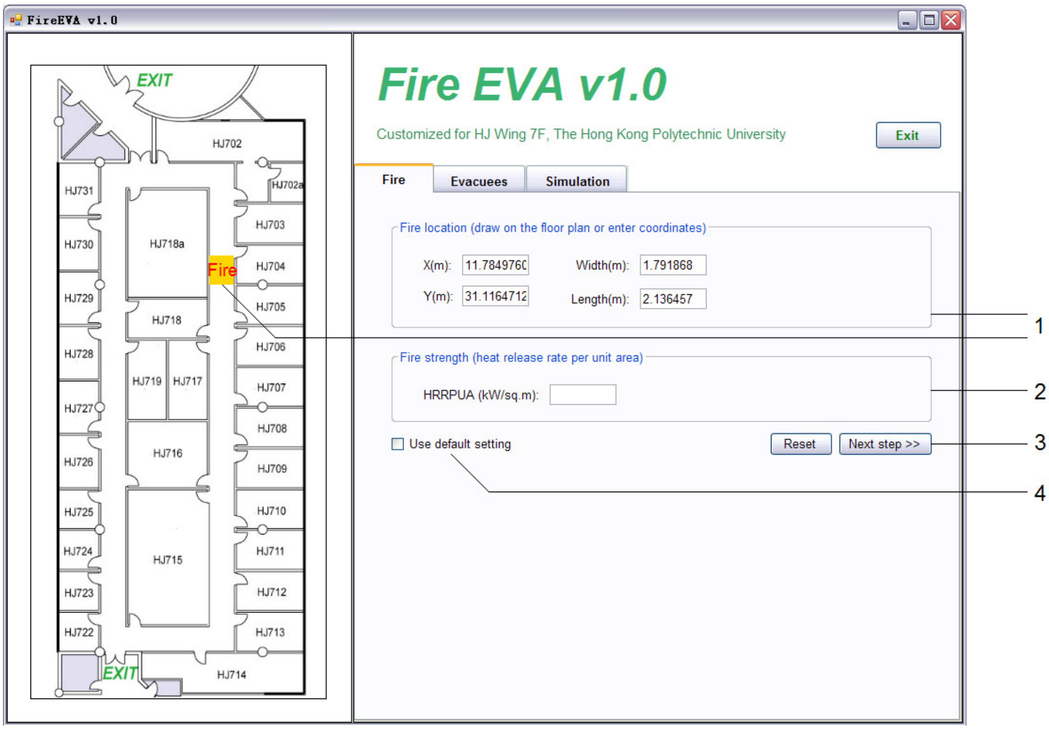


Figure 4.13 System interface: fire input

1. Interactive input of fire location 2. Input of fire strength (HRRPUA)

3. Resetting and going to the next step 4. Default settings

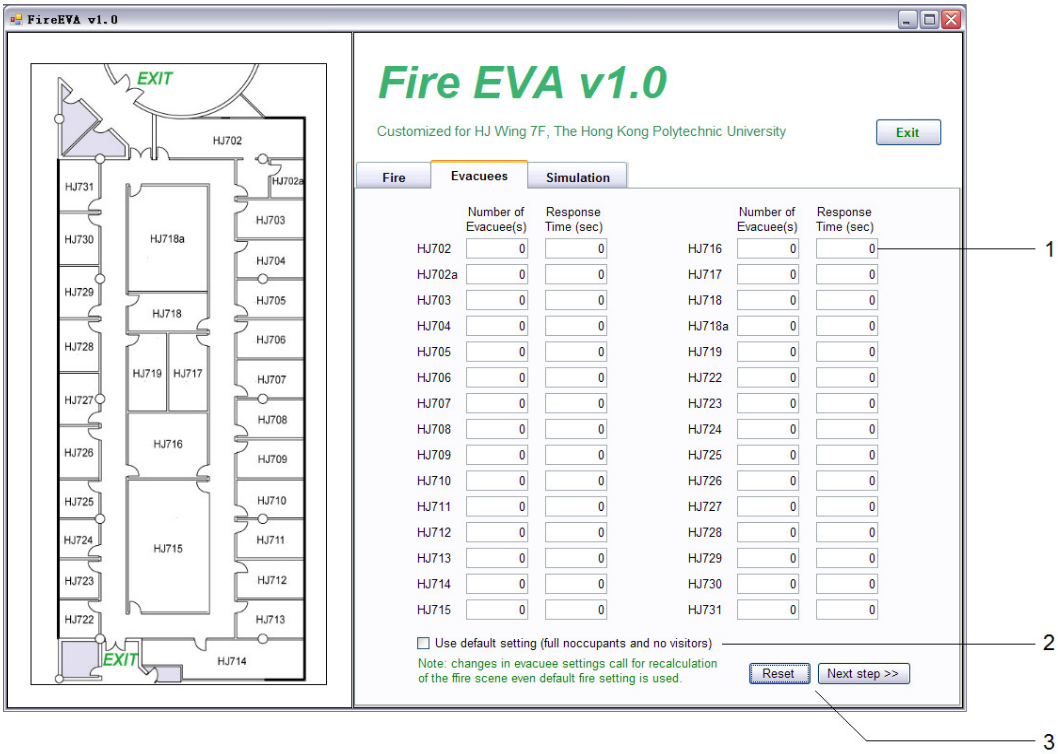


Figure 4.14 System interface: evacuee information input

1. Input of number of evacuee allocation and response time

2. Resetting and going to the next step 3. Default settings

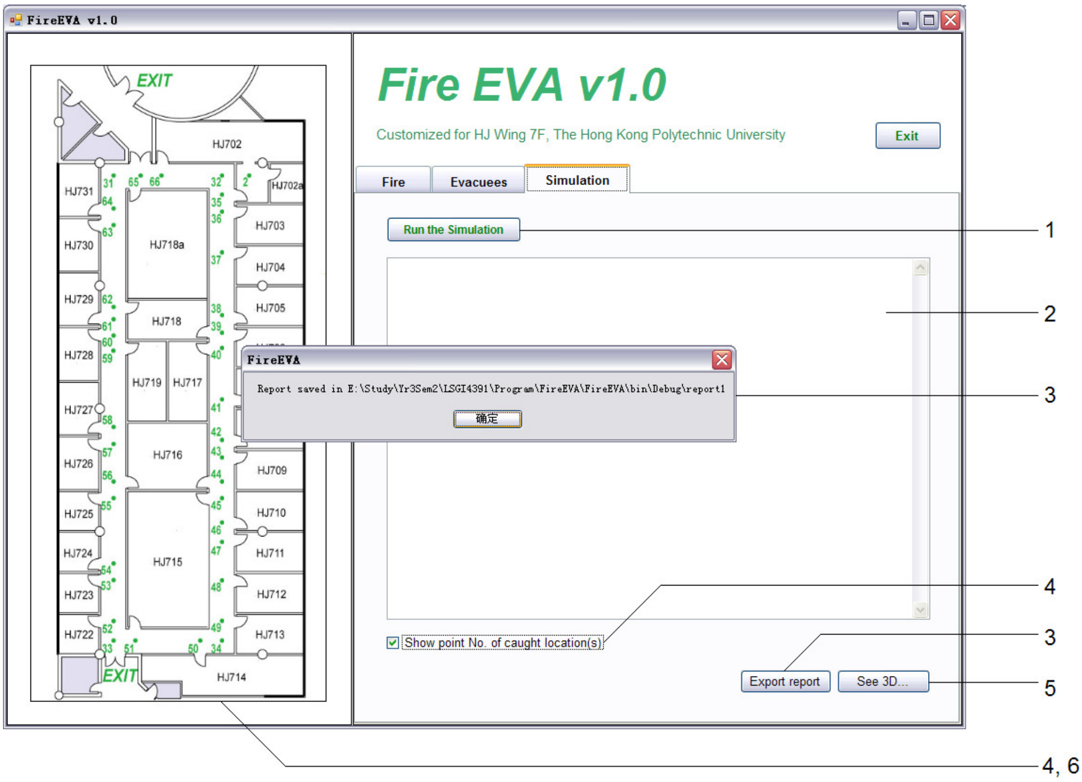


Figure 4.15 System interface: output

1. Simulation running: input reading, automatic launching of FDS for fire calculation, evacuation model calculation and result output
2. Field to generate the text report
3. Text report output to text files (.txt)
4. Toggling the base floor plan to show node number for checking the locations of fire risks
5. Automatic launching of .smv visualization
6. Field for two-dimensional visualization

5 Fire evacuation simulation results and analyses

5.1 System functionality test

In this section, a sample run of the system under a typical scenario about the fire and evacuees will be conducted. Through the simulation result, characteristics of the scenario will be analyzed, and various functionalities in this system demonstrated.

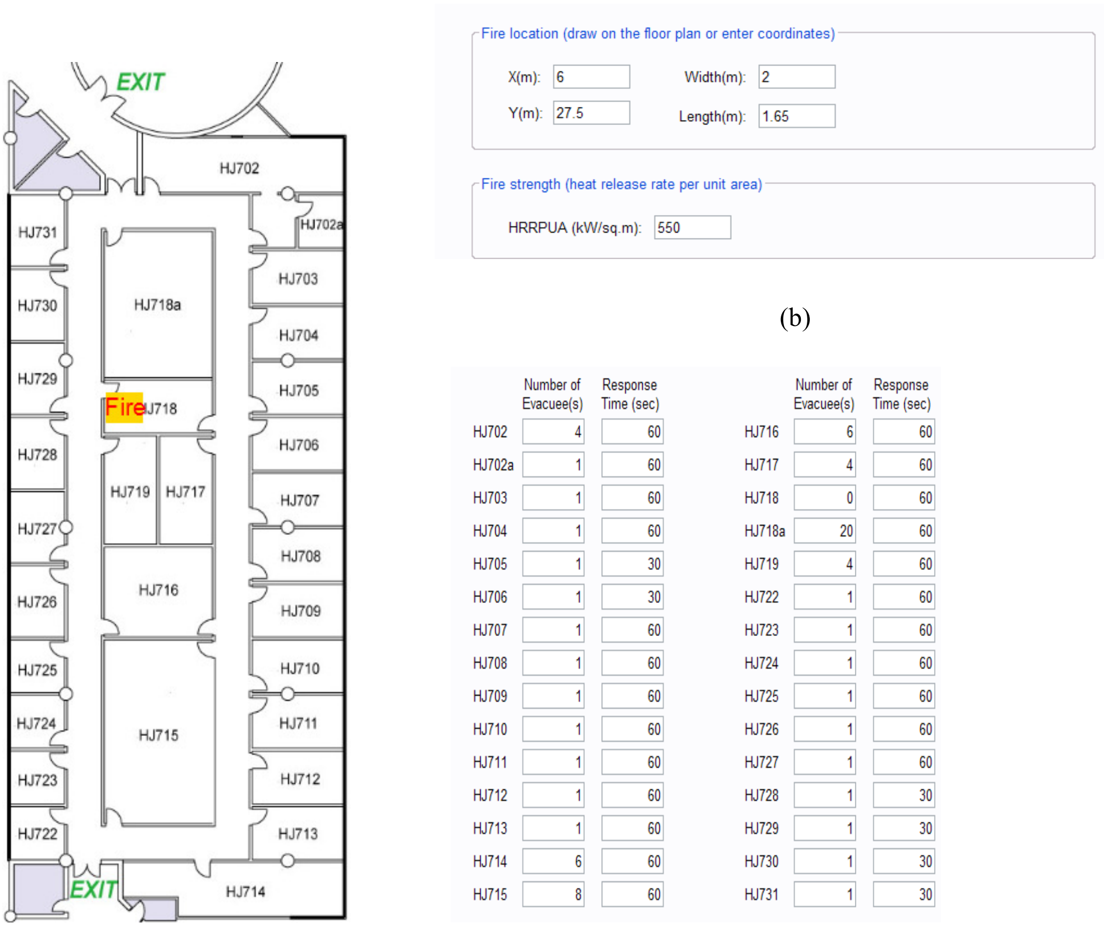
5.1.1 User input settings

In the sample simulation, the fire source is set in room HJ718 with a burning area of $3.3m^2$ and a HRRPUA of 550 kW/m^2 (Figure 5.1 (a)). The fire is designed following the study of Hu et al. (2006), in which an heat release rate (HRR) of $1800kW/m^2$ was obtained from the combustion test of a shopping booth taken by National Fluid Power Association in US, and it was verified as being appropriate to use a such fire setting to simulate fire incidents in a single room with usages like ticket office or souvenir store. HJ718 is a printing room with the similar size and combustible materials (mainly paper and plastics) to the situation concerned in Hu et al.'s study, hence the fire settings of that study are applied. While office doors in the study area are normally closed, the doors of HJ718 are usually open, and in FDS they are constructed as open all the time.

The allocation of evacuees is set to an "ideal" case where all the staff are in their offices, while offices of individual staff members contain no visitors. This situation is rare yet normally close to reality: most staff are usually in their offices at office hours, and there is likely only a few visitors, somehow compensating the absent staff, except occasional visitor groups in the meeting room. The meeting room HJ718A is assigned 20 evacuees which is about half of its capacity and the size of a common meeting in it.

As mentioned in section 4.3, the evacuee response time to the fire is highly variable and can have crucial effect on the evacuation. CFPA E (2009) suggested that in offices and universities where the evacuees are familiar with the environment, awake and trained about fire evacuation, and the building is equipped with automatic fire alarm system to give the alarm immediately after the fire is detected, the quickest responders and average responders have response time of 30s and 60s, respectively. Staff in the study area are regarded trained to fire, since the study area experienced fire alarms in the last few months, and Hong Kong residents typically have trainings of fire drill. Although the fire alarm system is not investigated, the voice alarm from quick responders should be equivalent, as shouts in corridors can be heard throughout the small study area with high connectivity to the corridors. Thus the suggested response time is adopted. A trail run of the fire simulation shows that by time = 30s, smoke entered room HJ703~HJ708 and HJ728~HJ731 through the vents at the top of the doors. Thus the response time is set to be 30s for these eight rooms and 60s for the others (Figure 5.1(b)).

Upon completion of user input, the program reads the inputs to the network object classes, calculates door opening times, writes fire initialization and door opening times into the FDS input file, and launches FDS for fire calculation. Empirical tests on the program shows that the longest travelling time of the evacuees rarely approaches 200s, and most evacuee groups finish the evacuation within 100s after the response time. Hence the duration of fire simulation are generated by the program as 200s plus the maximal response time, which is 260s for this sample run.



	Number of Evacuee(s)	Response Time (sec)		Number of Evacuee(s)	Response Time (sec)
HJ702	4	60	HJ716	6	60
HJ702a	1	60	HJ717	4	60
HJ703	1	60	HJ718	0	60
HJ704	1	60	HJ718a	20	60
HJ705	1	30	HJ719	4	60
HJ706	1	30	HJ722	1	60
HJ707	1	60	HJ723	1	60
HJ708	1	60	HJ724	1	60
HJ709	1	60	HJ725	1	60
HJ710	1	60	HJ726	1	60
HJ711	1	60	HJ727	1	60
HJ712	1	60	HJ728	1	30
HJ713	1	60	HJ729	1	30
HJ714	6	60	HJ730	1	30
HJ715	8	60	HJ731	1	30

(b)

(a) (c)

Figure 5.1 User inputs of the system functionality test
(a) Fire location on floor plan (b) Fire initialization parameters
(c) Evacuee allocation and response times

5.1.2 Results: fire, evacuation and fire risk assessment

The resultant ASETs for all nodes in the corridors are presented in Table 5.1. Only 8 out of the 36 nodes have its heat or smoke risk reached the threshold within the simulation time. ASET for the other nodes is ">260s", and if the travel time of the evacuees are within 200s, they will not encounter fire risk as long as they do not pass these eight nodes.

The effect of sprinkler functioning is evident by looking into the relation between the locations and types of fire hazards. As illustrated by Figure 5.2, even the heat reaches the threshold at node 39 and 62 very early (7.4s and 18.5s, respectively), it never reaches the critical value at other six nodes which are below sprinklers, or guarded behind sprinklers from the fire source. From time = 86.6s, the smoke hazard starts to reach the threshold at these nodes. An FDS output besides the main .out file, the .devc file for the `devc` namelist group objects, reveals that activated sprinklers can cool their surroundings and keep the temperature at around 50~60℃, and 115℃ threshold may never be reached. However, visibility continues to go down and may reach the threshold later. This phenomenon well agrees to the simulation result.

At node 39 and 62 where both hazards reach the threshold, the smoke becomes critical much later than the heat (190.8s and 91.7s for the smoke in contrast to 7.4s and 18.5s for the heat), so the other nodes might also have critical heat hazard if there were no sprinklers. Hence the sprinkler system should effectively protect this area against the overall fire hazard. This inference will be confirmed by the analysis in the next section.

Table 5.1 Result of the fire simulation. "-" means that the threshold value has not been reached ay the end of simulation.

Node	Heat hazard threshold time(s)	Smoke hazard threshold time(s)	ASET(s) & critical hazard type	Smoke observing time(s)
31	-	-	-	33.6
32	-	-	-	90.6
33	-	-	-	170
34	-	-	-	77.3
35	-	-	-	97.7
36	-	-	-	68.6
37	-	-	-	61.7
38	-	202.4	202.4, smoke	28.4
39	7.4	190.8	7.4, heat	7.4
40	-	112.7	112.7, smoke	34.2
41	-	-	-	51.9
42	-	-	-	68.8
43	-	-	-	61.5
44	-	-	-	132.8
45	-	-	-	134.2
46	-	-	-	136.4
47	-	-	-	139.9
48	-	-	-	143.1
49	-	-	-	67
50	-	-	-	189.4
51	-	-	-	255.9
52	-	-	-	214.7
53	-	-	-	-
54	-	-	-	-
55	-	-	-	248.8
56	-	-	-	230.1
57	-	-	-	222.6
58	-	-	-	176.1
59	-	-	-	148.4
60	-	205.9	205.9, smoke	116.6
61	-	86.6	86.6, smoke	47.2
62	18.5	91.7	18.5, heat	4.7
63	-	164.6	164.6, smoke	66.4
64	-	208.6	208.6, smoke	77.2
65	-	-	-	45.4
66	-	-	-	101.9

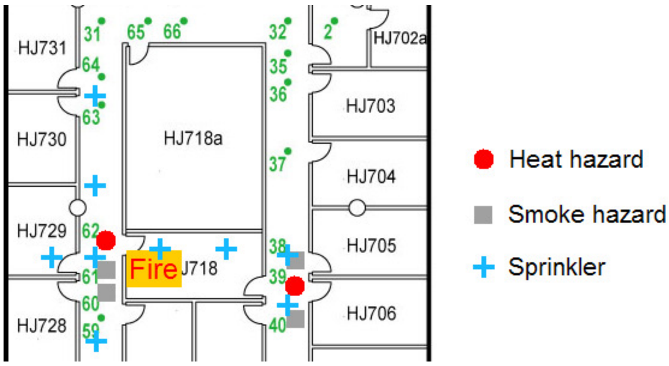


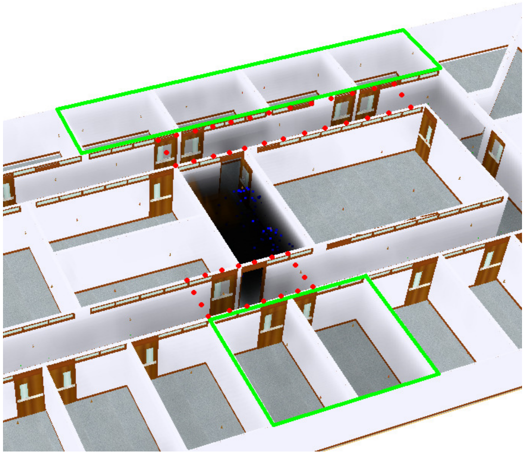
Figure 5.2 The effect of sprinkler functioning on fire hazards. Red circles and grey squares indicate that the heat hazard and the smoke hazard reaches the threshold earlier, respectively. Blue crosses are the sprinklers which are activated in the simulation.

The threshold smoke observing times for route selection, or the times when the visibility decreases to 10m at each node, are also listed in Table 5.1. The threshold time is reached at almost all the nodes by the end of simulation. This indicates the possibility for some evacuee groups to alter their exit selection through smoke observing, and for some other groups to be hindered by the smoke from exit selection. As explained in previous section, threshold visibility on other nodes implies the danger of exits, while threshold visibility at the evacuees' own location makes them lose the ability of exit selection. The effects of both situations will be discussed later together with the evacuation simulation result.

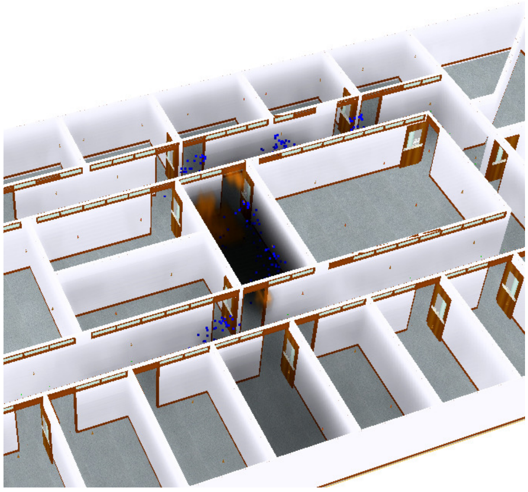
As expected in Chapter 4, Smokeview visualization turns out to be effective in facilitating result interpretation, through giving intuitive views to characteristics of the fire which are discussed above. In Figure 5.3, by time = 30s, the smoke has emerged in the six rooms (highlighted in green plain lines) where the evacuees are assigned a shorter response time than the others. The trail run mentioned above indicating that the smoke first enters these six rooms is different from the functionality test: the former does not contain door opening events, since door opening times are unavailable without even response times. Yet till time = 30s the functionality test contains no door openings either, so the two runs are identical up to that stage. The smoke is also the densest at the nodes with threshold hazards (highlighted in red dotted lines).

Flames in Smokeview do not represent the temperature directly, but they represent heat flow which also measures heat hazard. By time = 90s, flames have reached the doors of HJ718 and nearly cover node 39 and node 61 with critical heat hazards; actually the temperature there have reached threshold well before the flame. However, the flames, or heat hazards, appear to be stopped by sprinkler sprays and do not spread further even at time = 200s. on the other hand, the smoke continues spreading and becomes much denser at time = 200s.

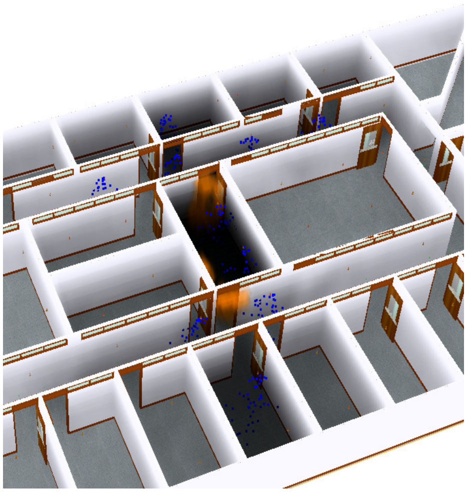
The evacuation simulation results and fire risk assessment are presented in Figure 5.4 and Figure 5.5. The total RSET is 141.5s, well before the end of the 260s fire simulation. RSET of each evacuee group shown in the text report considers only the last evacuee in the group, and to calculate average RSET on individual base, time delays among group members are deducted. For all the safe evacuees, the individual average RSET is 101.4s, including 57.8s response time and 43.6s travel time.



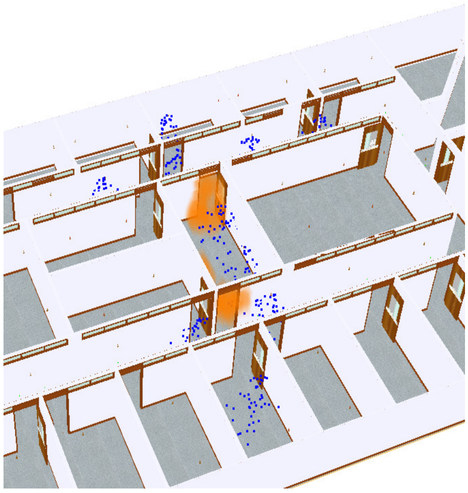
Time=30s



Time=90s



Time = 200s



Time = 200s, smoke unloaded for clearly Showing flames and sprinkler sprays

Figure 5.3 Smokeview visualization of the sample simulation

FireEVA v1.0 Evacuation Simulation Report

No. of evacuee groups: 29
Total No. of evacuee(s): 74
Total No. of safe evacuee(s): 69
total evacuation time: 141.5s

Group	Start Location	Evacuee(s)	Safe Evacuee(s)	Exit	Evacuation Time
0	HJ702	4	4	N	90
1	HJ702A	1	1	N	91.5
3	HJ703	1	1	N	81.5
4	HJ704	1	1	N	84
5	HJ705	1	1	N	56
6	HJ706	1	0	-	33.5
7	HJ707	1	1	S	121.5
8	HJ708	1	1	S	111
9	HJ709	1	1	S	109.5
10	HJ710	1	1	S	87
11	HJ711	1	1	S	85.5
12	HJ712	1	1	S	81
13	HJ713	1	1	S	78.5
14	HJ714	6	6	S	96
15	HJ715	8	8	S	108
16	HJ716	6	6	S	120
17	HJ717	4	0	N	72
19	HJ718A	20	20	N	141.5
20	HJ719	4	4	S	127.5
21	HJ722	1	1	S	69.5
22	HJ723	1	1	S	72
23	HJ724	1	1	S	73.5
24	HJ725	1	1	S	77
25	HJ726	1	1	S	82.5
26	HJ727	1	1	S	84
27	HJ728	1	1	S	58.5
28	HJ729	1	1	S	60
29	HJ730	1	1	N	47.5
30	HJ731	1	1	N	46

Fire risk assessment

Group	No. of evacuee(s) under risk	Location	Time
6	1	39	34
17	4	39	72

Figure 5.4 Evacuation simulation and fire risk assessment results: text report

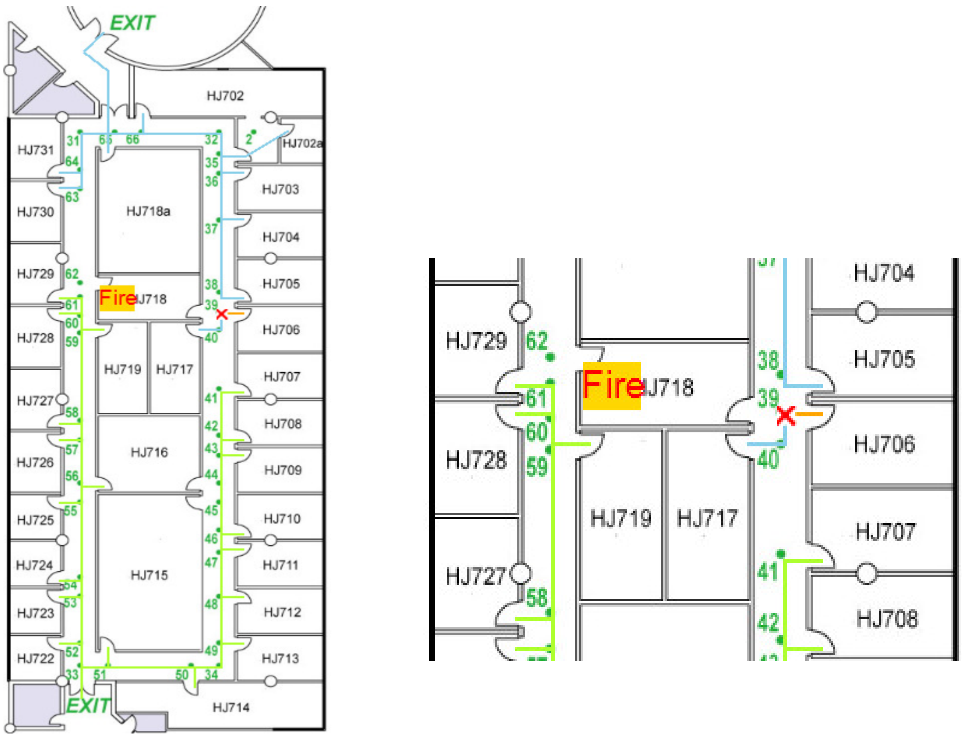


Figure 5.5 Evacuation simulation and fire risk assessment results: 2D visualization, overview and close view near the fire source

It is not surprising that the average response time is one third longer than the average travel time. Actually, researches show that in real-world fire incidents the response time is often twice or even three times as long as the travel time. (Sime, 1992; Proulx, 1995; Department of Emergency Services, Queensland Government, 2009?) The response time in the sample run is in fact relatively short, which results from the user inputs following a nearly ideal situation for quick response: alerted and trained evacuees who are familiar with the environment, and the immediate fire alarm.

Fire risks are reported at node 39 for evacuee group 6 from HJ706, and group 17 from HJ717. Node 39 is between the doors of HJ718 (the fire source) and HJ706, and it has both heat hazard and smoke hazard reached the thresholds in the fire simulation. Group 6 is predicted to be caught by fire immediately after it enters the corridor at time = 34s (see its orange route in Figure 5.5 indicating no chance to select an exit before the risk), and the risk is a heat hazard, since 30s is after the emerge of critical heat hazard (at 7.4s, see Table 5.1) and before critical smoke hazard (at 190.8s). Group 17 is under fire risk for another reason: this group enters the corridors after 60s response time from node 40, where the visibility has dropped below the 10m threshold to discriminate smoke propagating direction by time = 34.2s (Table 5.2). The evacuees are unable to select the safer south exit, and go to the nearer north exit by experience, eventually meet heat hazard at node 39.

In contrast to group 17, the evacuees from HJ719, HJ728 and HJ729 also has the nearer north exit as their initial selection, and they will encounter heat hazard at node 62 (Figure 5.5) starting from time = 18.5s (Table 5.1) if they move northwards. Fortunately, they enter the corridor before the visibility gets lower than 10m, and are able to select the safer south exit (Table 5.2).

Table 5.2 Ability of exit selection for four evacuee groups near the fire source

Origin of evacuee group	Entrance node to corridor & node's smoke observing time	Time entering corridor	Ability to select a safer exit
HJ706	Node 39, 7.4s	≈ 64s	No
HJ719	Node 59,148.4s	≈ 67s	Yes
HJ728	Node 60, 116.6s	≈ 34s	Yes
HJ729	Node 61, 47.2s	≈ 35s	Yes

5.2 Essentialities of functionalities in the system

This section examines various functionalities in the system and demonstrates that they are indispensible for the accuracy of simulation. The analyses are based on the system functionality test, as well as control tests where the system is run without a certain functionality to contrast the results with it. A function could be considered significant if its absence leads to evident discrepancies in simulation results, particularly in fire risk assessment, since the ultimate purpose of fire evacuation simulation is to enhance safety.

The examination goes through each system component that involves initial design, including two of the three major behaviours simulated in the evacuation model - exit selection and friction/repulsion, as well as the fire model and multi-stage risk assessment. Queuing behaviour and other functions in the evacuation model need no validation since they are existing mechanisms in classical network models.

5.2.1 Behaviour-based exit selection

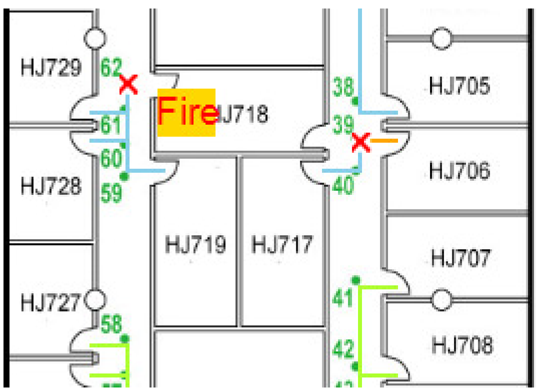
Chapter 2 has suggested that network evacuation models are typically based on building geometry, and usually produce optimal routes and underestimate RSET. Sometimes these models are considered appropriate for evacuation training and planning (Kisko et al., 1998), since they provide optimal evacuating solutions. However, the following discussion will show that behavioural and dynamic exit selection proposed by this study is necessary for even evacuation training and planning.

To examine the consequence of merely distance-based route selection, a control test is done by making evacuees move to the nearer exits regardless the fire situation. User inputs are the same as the functionality test. In results of the control simulation, the total evacuation time is still 141.5s. The last evacuee group finishing the evacuation in both runs is the group from HJ718A. The door of this room is very near to the north exit (Figure 5.5), and the evacuees almost immediately start to pass the exit after entering the corridor, so their evacuation time is mainly decided by queuing. Since there are much more members in this group than other groups, (20 in contrast to 1~4 for groups choosing the north exit), the queuing delay is largely caused by the group itself, and changes little even situations of other groups in the queue are changed by the control condition. Eventually, RSET of this group varies only slightly and becomes the same as the functionality test when rounded to 0.5s. The average travel time of all the groups drops to 39.8s, or 10% less than 43.6s in the functionality test. This agrees to the common opinion on underestimation of RSET by building geometry based evacuation models. The fire source is near the building centre and does not block many evacuees' ways to the nearer exits, and some evacuees do not change their exits to the farther but safer one due to the hindered sight by smoke, so only several groups alter their exit selections by behavioural rules, resulting in a small discrepancy in travel time between the functionality test and the control test.

However, this small number of exit selection alternations are significant considering the severe deviation of the control test from the functionality test in fire risk assessment. 6 evacuees in group 20, 27 and 28 are caught in fire because they move in direction of the fire, in addition to the 5 evacuees predicted unsafe in the functionality test (Figure 5.6). This prediction is rather unreliable, and it is unreasonable to suppose that evacuees insist on moving towards the danger for a nearer exit. In evacuation training and planning, if the requirement is only safe evacuation via optimal routes, then even the requirement is met, the real evacuation may not be successful due to the normally longer RSET than the optimal solution.

Group	No. of evacuee(s) under risk	Location	Time
6	1	39	34
17	4	39	72
20	4	62	74
27	1	62	38
28	1	62	36

(a)



(b)

Figure 5.6 Evacuation considering only the nearer exits

(a) Report of unsafe evacuee groups (b) Evacuation routes and fire risks near the fire source

It may be argued that fire blockages to certain routes can be defined before the simulation, so that a reasonable evacuation plan can be produced. However, simulation results in Section 5.1 indicate that some evacuees are unable to select a safer exit under low visibility (<10m), and resultantly move towards the hazards and encounter fire risks. A second control test is done, where the evacuees avoid passing node 39 and 62 with the severest hazard regardless of visibility at their locations, and all the evacuees are predicted to be safe, except the group from HJ706 whose entrance to the corridors is blocked by fire. Therefore predefining fire blockage can underestimate the fire risk.

Moreover, it is inappropriate to overlay ASETs and RSETs after finish calculating the evacuation, and just train people or plan to evacuate before ASETs. Some evacuees select exits earlier than others, and their changes of routes will affect others' movement by changing friction and queuing situations, even alter exit selections of the others. Thus the "smoke viewing time" have to be processed during the evacuation simulation. To sum up, the exit selection should be behavioural as well as dynamic.

5.2.2 Dynamic moving speed calculation

Various estimations on people's moving speed can lead to different results of RSET, which may further turn to different fire risk assessment. In the functionality test, if the moving speed is set to 1.2m/s which is the "no-friction" speed suggested by Equation 4.1, the average travel time is only shorten by about 10%, and no difference in fire risk assessment is generated. Indeed, the evacuees do not encounter much crowdedness in this particular simulation, and their evacuation is not very much prolonged by friction. However, the following control test will show a totally different situation of a long queue at the exit as fire hazard approaches.

In the control test, to avoid making the situation too complex and confusing, evacuees are supposed to go to the nearer exits without exit selection, and ASET is not overlaid with RSET at intermediate nodes to the exits. Only one ASET value of 40s after the evacuee response time is set at the node before the north exit (node65 in Figure 5.5). 40 occupants is assigned to the room HJ718, which simulates a relatively large meeting in the room. Numbers of evacuees in other rooms are the same as the functionality test.

Figure 5.7 shows the resultant fire risk assessments when the test is run with dynamic moving speed computation in contrast to with a constant speed of 1.2m/s. With the variable moving speed, many evacuees are reported under fire risks at node65, while if the constant speed is used, only a part of members from HJ718A are predicted to be unsafe. The surprisingly large disagreement results from that the constant speed can not reflect the reality of queuing at the north exit. When many people queue in a relatively narrow space to pass a door, they slow down not merely when passing the door by its flow capacity, but rather well before getting to the door, even they do not congest, because they are in a dense flow of people, and have to move slower in order not to conflict with each other. This is just the case in the control test when other evacuee groups try to get into the queue at node65, dominated by evacuees from HJ718A, to pass the exit. The constant speed model does not consider friction, and consequently misses a great potential danger in the evacuation as revealed by the variable speed model. This suggests that using dynamic speed estimation to simulate friction should be indispensible for getting reliable RSET and risk assessment results.

Group	No. of evacuee(s) under risk	Location	Time
0	4	65	124
1	1	65	274
3	1	65	271
4	1	65	274
5	1	65	278
6	1	65	278
17	4	65	136
19	24	65	101
20	4	65	120
27	1	65	226
28	1	65	224
29	1	65	218
30	1	65	218

(a)

Group	No. of evacuee(s) under risk	Location	Time
19	23	65	102

(b)

Figure 5.7 The effect of dynamic moving speed estimation on fire risk assessment Response time of all evacuees = 60s, ASET at node 65 adjacent to the north exit = 100s. (a) Risk report with dynamic moving speed (b) With the constant moving speed of 1.2 m/s.

Using a constant speed corresponding to average people density in the study area, rather than the “no-friction” value, helps little to improve the constant speed model. In the control test, the density of the 63 evacuees choosing the north exit on nodes passed by them (area = $341m^2$) is less than 0.2 person/m^2, and this is also under the “no-friction” situation in Equation 4.1. Even only the corridor area is counted (area = $131m^2$), the density is 0.48 person/m^2 and is still in “no-friction” case. Hence the approach of using average evacuee density will produce identical simulation result as not considering friction at all, and unacceptably miss many unsafe evacuees in the risk assessment. A very low density will not make evacuees move faster than the “no-friction” speed, while more people are at crowded nodes and have their moving slowed down, so the approach of using average evacuee density still overestimates people’s evacuation efficiency.

In EVACNET4, different speeds can be assigned to each link, and assigning evacuation bottlenecks slower speeds can reduce the error in RSET computation. Yet temporal variations of people density at each link are still error sources, and it can be difficult to estimate people density on a certain link for moving speed estimation, unless the density is calculated at each time point to derive and an average. However, if people density at each time point is obtained, it is even more convenient to work out dynamic moving speed than to derive the average. In a word, dynamic moving speed calculation based on instant evacuee density is superior to any of the three approaches above for getting reliable RSET.

5.2.3 FDS fire model components

It is somehow labour intensive to handle the long input code for FDS fire model construction, and FDS takes long CPU time for calculation, with further prolongation for additional model contents. Hence it is important to keep in the model only those components necessary and worthwhile for accurate simulation. The cases of three components are to be discussed: the dual thresholds of heat and smoke hazards, the sprinkler system, and the door opening events.

According to the simulation results in Section 5.1, the sprinkler system can reduce heat hazard much more efficiently than smoke hazard, and this causes the heat risk emerges earlier near the fire source while the smoke risk occurs earlier behind sprinkler sprays. Merely using either of the assessment measures will make ASET much longer than the actual situation, and will underestimate fire risks. Thus at least for the environment with a sprinkler system, neither of the dual thresholds can be eliminated.

The importance of the sprinkler system and door opening events is proved by control tests with the same user input as the system functionality test. When the sprinkler system is absent, the fire hazards propagate much faster, especially the heat hazard. As shown in Figure 5.8, even the most alerted evacuees from HJ730 and HJ731 with only 30s response time is under heat risk at the upper left corner of the corridor.

The absence of door opening events also lead to over-approximation of fire hazard propagation speed, and the condition is more evident for smoke hazard. The simulation produces identical fire risk assessment result as the system test. However, if the evacuee response time in HJ729 or HJ719 are set 30s later to time = 60s and time = 90s (30s and 60s in system test), entrance nodes to the corridor from these two rooms will have visibility less than 10m, causing the evacuees select the wrong exit and meet fire risks (Figure 5.9). Different individuals have much varying reaction speed in fire, and CFPA E (2009) pointed out that late responders in fire typically have a response time of no less than 3 times of early responders, so setting the response time 30s later here is reasonable. With presence of door opening events, the visibility does not decrease as fast, and the evacuees are safe even they response 30s later.

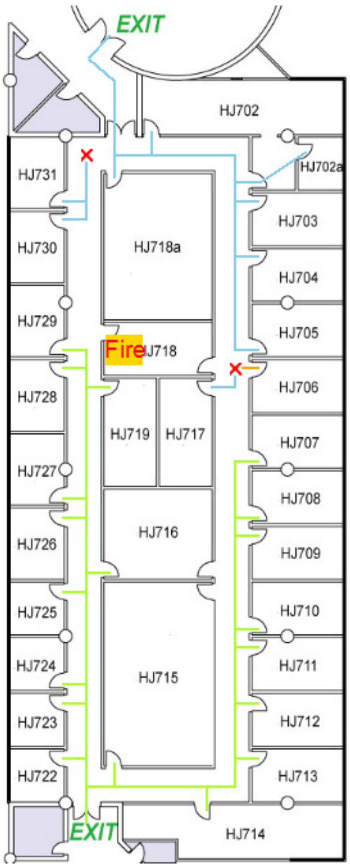


Figure 5.8 Evacuation overlaid to the fire simulation without the sprinkler system

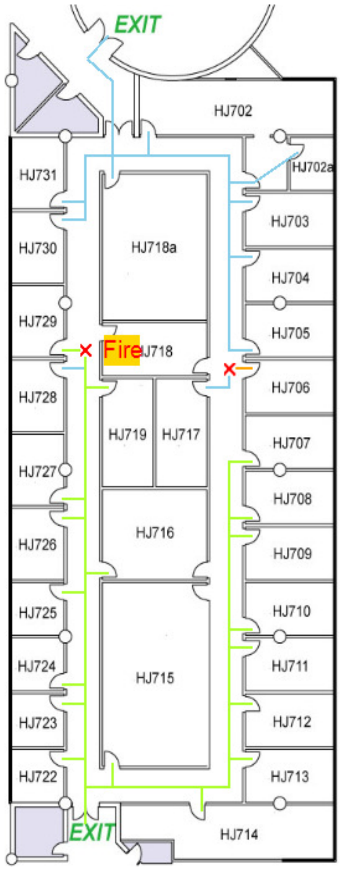


Figure 5.9 Evacuation overlaid to the Fire simulation without door opening events

5.2.4 Multi-stage fire risk assessment

Results of the system functionality test also validate the essentiality of multi-stage fire risk assessment. If the evacuation module is run without overlaying ASET with the same exit selections as the functionality test, all the evacuees will arrive at the exits well before the end of fire simulation. Since the hazard threshold is not reached at exiting nodes till the end of fire simulation, all the evacuees will be predicted safe. Thus single-stage risk assessment can overlook possible fire risks in the middle of evacuation, resulting in a false confidence on the safety of the assessed environment, which is most dangerous.

Moreover, single-stage risk assessment cannot identify causes of fire risks without identifying the location and time of each risk, while reasoning the risks can provide valuable safety suggestions for the assessed building environment. For instance, the functionality test reveals a major danger for smoke to hinder the selection of the safer exits, even the evacuees are familiar with the environment and need not to explore unknown evacuation routes. It is recommended to further investigate venting system in the study area to see whether this problem can be settled with existing facilities.

In addition, single-stage risk assessment can not handle unsafe evacuees in real time during the evacuation simulation, and calculates the queuing time delay and friction as if they were still in the moving crowds. In single-stage risk assessment, unsafe evacuees are regarded stop at the location of risks and removed from later queuing and dynamic moving speed computation. In this sense, multi-stage assessment can facilitate accurate calculation of RSET.

6 Conclusions

6.1 Overview

In this study, a GIS-based IFES is developed primarily aimed at two enhancements to existing studies: the network evacuation model emphasizing behavioural rules, and the multi-stage fire risk assessment.

Major extensions on data structure and computing algorithms are made to the classical network model to accommodate behavioural rules, and three essential evacuation behaviours are focused on: exit selection based on evacuees' knowledge, the location of fire hazards and the visibility at the time and location of exit selection; repulsion/friction; and queuing. Quantitative analyses are made for implementations of the former two behaviours which are initially designed by this study, and the results indicate that both behaviours are critical for a realistic simulation and reliable risk assessments. In general, this model can effectively simulate behaviours in evacuation once mainly applied to more sophisticated data structures like CA rather than network models, while still keeping the ease of the network model to be examined and adjusted by real-world data, as opposed to the difficulty to do so in CA models.

The multi-stage fire risk assessment takes the strength of GIS in dynamic spatial overlay to compare ASET and RSET at each location in the evacuation. Evacuees are judged as being safe only if they are safe at all locations, and unsafe evacuees are processed differently in real time. A control test proves that the multi-stage risk assessment can identify evacuees under risk who are missed by single-stage assessment, as expected in the review of relevant works and project objective.

To obtain accurate ASET for risk assessment, a detailed fire model with adoption of FDS is constructed, and its performance validated by quantitative analysis as well. The system are integrated and automated on Visual Basic platform with intuitive user inputs, outputs and visualizations, and a functionality test confirms its usability in a non-technical approach. The effort on system integration and automation is much meaningful for economic value of this system and the mission of GIS professionals to make Geo-IT accessible to the general public.

6.2 Limitations of the IFES

This study amends the network evacuation model in terms of behaviour simulation, yet there are still implicit limitations in the network data structure. The model only supports forward and backward movements along the network link but not horizontal movements. This may make behaviours like overpass difficult to simulate, and errors can be generated in evacuation route length, since only the centreline of each building component is modelled as the route, even the error is supposed to be small due to the usually narrow building geometry in study area. If the network is finely divided, like setting a node in x and y direction every 0.5m, the geometric errors can be significantly reduced, and overpass can be simulated since there are multiple lanes in the corridors. However, people movements in the model will become in sub-meter scale and not easily examined against real-world data. For example, the moving speed of the entire evacuee flow can be monitored through CCTV in fire incidents, while the frequency of overpass among the evacuees can be extremely hard to observe. This will considerably weaken the major advantage of network model over CA model which is the ease to be tested and adjusted against real-world data.

Besides, some design of the system is specific to the data provided. The exit selection takes place only once after each evacuee group firstly enter the corridor, and the way from a node to each exit is unique. It is suitable for the study area, but for more complex building structures, evacuees may need to select several intermediate doors before going to final exits, where the selection of intermediate doors can affect the choice of exit, and there may be multiple routes to an exit. Then the data structure needs further extension for multi-stage exit selection and networking algorithms for path searching.

6.3 Recommendations for further development

In current risk assessment, REST and ASET are used as single deterministic values, and the output is either “safe” or “unsafe”. Yet whether people can barely escape from fire hazards becomes uncertain if RSET and ASET are close to each other, and some evacuees judged as safe because their RSET is slightly shorter than ASET may also be under certain risk. It would be more objective to give the possibility of risk instead of a yes-no answer. As suggested by some scholars, ASET and REST can be treated as probability distributions. In this way the possibility of fire risk for each group at each location can be derived. The author further suggests that alarm can be given when the possibility of risk is over a critical value, and for multi-stage risk assessment, the process to handle unsafe evacuees can be triggered when the possibility of risk excesses the threshold.

Real-world data is one of the best tools to examine a simulation system, therefore it is desirable to test the system against evacuation data in reality concerning RSET, ASET and risk assessment. Assumptions in the system can be confirmed, and computational parameters can be adjusted to achieve higher accuracy.

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