Computational Modelling of Agent Based Path Planning and the Representation of Human Wayfinding Behaviour within Egress Models

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DECLARATION

I certify that this work has not been accepted in substance for any degree, and is not concurrently being submitted for any degree other than that of Doctor of Philosophy (PhD) being studied at the University of Greenwich. I also declare that this work is the result of my own investigations except where otherwise identified by references and that I have not plagiarised the work of others.

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Prof. Edwin Galea (second supervisor)

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ABSTRACT

The focus of this thesis is on wayfinding within buildings from an evacuation/circulation modelling perspective. Majority of the existing evacuation models simplify the process of wayfinding by assigning the shortest path to all agents. This is not a realistic representation of the actual route choices made by people in circulation/evacuation conditions. Wayfinding is a dynamic process and cannot be modelled as a static process by assigning pre-determined routes to the agents. Wayfinding is thus a very important aspect to be modelled accurately within evacuation/circulation models to simulate more realistic human behaviour.

The main goal of this thesis is to develop an agent based wayfinding model for the buildingEXODUS evacuation/circulation model. There were four major problems to be solved: spatial representation of the environment, implementation of graph search algorithms to generate choice set of routes for the agents to choose from, determination of factors that influence people's wayfinding behaviour and the development/integration of the agent based wayfinding model within the buildingEXODUS evacuation/circulation model.

The existing spatial representation technique in buildingEXODUS was modified to best suit the requirement of the wayfinding model. Various graph search algorithms such as A*, Dijkstra and Yen's algorithm were studied. Alternate algorithms were developed to quickly generate routes and were compared with the performance of the Yen's algorithm. Two surveys were then developed and published on line. A total of 1200 participants from various countries took the survey. The survey results were statistically analysed and was utilised to model the decision making behaviour of the agents in the wayfinding model. An agent based wayfinding model was then developed incorporating features such as: spatial representation in terms of a graph, application of route choice set generating algorithms, agents with their individual attributes using multi criteria decision analysis methods to choose routes and changing routes dynamically on encountering congestion or gaining new exit knowledge.

This wayfinding model was then integrated within the buildingEXODUS model. The buildingEXODUS model passes spatial information and agent location to the wayfinding model at the start of the simulation. The wayfinding model applies the graph search algorithms to generate routes and assigns routes (a set of target locations) to the agents. The buildingEXODUS model generates events under certain circumstances: when agents reach a target location, encounter congestion or learn the location of a new exit. The wayfinding model listens to these events and assigns a new route to the agents if an alternate route is more favourable than the initially chosen one. Therefore, there is constant communication between the fine node buildingEXODUS and the coarse node wayfinding models, with the latter being responsible for assigning routes to the agents and the former being responsible for navigating the agents from one target location to the next. Thus, a sophisticated wayfinding model incorporating data from surveys has been developed using C++ and has been integrated into the buildingEXODUS evacuation model.

The introduction of the wayfinding model brought about significant changes to the evacuation statistics produced by the buildingEXODUS model. The difference was more significant in buildings where there was more than one path to an exit. The default option of the existing evacuation models is to assign the shortest path to all the agents in the simulation whereas with the wayfinding model, agents choose alternative paths based on other wayfinding criteria as well such as time, number of turns, etc.

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1 Introduction

This thesis provides details of the development of a mathematical model to represent human wayfinding within software based evacuation and circulation models. Built environments such as shopping complexes, offices, stations and airports typically have more than one possible route to a destination. The destination could be the exit from a building, a platform in the train station or the boarding gate in an airport. This research describes the development of a wayfinding model consisting of mathematical and computational techniques. The model describes the wayfinding behaviour of the agents within evacuation models. The building space is represented mathematically by means of graphs. Graph search algorithms are applied to provide the agents in the wayfinding model a choice set of routes. Multi criteria decision making models are then applied to represent the decision making ability of people under normal circulation and emergency evacuation conditions. Data was collected by means of online questionnaires to simulate actual human wayfinding behaviour within evacuation and circulation models. The wayfinding model developed in this thesis may be applied to various enclosures such as ships, aircrafts and trains. However, the main focus of this thesis is on building environments. Existing evacuation models have a very simplistic representation of wayfinding. The model developed in this thesis is more sophisticated and attempts to incorporate more realistic wayfinding behaviour within evacuation models.

Why is it important to accurately represent human wayfinding behaviour within evacuation and circulation models?

[Grosshandler, et al., 2005] have listed a summary of twenty two unsuccessful evacuation incidents in the past. Amongst other factors, the key factors contributing to the loss of lives in these incidents are blocked or non obvious exits, crowd crush and inadequate exit capacity. These factors are directly related to wayfinding as excess usage of certain exit routes can cause blockage or crowd crush.

Blocked exits or non obvious exits played a major role in fifteen of these incidents. Majority of the occupants in these incidents were aware of the main exit alone. Therefore, blockage of the main exit in particular can have a devastating effect as in the Station nightclub [Grosshandler, et al., 2005] incident where the main exit was blocked within 102 seconds of the start of the fire [see Chapter 3 for the modelling details]. The non obvious location of the emergency exits in the Station nightclub had a detrimental effect on the egress of the occupants. One of the survivors of the incident who evacuated using an emergency exit said

*"It had an exit sign, but unless you're back in that area, you wouldn't know it. The way the club was shaped, it was out of the way."[*Grosshandler, et al., 2005*]*

Crowd crush at exits usually occur due to a large number of people trying to use the same exit. This is usually the main exit, which is often the most familiar exit to the occupants. In the E2 Nightclub stampede [Grosshandler, et al., 2005] in Chicago, twenty one people were killed and more than fifty were injured due to a crowd crush that developed at the main exit which was also the only exit familiar to most of the club patrons. Crowd crush can occur due to something very simple such as a person tripping over. In the haste to get out of hazardous conditions this could lead to a chain of events where people behind fall over the people on the floor creating a pile-up. The people at the front struggle to disentangle themselves from the pile of people on top. At the same time people at the back unaware of the conditions at the front continue to push forward which further increases the pressure at the front, making it even more difficult for the people at the front to escape. In the station nightclub incident such a crowd crush occurred at the main exit after just eighty five seconds from the start of fire. This seems to indicate that due to the dark and smoke filled conditions the occupants were not aware of the alternate emergency exits that were in the near vicinity. One of the survivors from the station nightclub said

"got into entry hall, it was chaotic with people coming from two directions into foyer, like a funnel. The smoke came in. [The occupant] started pushing and shoving his way to front; 'I could feel myself walking over' people; he could feel the heat on his back. Front doors were open. He was almost out when he tripped over someone who had fallen, and was laying perpendicular to front door. [The occupant] caught himself but as he was halfway up, people behind him fell on top of him. 30-35 people on him. Half his body was out of the door. His waist was where the door was. [He] felt himself being yanked back in. Grabbed bottom metal bar [outside the main entrance]... Finally, [on the] third or fourth pull, [the occupant's] other shoe popped off and he came sliding out."[Grosshandler, et al., 2005]

Inadequate exit capacity has been mentioned as the contributing factor in sixteen of the twenty two unsuccessful evacuation incidents. Inadequate exit capacity is where the number of exits and their size is insufficient to evacuate a building without any casualty. The exit capacity of a building depends on the number of people in the building. Building codes generally calculate the maximum occupant load for a building based on either the exit capacity or the area. These methods are based on prescriptive codes such as NFPA [NFPA, 2009] and do not take into account the human factors involved in an evacuation process. An alternative method to assess the maximum occupant load for buildings is to use performance based codes. Here computer models such as fire and evacuation models are used to predict how fire and people are likely to behave. However, current evacuation models need to possess more advanced wayfinding features to make them more reliable in such applications. It is no good simulating agents down to the millimetre when they will not be taking that route anyway. Existing evacuation models use simplistic wayfinding algorithms where occupants go to the nearest exit or to a manually assigned exit [Kuligowski, 2008].

1.1 Research Motivation

According to [Arthur and Passini, 1992] wayfinding is a continuous spatial problem solving process under uncertainty. This definition of wayfinding does not consider familiar journeys to be a wayfinding act. However, according to the same authors

"To take a familiar route is nothing other than the execution of an already recorded decision plan and is therefore also a part of wayfinding and problem solving. The only difference is that the emphasis has shifted from decision making to decision execution.".

There are many definitions of wayfinding by different authors to suit their specific application. [Conroy, 2001] has discussed some of these definitions. Within the building environment, wayfinding describes the process by which an individual located within a complex enclosure decides on a path or route in order to reach a goal location. Within the building evacuation context, wayfinding describes the process in which the individual attempts to find a path which leads them to relative safety, usually the exterior of the enclosure.

The process of wayfinding requires the individual to have a cognitive or mental map of the space. Cognitive mapping has been defined as the process by which an individual acquires, stores, recalls and decodes spatial information [Downs and Stea, 1973]. According to the Landmark, Route, Survey (LRS) model [Siegel and White, 1975], cognitive mapping involves individuals first extracting key landmarks from the environment. Within the built environment, these landmarks may be internal exits, external exits, rooms, escalators, stairs, lifts, sculptures, etc. Route knowledge then develops as the individual associates landmarks with routes and a mental map of the required route is formed. Survey or configurationally knowledge is said to have been attained when the map is more complete and the person can find a path from any point in a building to any other point even though he/she may not have traversed that path.

In most evacuation modelling tools, the process of wayfinding is either ignored or grossly simplified. In a recent review of 30 evacuation models wayfinding features were only mentioned in the context of two models [Kuligowski, 2008] [Kuligowski and Peacock, 2005]. On the whole, evacuation models assume that the simulated agents have complete knowledge of the structure and so follow a potential or distance map to their nearest exit.

This thesis provides a framework for representing wayfinding within evacuation and circulation models. As part of this work the thesis describes an approach to representing Spatial Recognition – or the connectivity of the building space - and cognitive mapping within the “mind” of the agent and how this is used for wayfinding.

A choice set [Daamen, 2004] denotes a list of options, a collection of possible routes to exit from an enclosure. Given such a choice set of routes, this research describes the decision making process of individuals under normal and emergency conditions. Each agent in the wayfinding model has his/her own attributes and is allowed to exercise his/her decision making ability to choose among available routes at various circumstances during the simulation. For example when an agent experiences significant congestion/hazards and her patience runs out she is allowed to re-evaluate her route options and choose an alternative route.

To model the decision making process of individuals the factors affecting wayfinding were first identified. A literature review of past urban wayfinding studies suggests that distance, time, angles, turns, length of first leg and decision points are the most important factors affecting urban wayfinding [Golledge, 1999]. In this thesis two surveys (Chapters 6 and 7) were carried out to determine the relative importance of these and some additional factors in the building environment from an evacuation and circulation modelling perspective. The surveys were analysed and the weights for the wayfinding criteria have been incorporated into the wayfinding model.

In this research a novel wayfinding model (see Chapter 7) that attempts to represent the manner in which people wayfind within structures is introduced and demonstrated on several hypothetical and real buildings. The wayfinding process has been defined or explained by many authors from various disciplines in a manner that best suits their application of wayfinding. In this thesis the wayfinding process is said to consist of four steps. The first step is to encode the spatial information of the enclosure in terms of a graph. The second step is to apply graph search algorithms to find possible routes to the destination. The third step assigns a cost to the routes based on the agent's personal route preferences such as "least time" or "least distance" or a combination of criteria. The fourth step is the route execution and refinement. In this step, the agent moves along the chosen route, reassesses the route at regular intervals and may decide to take an alternative path if it is more favourable e.g. initial path is highly congested or is blocked due to fire. Therefore, in this thesis wayfinding is defined to be the process by which an agent possessing a cognitive map makes sequential route choices (decision making) based on wayfinding criteria and local congestion to exit from a building.

1.2 Research Objectives and Questions

The main research objective of this thesis is to answer the following question:

Question 1: How to represent human wayfinding in computer models?

The main objective of this thesis is to utilize mathematical and computational modelling techniques to develop a wayfinding model representing human wayfinding within evacuation and circulation models. Most evacuation models use optimizing techniques such as agents choosing the nearest exit and the shortest paths to that exit. However, this leads to unrealistic evacuation dynamics as people in real life would be capable of taking a familiar less congested path in preference to a shortest path. Hence there is a pressing need to improve the existing functionality of evacuation and circulation modelling tools by introducing a wayfinding model that takes into account other human wayfinding factors such as time, number of turns, number of decision points, etc as described in Chapter 7.

In order to fulfil the main goal of this thesis, a number of sub goals were formulated:

- Review state-of-the-art of spatial representation techniques and choose the best suited technique for representing building wayfinding.

- Review state-of-the-art of graph search algorithms and choose the best algorithm to provide a choice set of routes to the agents in the wayfinding model. If the existing algorithms are not suitable develop new graph search algorithms.

- Analyse the wayfinding features in current evacuation models with a special focus on the buidingEXODUS model to determine the strengths and weaknesses of the existing methods.

- Understand wayfinding theory and design questionnaires specific to wayfinding in buildings and evacuation models in order to determine the relative importance of the identified wayfinding criteria.

- Develop a novel wayfinding model which has features like decision making, redirection due to congestion, redirection due to signage, etc.

- Implement the relative importance of the wayfinding criteria determined from the surveys in the wayfinding model.

- Demonstrate the wayfinding model implemented within buildingEXODUS by simulating the evacuation of real and hypothetical buildings.

Question 2: How do existing evacuation models represent human wayfinding?

Chapter 2 provides details of the research performed to gather the state-of-the-art on the wayfinding features implemented within evacuation models. The buildingEXODUS model was readily available and has sophisticated features (spatial graph generation, agent based behavioural model and agent navigation) that are useful for implementing a wayfinding model. Hence a real life evacuation incident was modelled in buildingEXODUS to further analyse the existing wayfinding features and identify vital additional features to incorporate in the wayfinding model developed for this thesis. The Station nightclub incident [Grosshandler, et al., 2005] was selected for this purpose as this was not only a major incident but was also a real life example of how poor building design, from a wayfinding perspective, can contribute to a severe disaster. The details of this study are presented in Chapter 3 which addresses Questions 2 and the following related questions:

Question 2.1: Do existing evacuation models represent human wayfinding accurately?

Question 2.2: What factors affect human wayfinding decisions?

Question 2.3: How does building design affect the wayfinding process?

Several deficiencies in the wayfinding features of the buildingEXODUS model were identified while reconstructing the Station nightclub fire incident. The factors affecting human wayfinding decisions were identified by a thorough examination of the incident through the official report [Grosshandler, et al., 2005] and newspaper accounts of the incident. The effect of the building design on the wayfinding process was examined by carrying out simulations of the actual incident and with proposed modifications to the building structure.

Evacuation models incorporate basic wayfinding features (see Table 1-1). All evacuation models assign a cognitive map to the agents consisting of exit knowledge and the shortest routes to those exits. However, in this thesis a major difference is that the agents possess a more detailed cognitive map enabling them to choose suboptimal routes rather than just the nearest or shortest routes to the exits. Existing evacuation models represent the decision making behaviour as a simple exit choice. In this thesis, agents make route choice instead of exit choice. Existing evacuation models represent the redirection of agents due to signage, congestion and hazards. The model developed in this thesis is capable of representing redirection of agents due to signage, congestion and hazards, as in other models. However, the difference is that these other models used only distance and time whereas in this thesis agents consider other wayfinding criteria [see Chapter 2, Section 2.3]. Complex wayfinding features such as affordance, landmarks such as fountains or points of interest, social interaction is not considered in thesis. The wayfinding model developed in this thesis could be adapted to include these features.

Table 1-1: A comparison of the wayfinding features in existing evacuation models and the wayfinding model developed in this thesis.

Wayfinding Features	Existing evacuation models	Wayfinding model
Cognitive maps	Exit knowledge	Route knowledge
Route choice	Shortest/optimal/signage routes considering just distance and time.	Suboptimal route choice considering additional wayfinding criteria such as turns, angles etc as well as distance and time.
Redirection	Redirect to exits	Redirect to alternate routes.

Question 3: How is the building space represented in wayfinding models?

Space is a continuous region. However, in wayfinding models space is often represented as a graph consisting of nodes at important locations and links representing the pathways between these locations. This gives rise to a sub-question of Question 3 such as:

Question 3.1 What are the important elements of a building?

According to Lynch [Lynch, 1960], who is regarded as the father of human wayfinding research, people form an image of the city through its elements which he called paths, edges, districts, nodes and landmarks. Paths are the traversable areas such as roads or walkways. Edges are the boundaries or areas that are not traversable such as walls or fences. Districts are distinct regions within a city that have something in common. Nodes are strategic decision points like junctions along a path. Finally, Landmarks are physical objects such as a clock tower that provides a sense of direction for people.

Similarly, the important elements in the building environment are internal exits, external exits, rooms, corridors, escalators, stairs, sculptures, etc. This thesis only deals with single floor geometries and hence escalators and stairs are not modelled. However, they can be included as nodes in the existing model with a few modifications. Objects in the building such as sculptures, fountains and other exhibits of interest are presently not modelled and may be included in future. Two kinds of spatial representation techniques have been considered in this thesis. Room graphs only consider rooms and the external exits. Route graphs consider rooms, internal exits and external exits. The comparison of these spatial representation techniques is described in Chapter 7. A description of other techniques such as axial maps, Isovist fields, visibility graphs is described in Chapter 2.

Question 4: How to generate a choice set of routes?

Generating a choice set of routes is a very important aspect of the wayfinding model implemented in this thesis. There are various graph search algorithms to find the optimal path between two nodes. Optimal in terms of a cost such as distance, time, etc. However, there are very few algorithms that can find sub optimal paths between two nodes. Evacuation is a dynamic process where the number of people along a route varies over time and a path that is optimal at the start may not be so during the process of evacuation. Hence providing a choice set of routes by generating sub optimal paths is an important requirement for the wayfinding model. The existing search algorithms in the literature were first reviewed and the most suitable ones were implemented in C++. Wxwidgets [Smart and Hock., 2005], an open source and cross platform GUI library was used to provide the graphical user interface functionalities. Novel graph search algorithms were then developed to suit the specific requirements of the wayfinding model (see Chapter 4). In order to determine the best algorithm for the wayfinding model they have been compared in terms of

- The number of routes found
- The quality of the routes found
- The time complexity of the algorithms
- The space or memory complexity of the algorithms

The number of routes found by the algorithms is an important attribute; the more the routes computed the better. The quality of the routes refers to the ability of the algorithms to find routes of non-decreasing distance, i.e. the shortest path is found first followed by the second shortest and so on. The time complexity refers to the time taken by the algorithms to run and space complexity refers to the memory consumed.

Question 5: How to represent the movement of the agents?

Room/route graphs which are used to represent space in the wayfinding model are both coarse node representations. A coarse node representation is where the space is divided into regions like rooms, stairs, escalators, etc and the occupants move from one region to another. However, this coarse node representation is only used by the wayfinding model to assign routes to the agents in the fine node buildingEXODUS model. A fine node model is where the space is divided into blocks of certain size. For example in the buildingEXODUS model each block or node represents a space of 0.5m X 0.5m [Galea, et al., 2006] which is also the same space occupied by the agents or occupants in the model. The wayfinding model is only responsible for the assignment of routes by repeatedly specifying the next target node to the agents. The physical movement of the agent is dealt by buildingEXODUS. The agents may take the shortest path between two target points along a route or make a detour around other agents and obstacles to reach the target. This integration of the coarse node wayfinding model with the fine node buildingEXODUS model is described in more detail in Chapter 7.

Question 6: What factors influence wayfinding in the built environment?

A literature review was performed to identify the factors affecting wayfinding. However, most of the important wayfinding studies which were considered relevant for the development of the wayfinding model in this thesis were specifically for urban environments. This gives rise to the following sub question:

Question 6.1: Are urban wayfinding factors appropriate for a building wayfinding model?

Some of the urban wayfinding factors may be relevant for buildings as well. For example, it is likely that distance and time would affect the wayfinding decisions in any environment. However, the order of importance of these factors may vary depending on the nature of the environment. Some of the urban wayfinding factors such as the “most scenic/aesthetic” route may not be relevant in the building environment and are also difficult to include in a 2D model. There may also be new factors that influence the wayfinding behaviour of people in the building environment. This gives rise to the following question related to Question 6:

Question 6.2: How to identify the building wayfinding factors and the importance of these factors in a building environment?

In determining the factors that are important in wayfinding in the built environment, a methodological question which was added was,

Question 6.3: How do we determine the factors influencing wayfinding decisions?

There are a number of ways this can be addressed for example: experimental techniques, interviewing techniques and questionnaires. Given the large number of people that were required for analysis, and given that we wanted to also explain the following question,

Question 6.4: Does culture influence wayfinding decisions?

it was decided that an international web based questionnaire was the best approach. An experimental approach would not be practical given the limitation of the PhD project and the international nature of the investigation. Though current wayfinding literature does not consider cultural factors, a human factors study [Scharine and McBeath, 2002] suggests that handedness and the side of the road we drive on may have a significant influence in path selection. Therefore research questions that were addressed in the questionnaires are

Question 6.5: What is the significance of building wayfinding criteria like left handed or right handed paths?

Question 6.6: Do left handed people prefer taking left handed paths and right handed people prefer to take right handed paths?

Question 6.7: Do people prefer Longest Leg First paths (LLF) over Shortest Leg First (SLF) paths?

Question 6.8: Do people prefer LLF/SLF paths over right/left paths?

Question 6.9: Do people prefer the most direct paths to the LLF/SLF paths or right/left paths?

Question 6.10: What urban wayfinding criteria are applicable to building wayfinding?

Question 6.11: What is the relative importance of the various building wayfinding criteria with respect to each other?

Question 6.12: What is a realistic distribution of weights for the different wayfinding criteria for the general public?

Question 6.13: What routes do people choose to exit from a building in emergency and circulation scenarios?

Question 6.14: Does the environment have an influence on wayfinding decisions?

A couple of questions related to the design of the questionnaires were also posed such as:

Question 6.15: What degree of familiarity should the participants have with the maps involving the wayfinding tasks?

Question 6.16: Should the participants be queried on their decision making ability as an individual or should they be asked about their decision making ability as a group?

The novel questionnaires carried out in this thesis answering Question 6 and the related questions have been described in Chapters 5 and 6.

Question 7: How to model the decision making ability of people?

According to Passini [Passini, 1992], wayfinding is “problem solving under uncertainty”. However, this applies only when the person in not familiar with the wayfinding environment. When a person is familiar with the environment, there is less uncertainty involved. However, it still involves the movement of the person along a predetermined route with possible redirection due to environmental conditions such as fire, hazards and congestion. Also the person needs to decide a route to take among a set of alternatives. There are a number of criteria affecting wayfinding decisions such as distance, time, turns, etc, that people apply on a number of alternatives available such as the different paths in an environment. Chapter 7 describes the decision making strategies implemented in the wayfinding model. Another question related to Question 7 is:

Question 7.1: How do people structure decisions?

According to [Arthur and Passini, 1992], wayfinding decisions are hierarchically structured with the most general decisions at the top and more specific decisions at the bottom. For example when planning a road trip from London to Paris, general or long term decisions could be which cities to pass through while specific decisions or medium term decisions could be deciding the route to travel from one city to another. The decision to turn right or left at a particular intersection in order to reach a medium term or long term goal could be an even more specific or a short term decision. Details on the long term, medium term and short term decisions included in the wayfinding model developed for this thesis has been provided in Chapter 7.

Question 7.2: At what locations do people evaluate route choices?

The obvious location at which people evaluate route choices is at their initial start location. In addition route choice could also be re-evaluated at decision points. Any location where there is more than one possible route can be said to be a decision point. Re-evaluation of route choices at each decision point could however lead to agents in the simulation retracing their path or even fluctuating between decision points. More details on the re-evaluation of route choices at decision points have been provided in Chapter 7.

Question 7.3: Under what circumstances do people redirect from their present path?

In addition to re-evaluating route options at decision points, the agents should also be able to redirect en route to the present target node. Under certain circumstances it should be possible for agents to re-evaluate route options en-route and not simply wait for the next decision point. For example if the initial path is congested, blocked or hazardous. Under these circumstances it should be possible for the agents to redirect. The mechanism developed to allow this type of redirection has been described in Chapter 7.

1.3 Research Hypothesis

The main hypothesis of this thesis is that human spatial knowledge and wayfinding behaviours can be represented within evacuation models using graph theory and computational tools. It is expected that an advanced wayfinding model taking into account human wayfinding characteristics will be immensely beneficial to evacuation and circulation modelling tools.

Majority of the existing models simplify the wayfinding process by considering only distance and time to reach the goal or exit. In this thesis other important wayfinding factors such as the number of turns, angle of the turns, decision points, etc are considered along with distance and time.

In the EVACSIM model [Lovas, 1998], the agents move from one decision point to another. When an agent has to choose a decision point among a set of traversable decision points, a route choice model is employed to make this decision. The route choice model assigns a certain probability for each traversable decision point based on some criteria such as always turn left, random choice, local shortest path, global shortest path, frequently used paths, etc. Lovas's route choice model comes closest to the route choice model implemented in this thesis. Both models share the same hypothesis that routes are selected based on the agent's personal attributes and that the agents re-evaluate their options at each decision point. However, the wayfinding model implemented in this thesis involves a lot more attributes than just distance. The decision to go to the next decision point is based on scores assigned to the entire path rather than just the attributes of the next decision point. The route choice model of Lovas's will be discussed in more detail in Chapter 2, Section 2.7.

Another hypothesis of this thesis is that agents have knowledge of at least one route to exit from the building. This hypothesis is based on the assumption that a person inside a building will know at least one route out of the building which is the route that he/she took to enter it. However, it is possible that occupants in large enclosures may get disoriented if they are unfamiliar with a building. The implementation of the wayfinding behaviour of people unfamiliar with the building can be simulated by introducing fuzziness in their route knowledge. For example, agents could be randomly assigned a subset of routes from the set of computed routes.

An important requirement of the wayfinding model developed in this thesis is for it to work in both normal circulation and emergency evacuation situations. The difference between the two modes is that in normal circulation conditions occupants exit the enclosure without any external stimuli whereas in emergency evacuation situations occupants need to exit the enclosure under environmental stimuli such as smoke, fire, etc. Also in emergency evacuation situations dynamic path planning needs to be applied as some routes may get unusable due to the hazards developing. The buildingEXODUS model has the capability to simulate occupant interaction with hazards like smoke and hazardous gases. The wayfinding model developed in this thesis can be used for both circulation and emergency conditions, but the emphasis is more on circulation. Demonstration of the wayfinding model under emergency conditions is left as a future work.

1.4 Major Outcomes

A state-of-the-art review of path planning techniques, factors affecting wayfinding, wayfinding experiments, wayfinding models, wayfinding features implemented in evacuation models has been presented in Chapter 2. The findings of this study form the basis of the wayfinding model developed in this thesis. However, gaps have been identified most of which have been addressed in this thesis however, some are left as future work.

The major outcome of this thesis is the development of an agent based wayfinding model utilising mathematical and computational modelling techniques. This sophisticated wayfinding model adds more credibility to evacuation models such as buildingEXODUS by modelling the spatial knowledge and wayfinding behaviours of people which have been ignored by the majority of the evacuation models existing today. Existing graph search algorithms have been investigated and novel algorithms to solve the K-shortest paths problem have been developed in this thesis (see Chapter 4).

Another major contribution of this thesis is an international survey that was conducted to determine the relative importance of the different wayfinding criteria within buildings. Though similar surveys have been carried out in urban environments, this survey is different as it not only determines the order of importance of the wayfinding criteria but also determines the relative weight of each criterion. This survey is also the first of its kind to be carried out for building environments and from an evacuation modelling perspective. The results of these surveys are more reliable than the existing ones as they are statistically significant and more than one task has been used to determine the importance of the wayfinding criteria (see Chapters 5 and 6).

Normalization and Multi Criteria Decision Analysis theory has been applied to model the decision making capability of people. Normalization here refers to the conversion of dissimilar values such as distance in meters and time in seconds to values between zero and one so that they can be compared. The agents in the simulation are assigned knowledge of the values of the different path attributes such as length of the path, time taken to traverse the path and other attributes as described in Chapter 7. These values are normalised and the weighted sum method is used to determine a path from a list of paths in their choice set (see Chapter 7).

Another contribution of this thesis is the forensic analysis of a real incident to determine the wayfinding difficulties experienced by people in a real emergency evacuation situation. The building design was analysed and alternative designs were suggested that could have improved the evacuation process. This result of this analysis has influenced the wayfinding model and finally it is used as one of the test cases in the final validation study (see Chapters 2 and 8).

1.5 Intended Audience

The research performed in this thesis is multi disciplinary in nature and researchers from various fields would find parts of this thesis interesting. The state-of-the-art review performed in Chapter 2 should interest researchers in the field of path planning, wayfinding and evacuation modelling. The coupled fire and evacuation simulation carried out in Chapter 3 should interest researchers in the general field of fire engineering and science. The sub optimal path planning techniques developed and analysed in Chapter 4 should interest researchers in operations research and path planning fields. The Yen's algorithm [Yen, 1971] which is generally utilised in the field of operations research has been used to compute routes of a non-decreasing magnitude in this thesis. This is a useful feature which can be used in transport modelling to provide alternate routes to people. The questionnaires described in chapters 5 and 6 should interest urban/building planners and human behaviour researchers as they describe the wayfinding nature of people and what routes people are most likely to take during circulation and emergency conditions. Using this information one can identify possible areas of congestion and improve the capacity of popularly used routes. The empirical data provided by the surveys carried out in this thesis will be useful for modelling route choices in urban environments and large scale evacuations as well. The wayfinding model developed in this thesis (see Chapter 7) can be used within any evacuation model. Thus model developers can utilise the concepts and methods introduced in this thesis to design a wayfinding model suiting the specific requirements of their model.

1.6 Structure of the Thesis

Chapter 1 (Introduction): This chapter provides a brief introduction to the subject area of this thesis. The research questions that need to be answered have been outlined. A few features and limitations of the wayfinding model developed in this thesis have been stated briefly. The main research objective and hypothesis of the thesis have also been presented.

Chapter 2 (Literature Review): This chapter provides detailed analysis of some of the questions raised in Chapter 1. A survey of spatial representation techniques, path planning techniques, wayfinding studies and wayfinding features implemented in evacuation models have been described. Gaps in the literature have been identified, most of which have been implemented in this thesis, however some have been left as future work.

Chapter 3 (The Case Study- The Station Nightclub Fire): In this chapter a real life incident was modelled using buildingEXODUS to identify existing wayfinding capabilities of evacuation models, analyse behaviour of people in emergency evacuation situations, identify wayfinding difficulties that manifested during the incident and analyse the building design from a wayfinding perspective.

Chapter 4 (Implementation of Route Choice Set Generation Algorithms): This chapter provides details of the spatial representation and path planning techniques that were developed for the wayfinding model. The emphasis is on path planning techniques as it is vital in designing a very efficient methodology that can generate a large number of routes in reasonable time from complex graphs.

Chapter 5 (Wayfinding Questionnaire 1): The details of the first wayfinding questionnaire are provided in this chapter. This questionnaire was carried out to determine the relative significance of wayfinding criteria such as handedness and length of the first leg of paths. The design of the questionnaire, results and the statistical analysis is presented.

Chapter 6 (Wayfinding Questionnaire 2): The details of the second wayfinding survey are provided in this chapter. The most important criteria was determined from the first questionnaire. The relative significance of a second set of wayfinding criteria namely distance, time, turns, sharp turns and decision points with respect to the most important criteria from the first questionnaire was then determined. The weights for all the wayfinding criteria in both questionnaires were then determined.

Chapter 7 (The Building Wayfinding Model): This chapter describes the development of a coarse node wayfinding model which utilizes the spatial representation and path planning techniques developed in Chapter 4. The wayfinding model also benefits from the data collected in the two surveys described in Chapters 5 and 6. The integration of the wayfinding model developed in this thesis into the existing code of the buildingEXODUS model is one of the most challenging aspects of this thesis details of which have been provided in this chapter. The basic functioning of the wayfinding model within buildingEXODUS is illustrated with the help of three simple test cases involving hypothetical buildings. This chapter also provides details of the more advanced features included in the wayfinding model such as congestion due to redirection and occupant interaction with signage.

Chapter 8 (Conclusions): The conclusions of this research have been provided. The questions posed in Chapter 1 have been answered.

Chapter 9 (Future Work): Future work identified during this research and ideas on how to implement them has been provided in this chapter.

Figure 1-1 shows the organisation of the chapters in this thesis. Chapters 2 and 3 describe the requirements analysis phase which forms the basis of the features included in the wayfinding model. The data collected in Chapters 5 and 6 have been incorporated into the wayfinding model. The core of the mathematical and computational modelling required for the wayfinding model has been described in Chapter 4. The actual wayfinding model developed has been described in Chapter 7. The wayfinding model has been validated by testing it on complex building geometries. Chapters 9 and 10 provide the conclusions and future works for the thesis.

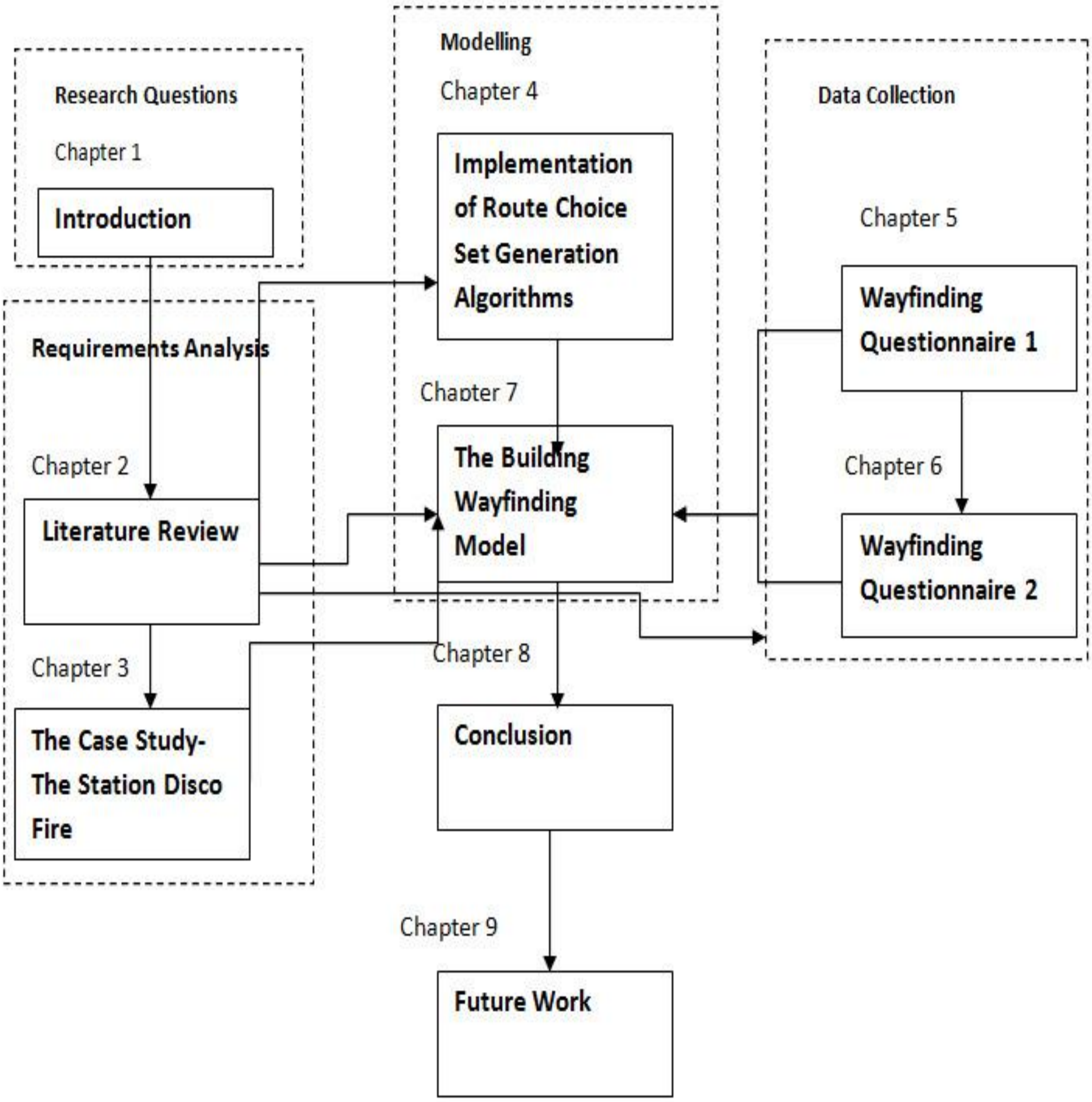


Figure 1-1: The organisation of the chapters in this thesis.

2 Literature Review

2.1 Introduction

In this chapter the background to the process of wayfinding and techniques required to develop a wayfinding model are discussed. An overview of the existing literature on all the major seven questions posed in Chapter 1 has been provided. This chapter starts with a look at wayfinding and the processes involved in wayfinding. Section 2.3 looks at the factors that influence wayfinding which is very important to model the decision making ability of people. Wayfinding experiments conducted in the past are described in Section 2.4. Signage is an important graphical information system aiding wayfinding and thus signage features implemented in evacuation/circulation models is described in Section 2.5. Traditional wayfinding models are looked at in Section 2.6. The wayfinding features implemented in evacuation/circulation models are investigated in Section 2.7.

2.2 What is wayfinding

In the past wayfinding studies have been performed by urban planners such as Lynch [Lynch, 1960], architects/environmental psychologists such as Arthur, Passini [Arthur and Passini., 1992], Downs and Stea [Downs and Stea, 1973], psychologists such as Tolman [Tolman, 1948] and behavioural geographers such as Golledge [Golledge, 1999] and Raubal [Raubal, 2001]. Thus, wayfinding has been studied by psychologists, human behaviour researchers and urban/building planners/architects. Lynch was the first to use the term way-finding in his book "The Image of the City". He emphasised that the mental map, or the image of the environment possessed by an individual is a vital requirement for wayfinding. According to him wayfinding involves the construction of a mental map and its interpretation to guide a person to a desired location. However, Lynch being an urban planner, focussed more on how the elements of an urban environment such as a city influence the mental map that people possess of that city and less on how this information translates to wayfinding behaviour.

Passini acknowledges that the mental map or cognitive map is an important pre-requisite and goes on to discuss how people make use of this knowledge in the act of wayfinding. According to [Passini, 1992], "wayfinding is a continuous spatial problem solving process under uncertainty". Arthur and Passini [Arthur and Passini., 1992] provide a more complete definition of wayfinding as being the process of reaching a destination in a familiar or unfamiliar environment involving three processes: "information processing, decision-making and decision execution". Information processing is the processing of the spatial information; e.g. affordance, signs. Decision making in this context refers to the process by which an individual decides on a particular route. Execution of the decision is the movement of the individual along the route chosen which may involve redirection if a more preferable route is found. However, Arthur and Passini have focussed more on the architectural aspects of wayfinding such as how buildings can be designed to provide better wayfinding features.

Conroy [Conroy, 2003] has analysed various definitions of wayfinding and finally uses the following definition in her thesis – "wayfinding is the act of travelling to a destination by a continuous recursive process of making route-choices whilst evaluating previous spatial decisions against constant cognition of the environment". According to this definition, an important aspect of wayfinding is to have a goal or a destination. Route choices are made repeatedly at decision points and are influenced by previous actions taken by the individual at these locations. Cognition of the environment is another important aspect of wayfinding. An individual may know what to do at a decision point; However, this is of little use if he cannot match the mental picture of the environment with the actual perception of it.

Wayfinding is thus a complex task which can be broken down into a number of activities such as cognitive mapping, decision making, movement or decision execution and re-evaluation or route refinement. These processes define the actual human wayfinding behaviour which provides an important theoretical background for the wayfinding model. Thus, wayfinding can be considered to be a psychological process involving human behaviour. However, the main goal of this thesis is to represent wayfinding within computer models which requires a few more processes such as spatial representation and path planning. These processes will be discussed further in the rest of this section.

2.2.1 Cognitive Mapping

Downs and Stea [Downs and Stea, 1973], define cognitive mapping as the process by which an individual acquires, stores, recalls and decodes spatial information. Tolman [Tolman, 1948] was the first to use the term "cognitive map". He performed a series of experiments involving rats finding food in a maze. A hungry rat was placed in a maze and was allowed to wander until it found the food box. This was repeated in the same maze once in every 24 hours. It was found that the rats took less time and made fewer errors between trails and were finally able to find the food quickly making no errors at all. According to Tolman, this is as a result of a cognitive map like representation of the environment getting established in the rat's brain. Tolman then concluded that humans similarly construct a map like representation of an environment to guide their everyday movements.

According to Tolman [Tolman, 1938], the factors that determine the action taken at a choice point not only depends on the presentation of the choice point but also depends on the subsequent goals and consequences of turning left or right at the choice points. The decision taken at such a point would depend on the previous actions taken by the rat at the choice point in the previous trails and the results of each action.

According to the Landmark Route Survey (LRS) model proposed by Seigel and White [Seigel and White, 1975], people first extract landmarks from the environment. The landmarks in a building could be internal exits, external exits, rooms, escalators, stairs, lifts etc. This forms the landmark level knowledge. Route knowledge then develops as landmarks are connected by routes. At the route level knowledge, the person develops a mental map containing the landmarks and the connectivity between them. Survey or configurational knowledge is said to have been attained when the map is more complete and the person can find a path from any point in a building to any other point even though he/she may not have traversed that path. In this thesis a graph containing the different building elements and the connectivity between them is used to represent the cognitive map of people (see Chapter 4, Section 4.2.3). In multi-agent simulations, it would be computationally expensive to design each individual possessing a cognitive map and applying search algorithms to find a route from one point to another. Hence in this thesis, the computational load is simplified by running the search algorithms and assigning route knowledge to the agents in the simulation before the start of the simulation.

According to Kuipers [Kuipers, 2001], the human cognitive map can be compared to a "skeleton" consisting of important landmarks and paths connecting these landmarks. Expert wayfinders are capable of using this "skeleton" to aid the process of wayfinding. They find the closest point on the "skeleton" from their initial location and trace a path to the destination.

A wayfinding experiment conducted on 24 participants in an unfamiliar building [Murakoshi and Kawai, 2000] consisted of both wayfinding tasks and tasks to test their cognitive mapping ability. Participants who did not have a good cognitive map (i.e. with incomplete cognitive maps) of the building performed on par (with respect to wayfinding) with the participants who did have a good cognitive map. This was due to the participants mainly resorting to route scenes, schema like knowledge, environmental affordances and information seeking heuristics to find their way through the artificial environment.

It was first suggested by Darwin, that it may be possible for animals to navigate by a system of dead reckoning or path integration. “Path integration is the capability of an animal to continuously compute its present location from its past trajectory and thus return to the starting point by choosing a direct route instead of retracing its outbound path” [Muller and Wehner, 1988]. Golledge [Golledge, 1999] has provided evidence that humans, apes, some birds and some mammals use a map like representation to aid their wayfinding process while insects, some other mammals and birds make use of dead reckoning or path integration to find their way.

2.2.2 Spatial Representation

In mathematics and computer science graph models are used to represent the human spatial environment [Franz, et al., 2005]. A graph consists of a set of vertices (nodes) and a set of edges (arcs) connecting the vertices. Mathematically a graph is defined as

$G = (V, E)$ [West, 2001] [Gross and Yellen, 2006]

Where G is the graph,

V is the set of vertices or nodes in the graph and

E is the set of edges connecting the vertices

Spatial elements such as rooms, corridors, doors can be represented as nodes and the arcs connecting them denote the spatial connectivity between these elements. The cognitive map of the agents can thus be represented by graphs and graph search algorithms can be applied to determine routes. The nodes can have attributes such as location and area. The arcs can also have attributes such as length and capacity. These attributes can be used to guide the search algorithms and also to navigate the agents in the space. Spatial representation is thus vital for the path planning algorithms which are discussed in Section 2.2.3.

An isovist or viewshed [Hillier and Hanson, 1984] [Benedikt, 1979], is the visible area from a location in space. The isovist approach of spatial representation thus consists of a set of points called isovists from which visibility polygons are generated (see Figure 2-1). The corners of the polygon form the nodes of the graph and the line segments of the polygon forms the edges of the graph. A main disadvantage of this approach is the choice of the location of the isovists and deciding which edges need to be chosen.

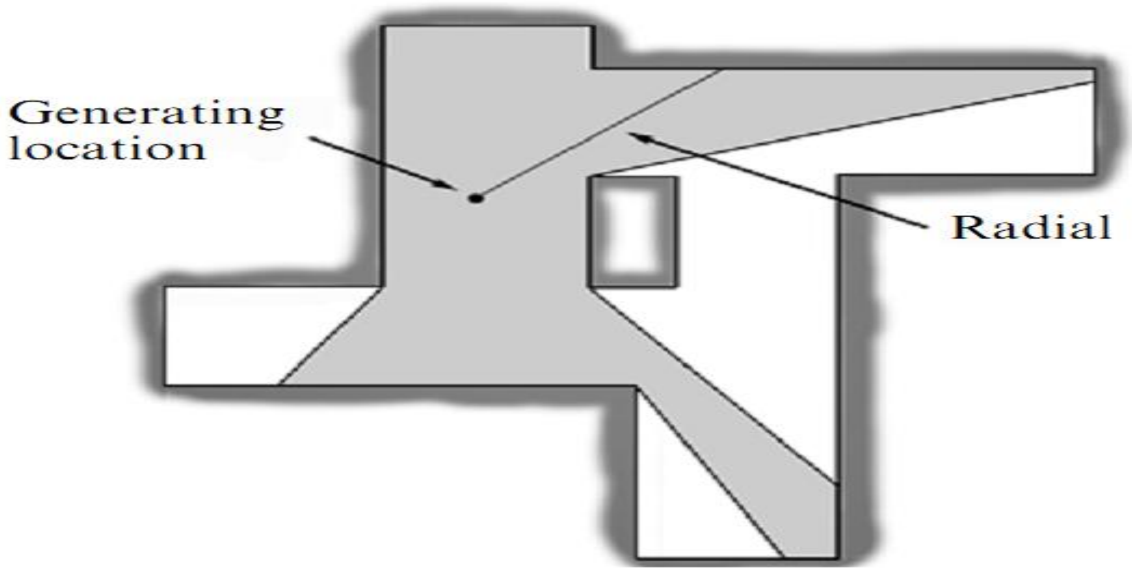


Figure 2-1: An Isovist polygon showing the visible region from a generating location [Turner, et al., 2001]

Visibility graphs are popularly used in robotics for effective collision avoidance [Tomas and Wesley, 1979]. The edges of polygonal obstacles are the nodes of the graphs and each node is connected to other nodes in the graph if there is no obstacle in between. A more efficient representation of space has been proposed by Chooramun, et al [Chooramun, et al., 2010]. where instead of placing a node at each corner of the obstacle, nodes are only placed at locations where the internal angles are concave thus reducing the number of nodes and hence the complexity of the graph. These graphs are called navigational graphs and are significantly more efficient than visibility graphs as they decrease wall detection tests by agents.

According to Werner, et al [Werner, et al., 2000], navigational knowledge can be modelled by representing decision points as nodes and the routes or connections between these nodes as edges of the graph. The graph thus formed is called a route graph. However, another methodology is required to identify the decisions points and the connections between them. Techniques such as Voronoi diagrams and Delaunay triangulations are popularly used to create route graphs [Wallgrun, 2009].

Figure 2-2a shows a sample space containing the points S1 to S10. These are usually called Voronoi sites which could represent the obstacles in free space. Figure 2-2b shows the Voronoi graph of the sample space. The sample space has been divided into regions called Voronoi cells (C1 – C10) surrounding each site. Each cell consists of those points in the sample space that are closest to the respective site. For example all points in the cell C1 are closest to site S1 than to any other site (S2-S10). The Voronoi edges are formed by the points that are equidistant to two are more sites. For example the Voronoi edge between C1 and C2 are formed by the points that are equidistant to sites S1 and S2. The Voronoi vertices V1 to V10 are formed at the intersection of the Voronoi edges.

Figure 2-2c shows the Delaunay triangulation of the same sample space. The Delaunay triangulation is a triangulation of the convex hull [Cormen, et al., 2009] of the sites. A triangle is drawn connecting any three points or sites and if the circum-circle of this triangle does not contain any other site then the triangle is retained. All sets of three points in the convex hull are similarly tested.

Voronoi graphs and Delaunay triangulations are commonly used to represent the motion space for robots and plan robot motion within the space. They are very efficient for planning paths without obstacles. However, the wayfinding model in this thesis requires a simpler graph to determine the mid-term and long term goals rather than the short term goals (see chapter 1, Question 7.1). The actual navigation of the agents and collision detection are short term goals which can be performed by the fine node buildingEXODUS model.

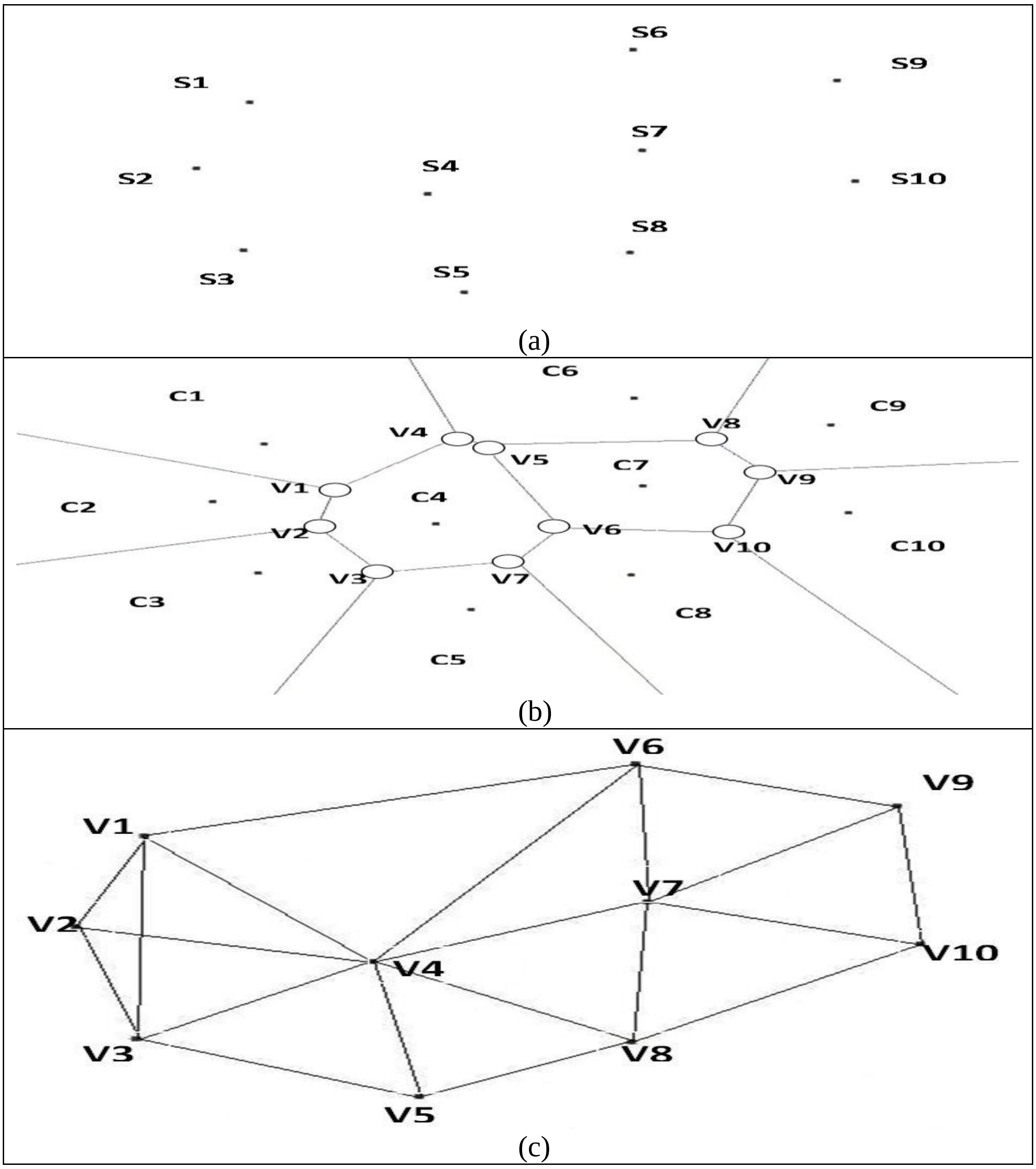


Figure 2-2: (a) Shows a sample space with sites or obstacles; (b) shows the Voronoi graph of the sample space and (c) shows the Delaunay triangulation of the sample space.

2.2.2.1 Spatial representation in evacuation/circulation models

Evacuation models generally use one of the following three models to represent space: Fine node model, coarse node model and continuous region model. In addition to representing space these models are also used for the navigation of the agents.

- **Fine node model:** This model follows the occupancy grid technique from artificial intelligence [Franz, et al., 2005]. The entire floor space is filled with a number of cells having a specific area like 0.5 m^2. This results in a dense graph where each cell is connected to a maximum of eight neighbouring cells. The occupants are usually assigned a walking speed which is independent of the other agents in the geometry. buildingEXODUS, STEPS and EVACSIM are some examples of fine node models.

- **Coarse node model: -** The floor is divided into regions like rooms, stairs, escalators, etc and the occupants move from one region to another. Occupants travel speed depends on the density of the population in the region. EVACNET, SIMULEX and WAYOUT are some examples of coarse node models.

- **Continuous region model: -** This is the most realistic and most computationally expensive method of representing space. The entire floor is modelled as a continuous region. Simulex, ASERI and Legion are some examples of continuous region models.

A major difference between the fine node models and coarse node models is that the former treats the agents as individuals and the latter treats the agents as a group. For example, in fine node models each agent has his/her own attributes such as speed whereas in the coarse node models a group of agents in a particular compartment have a certain speed which depends on the density (number of agents) in the compartment. There are advantages and disadvantages in both fine and coarse node methodologies to represent space in evacuation/circulation models. In the fine node models it is possible to view the agents during the simulation and introduce specific behaviours such as overtaking; However, the speed of the agents cannot be controlled to take into account the density of the compartment. Coarse node models are useful in that the occupancy level / population density of a region can be taken into account, but it is not possible to model individual differences – in terms of individual attributes or individual behaviours. Continuous region models are more accurate in terms of agent navigation since the agents instead of jumping from node to node as in the fine node model, move through a continuous space. However, a major disadvantage of the continuous region models is the poor computational performance.

Considering that each method of representing space in evacuation/circulation models has some advantages and disadvantages, recently there has been a combination of the two or even all three methods to represent space. A hybrid spatial discretisation methodology has been proposed by Chooramun, et al [Chooramun, et al., 2010] which combines the advantages of all three methodologies. Majority of the space is represented in fine node while certain regions requiring greater accuracy are modelled as continuous regions and certain regions not requiring positional accuracy are modelled as coarse regions.

The method used to represent space in evacuation/circulation models determines the route choices of agents in the model. For example, in a coarse node model only long term and medium term decisions (see Chapter 1, Question 7.1) can be implemented. Short term decisions such as overtaking cannot be implemented in coarse node models.

The wayfinding model in this thesis used a coarse node representation of space. However, this coarse node representation is only utilised for the medium term and long term decisions of the agents. The fine node buildingEXODUS model is used for the short term decisions such as obstacle avoidance, overtaking, etc. Therefore, there exists a coupling between the coarse node wayfinding model and the fine node buildingEXODUS model (see Chapter 7, Section 7.3). Though the wayfinding model developed in this thesis has been implemented for the fine node buildingEXODUS model, it can also be used in continuous models as well. This is due to the wayfinding model being responsible for assigning routes to the agents alone and does not deal with the actual movement of the agent along the routes.

2.2.3 Path Planning Algorithms

An important requirement of the wayfinding model is the provision of routes to the agents in the simulation. There are numerous shortest path algorithms but comparatively fewer algorithms that can provide a choice set of routes like the K-shortest paths method. Majority of the existing evacuation/circulation models use a shortest path algorithm such as the A* [Hart, et al., 1968] or the Dijkstra algorithm [Dijkstra, 1959].

2.2.3.1 Shortest path algorithms

Shortest path algorithms find the shortest or optimal path between two nodes. Optimal here may refer to distance or other factors such as time. Most of the existing evacuation/circulation models assign the shortest paths to the agents in the simulation.

2.2.3.1.1 Uninformed Search

Uninformed search algorithms are the equivalent of a blind search algorithm where the search proceeds without any heuristics to guide the search process. However, there is a certain rule that is applied to predict the next node to examine.

The breadth-first search is an uninformed search algorithm where the nodes at a certain level are expanded first. The head nodes at level 0 are first expanded. The child nodes of the head nodes at level 1 are then expanded and the search proceeds likewise till the goal node is reached. Yuen and Feng [Yuen and Feng, 1994] have applied the breadth first search algorithm to find a solution to the Eight Queens puzzle which deals with the placement of 8 queens on a 8X8 chessboard such that no queen can capture any other queen using the standard chess queen's moves.

The time and space complexity of the breadth first search is $O(b^d)$, where b is the number of successors for each node and d is the depth of the goal node. Hence, the breadth first search is not a very efficient one in terms of both memory and time. In the literature this problem has been solved by using distributed and parallel computing. For example Yoo, et al [Yoo, et al., 2005] have applied the breadth first search on graphs having three billion nodes and 30 billion arcs using distributed and parallel computing.

In the depth first search, the deepest node in the current branch is explored first. If the deepest node has no children, then the search backtracks expanding the last unexplored node along the same branch. This backtracking continues until the root node of the branch is reached. Since in the worst case scenario all nodes have to be examined the time and space complexity of the depth first search is the same as the breadth first search. But the memory requirements of the depth first search can be improved by deleting a node once all its descendents have been expanded. In this case the space complexity of depth first search will be bm+1 nodes where b is the branching factor and m is the maximum depth of the tree [Russel & Norvig, 2002].

2.2.3.1.2 Informed Search Algorithms

Informed search algorithms make use of heuristics to make the search process more efficient. A better guided search algorithm expands fewer nodes and takes less time to find the shortest or optimal path.

The A* algorithm is one of the best graph search algorithms in terms of space and time complexities [Sathyaraj, et al., 2008]. The A* algorithm evaluates nodes by the f-cost which is the sum of g-cost (cost to reach a node from the start node) and h-cost (cost to reach the goal node). The A* algorithm is optimal if the h-cost heuristic never overestimates the goal cost [Hart, et al., 1968] [Dechter and Pearl, 1985]. However, to make the search quicker the h-cost heuristic can be an underestimate of the actual goal cost in which case the A* algorithm is not guaranteed to find the optimal path. The A* algorithm maintains an open list and a closed list. The candidate nodes to explore are placed in the open list. While it is not necessary to keep the open list sorted, the lowest f-cost node from the open list is chosen to be expanded next. The expanded nodes whose scores are finalised are placed in the closed list. When the goal node is in the closed list a path has been found.

The A* algorithm is used in robot path planning and in games [Botea, et al., 2004] [Dechter & Pearl, 1985]. There are many variations of the A* algorithm like the D* algorithm [Stentz, 1994], Iterative Deepening A* algorithm and Lifelong planning A* algorithm. Veeraswamy and Amavasai [Veeraswamy and Amavasai, 2006] introduced an additional heuristic to the A* algorithm which was found to improve the efficiency of the A* algorithm. A similar heuristic will be used in this thesis, details of which have been provided in Chapter 4, Section 4.4.1.1.

The Dijkstra algorithm [Dijkstra, 1959] is similar to the A* algorithm, the difference being that only the g-cost is used as the heuristic function. Dijkstra algorithm expands more nodes than the A* algorithm as it does not use the h-cost heuristic to guide the search process. However, there are situations in which the Dijkstra algorithm is preferred over the A* algorithm. For example if there are multiple target locations and it is not known which is closer then it is better to use the Dijkstra algorithm. Another advantage of the Dijkstra algorithm is that it finds the shortest distance to every node in the graph from the source node. The Bellman-Ford [Bellman, 1958] and Floyd-Warshall algorithms [Floyd, 1962] make use of similar concepts but are better at finding paths in graphs with negative costs.

2.2.3.2 The K-shortest paths method

Uninformed search algorithms are very simplistic using brute force to find the solution. Informed search algorithms are more sophisticated and efficient as they use heuristics to direct the search process. Unlike the shortest paths algorithms, the K-shortest path family

[Chabini and Ganugapati, 2001] [Martins and Pascoal., 2003] [Park and Rilett, 1997] require finding the shortest path, next shortest path and so on up to K shortest paths where K is a positive integer.

Most evacuation/circulation models utilise the shortest path algorithms assuming that people only choose the shortest paths. These models would produce highly unrealistic results when there is more than one path from source to destination since all agents would be forced to take the shortest path regardless of the congestion. Hence it is vital to provide not just the shortest path but a choice set of paths to the agents in the simulation (see Chapter 7, Section 7.2.2).

The K-shortest paths problem deals with finding the K shortest paths between two nodes in a graph. This is a classical network problem and many [Bock, et al., 1957] [Pollack, 1961] [Clarke, et al., 1963] have tried to find a solution for it. However, Yen [Yen, 1971] provided a classical solution for this problem which is more efficient than the others. Yen's algorithm starts by finding the shortest path between the source and destination by using one of the shortest path algorithms such as the Dijkstra algorithm. Yen's algorithm assumes that the other shortest paths are a deviation from this shortest path. The next shortest path is determined by finding the shortest paths from the set of deviations of the previous shortest path. The algorithm continues until K such shortest paths are found. The original K-shortest paths problem determines all possible paths including loops as well. However, Yen's algorithm falls solves the "K-shortest paths with constraints" problem. The constraint here is that of finding loop less paths alone. The K-dissimilar paths method [Park and Rilett, 1997] finds K shortest paths with each path differing from the least cost path by a certain number of nodes, arcs or cost.

The K-shortest loop less paths problem can be said to be more suitable for the wayfinding model developed in thesis than the original K-shortest paths problem allowing loops. It is assumed that people evacuating from a building will not take a path with a loop unless they had a specific reason to. For example, a person evacuating a building through an exit will not unnecessarily meander to a tea point which is not along his chosen path unless he wanted to have a cup of tea along the way! However, if there was an alternate route which was slightly longer but less congested, he might consider choosing the quicker route. The K-dissimilar paths algorithm [Park and Rilett, 1997] may be useful in networks where there are many paths with little difference in the path cost. However, an alternate methodology has been used in this thesis to ensure that similar routes are not found (see Chapter 4, Section 4.3.3). Therefore the K-shortest loopless paths method may be considered to be the best to provide a choice set of routes to the agents in the evacuation/circulation model. Yen's algorithm to solve the K-shortest loop less problem can be implemented in $O(Kn(m+n\log n))$ worst case time using modern data structures [Martins and Pascoal., 2003].

The disadvantage of the Yen's algorithm is that it is designed for finding paths between a pair of nodes. To find paths between another pair of nodes, it is required to run the Yen's algorithm again. Consider a complex building consisting of hundred rooms with four exits. The Yen's algorithm would have to be run 400 times (100 * 4). While the Yen's algorithm is the best available solution (in the literature) for generating route choice sets for the wayfinding model, it may not be the ideal solution for large buildings in terms of the time taken. Therefore, novel graph search algorithms have been developed in this thesis which generates paths from all nodes in a graph to all exits (see Chapter 4). The performance of the algorithms developed in this thesis will then be compared with that of the Yen's algorithm.

2.2.4 Decision Making

Decision making is a very important aspect of wayfinding. In uncertain conditions people have to decide what route to take to reach their destination. They may sequentially make decisions at each intersection having more than one possible route. Decision making is also involved under familiar conditions as well. For example a person may need to decide on a choice of route from a set of available routes. In this case a decision may be taken at the start and the person may just follow this route. He/she may change the original decision if they encounter some obstruction or they discover a more favourable route along the way.

According to Arthur and Passini [Arthur and Passini., 1992], there are two main decision models: the optimizing model and the satisficing model. In the optimising model, the person considers all possible options and chooses an optimal solution. In the satisficing model, the person chooses an acceptable solution without seeking the optimal solution. The authors go on to say that in life some people will follow the satisficing model whereas others will follow the optimising model.

The decision making model implemented in this thesis can be said to be more of an optimizing model than a satisficing model as the agents consider all routes in their knowledge in order to decide on a particular route. The satisficing model could be implemented by introducing fuzziness in the decision making process which is left as a future work. The main focus of this thesis is on the decision making process of people when they are familiar with the building and have a choice set of routes to choose from. Each route has its attributes such as distance, time, number of turns, etc. Each agent has his own attributes such as his preference for the least distance path, least time path, least number of turns path, etc. This is a classical problem of Multi Criteria Decision Analysis (MCDA). There exist many methods [Triantaphyllou, E., 2002] to solve this problem. The Weighted Sum Model (WSM) has been chosen as the best suited model for representing the decision making behaviour of people in the wayfinding model. More details of this implementation are provided in Chapter 7, Section 7.2.2.1.7.

2.2.5 Movement or Route Execution

Evacuation models simulate the movement of the agents in two different ways macroscopic and microscopic. Macroscopic models treat the occupants in a simulation as a homogenous group with common attributes. The agents in the simulation could be assigned travel speeds which are based on the density of the agents in the region. Microscopic models treat the occupants as individuals interacting with the rest of the population. Kneidl, et al [Kneidl, et al., 2010] have coupled microscopic and macroscopic techniques creating a control cycle. At each time step the output from one model is used to feed the input for the other. Network flow theory and optimisation principles are used to model the movement of the agents in the simulation. In this thesis, there is a similar coupling of a coarse node and fine node models. The wayfinding model is a coarse node model consisting of only important nodes such as room nodes and exit nodes, whereas buildingEXODUS is a fine node model. The routes taken by the agents in the fine node buildingEXODUS is determined by the coarse node wayfinding model. More detail on this coupling is provided in Chapter 7, Section 7.3.

2.2.6 Route Refinement

Route refinement occurs when a person chooses an initial route based on limited knowledge (i.e. they are not aware of the full set of routes) and during the execution or movement along that route, decides to follow an alternative route when presented with new information. Route refinement may occur due to:

- Signage: - A person traversing an initial route may see an exit sign and may choose to follow the path indicated by the exit sign rather than follow their initial path.

- Affordance: - Affordance is a theory that is used to explain "how individuals perceive the things that they see" [Gibson, 1978]. A person traversing an initial route may see an emergency exit door and may decide to use it.

- Social Influence: - A person traversing an initial route may come across a friend or communicate with a person of authority and may decide to take an alternate route.

- Congestion: - If the initial route is congested, the person may wish to choose an alternative less congested route.

- Hazards: - A person exiting from a building that is on fire may choose an alternative route if they perceive the initial route to be more hazardous.

2.3 Factors Influencing Wayfinding

The previous section discussed wayfinding and explained the processes involved in the act of wayfinding. Section 2.2.3 discussed techniques to provide a choice set of routes for the agents and Section 2.2.4 discussed the decision making ability of people. However, given a choice set of routes it is important to determine the factors that influence wayfinding or the route choice (decisions) of people. Most of the studies analysing factors that influence wayfinding have been in the urban field [Golledge, 1995a] [Golledge, 1995b] [Conroy, 2001] [Conroy, 2003]. There are relatively fewer wayfinding studies in the built environment [Scharine and McBeath, 2002] [Xie, et al., 2009]. Most of the evacuation/circulation models assign the shortest paths to the agents and concentrate more on exit selection methods. Therefore, the only wayfinding factors current evacuation/circulation models incorporate are distance and time. However, for more realistic wayfinding behaviour additional factors need to be included.

According to Golledge the most important urban wayfinding criteria listed in the order of importance are: shortest distance, least time, fewest turns, most scenic/aesthetic path, first noticed, longest leg first, many curves, many turns, different from previous and shortest leg first. Among these factors the following are chosen for the building wayfinding model implemented in this thesis: shortest distance, least time, fewest turns, longest leg first and shortest leg first. The most scenic/aesthetic route is not considered as in buildings there will less scenic/aesthetic characteristics and the routes available would typically be more uniform. The first noticed route according to Golledge is the route that people initially develop a liking to for some reason which is usually a route leading in the general direction of the exit. This factor has not been considered as the definition of 'first noticed' route is not very clear and more research has to be done in order to determine what exactly is the 'first noticed' route. The 'different from previous' route refers to the attribute of people where they like to take a different route from the usually or previously chosen one. For example people may want to choose a different route from the one they usually take in order to make it more interesting. This factor has not been considered in this research as it is not considered to be a very important factor for evacuation/circulation modelling. The 'many turns' factor has also not been considered as it is the exact opposite of the 'fewest turns' factor.

According to Conroy [Conroy, 2001] [Conroy, 2003] people prefer to take the path that has the least deviation from a straight line as long as that path leads them to the destination. For example, if at an intersection there are three paths heading at 30^0, 90^0 and 100^0 people would prefer to take the path with 100^0 as long as this path leads them in the direction of the exit. In other words people prefer to take a path as close to a straight line as possible as long as it leads them to the final destination. Hence in this research an additional wayfinding criteria being tested is the angle of a path. Based on Conroy's study, it is assumed that people will prefer to take a path whose angle averages as close to 180^0 as possible.

According to Scharine and McBeath [Scharine and McBeath, 2002], handedness and driving side of people has an influence in the paths taken by people. Though they have made their conclusions based on a very small sample, they conclude that handedness and driving side have a strong influence with the former having more influence in the path choice of people. They also state that handedness and driving side have an additive influence. For example, a right handed person driving on the right side of the road would be more likely to take a right handed path than a right handed person driving on the left side of the road.

Though Scharine and McBeath have concluded that handedness of paths has a considerable effect on wayfinding decisions, urban wayfinding researchers such as Golledge and Conroy have ignored handedness of the paths as a factor. In fact Conroy [Conroy, 2001] and Bailenson [Bailenson, et al., 2000] have concluded through an analysis of their experiment results that handedness of paths is not an influential factor. In this thesis the genetic (handedness) and cultural (side of the road they drive) components have been tested. The first of the two surveys carried out in this thesis mainly checks if the handedness and the driving side of the people have any effect in the choice of right/left handed paths.

Raubal [Raubal, 1997] [Raubal, 2001] has developed a choice and clue model to compare the complexity of buildings and has demonstrated this methodology through the comparison of the Vienna International Airport in Austria and the Frankfurt International Airport in Germany. According to Raubal the complexity of a building is a measure of the number of decision points in the building, the number of choices at each decision point and the clues available at those decision points [Raubal and Egenhofer, 1998] [Raubal, et al., 1997] [Raubal and Worboys, 1999]. While it is good to have less decision points in a building, the complexity of route choice at decision points can be simplified by providing appropriate signage. Best [Best, 1970] has shown that people perceive routes with many decision points to be more complex than routes with less decision points. People generally have a tendency to minimise complexity when it comes to wayfinding. Therefore, 'least decision points' is also considered as a wayfinding factor for the building wayfinding model.

In summary, this review on urban wayfinding and human factors literature has identified a number of factors that might influence route selection. The research has suggested that these factors have a greater/lesser impact on this process. However, there are more factors that influence wayfinding behaviour such as:

- Enclosure familiarity
- Social interaction
- Environmental information
- Spatial orientation
- Exit selection

Each of these factors will be described in more detail in the remainder of this section.

2.3.1 Enclosure familiarity

Enclosure familiarity refers to the cognitive maps people have of their environment. A person may have a perfect (or configurational) level knowledge [Siegel and White, 1975] of the building or may have a partial knowledge consisting of route scenes [Murakoshi and Kawai, 2000]. The familiarity a person has with a building will influence the routes he takes and will also affect his confidence. The more a person is familiar with the building the more confident he will be on his selection of routes. A person who is unfamiliar with a building may be more likely to follow other people. Existing evacuation models assume all agents have knowledge of at least one path to the exit. However, it is possible that due to smoke people can become completely disoriented and move blindly or randomly as they (plausibly) did during *The Station nightclu*b incident (see Chapter 3, Section 3.2). Modelling the wayfinding behaviour of people who are partially or completely unfamiliar within a building may be considered in future. Complexity of space is an important factor which will have an impact on the enclosure familiarity of people [Lynch, 1960].

2.3.2 Social interaction

In buildings and urban environments social interaction such as asking other people for directions or following the crowd is an influential factor deciding route choices. This social or crowd effect can be said to be more important in buildings than in urban environments as buildings are more likely to be congested than urban environments. People could be exiting as a group where there may be one person making the key route choices and others follow him/her. This is a complex factor affecting building wayfinding and may be considered in future.

2.3.3 Environmental information

Environmental information such as signs, affordances play an important role in the route choices of people. In this thesis one of these factors, signs, has been considered. The cognitive maps of the agents only consist of the routes leading to the exits the agents have knowledge of. When the agent notices a sign to a previously unknown exit and hence learns its existence, their cognitive map will be updated to include the routes to this exit as well. Environmental information may also include hazards such as smoke and hazardous gases. These factors may be considered in future.

2.3.4 Spatial orientation

Spatial orientation refers to the ability of an individual to establish a frame of reference in space [Passini, 1992]. People who have a general directional knowledge of their target move or choose routes leading to the target. In the absence of an incomplete cognitive map, people make use of spatial orientation, environmental affordances and other heuristics to find their target or exit [Murakoshi and Kawai, 2000].

2.3.5 Exit selection

In buildings, exit selection plays an important role in the route choices of people. People prefer to use familiar exits over unfamiliar or nonemergency exits over emergency exits. Existing evacuation models use formulas taking into account distance and time to assign exits to agents (see Section 2.7). The wayfinding model in this thesis differs by modelling route choices of people rather than exit choices. According to Arthur and Passini [Arthur and Passini, 1992] wayfinding is a hierarchical process where people first choose their destination and then choose the routes to that destination. The implementation of such a hierarchical wayfinding model would be very useful to model large multi enclosure buildings which may be considered in future.

A number of factors influencing human wayfinding have been identified and discussed in this section. The main goal of this thesis is to model the cognitive aspects of the wayfinding behaviour of people who are completely familiar with a building. Therefore, the factors that are considered for further research in this thesis are:

- Shortest distance
- Least time
- Fewest turns
- Longest leg first
- Shortest leg first
- Least angle path
- Least decision points path
- Right handed path and
- Left handed path

These factors will be further discussed in Chapter 5, 6 and 7. Though most of these wayfinding criteria have been selected from past studies, these studies have been based on very small samples and have been designed from an urban wayfinding perspective. Also, since factors from different studies have been selected it is important to determine the relative importance of the chosen wayfinding factors with respect to each other. Two surveys have thus been designed and performed as part of this thesis. These have been designed to test the importance of the wayfinding factors. The importance or weight of the wayfinding factors determined from the surveys will then be introduced as personal wayfinding attributes of the agents in the wayfinding model.

2.4 Wayfinding Experiments

Golledge [Golledge, 1995a] [Golledge, 1995b] performed a series of wayfinding studies for The University of California Transportation Centre. Golledge's work forms a basis for the wayfinding experiments carried out in this thesis. In [Golledge, 1995a], 32 subjects were shown maps containing routes on a spreadsheet. According to this study the criteria affecting wayfinding in order of preference with the first being the most important are: "shortest distance, least time, fewest turns, most scenic/aesthetic, first noticed, longest leg first, many curves, many turns, route different from previous one and shortest leg first".

Some of the drawbacks of Golledge's study are:

1) Least time route was perceived to be the diagonal route which is of the same length as the shortest distance route. Golledge assumed that people will perceive a diagonal route to be least effort or less time route which may not be correct.

2) The importance of the wayfinding criteria was determined based on rating tasks alone and were not based on the wayfinding tasks.

3) The participants had to choose between more than two paths from origin to destination.

In the surveys carried out in this thesis care has been taken to stave off these drawbacks. The least time path is modelled as a path with more doors which is a clear indication of taking more time. A rating task similar to the one carried out by Golledge [Golledge, 1999] is also included. However, the importance of the wayfinding tasks is determined by a combination of wayfinding tasks and rating tasks as well. All wayfinding tasks in this thesis consist of only two possible paths to the exit which is simpler as only two wayfinding factors are tested at a time.

Conroy has studied route choice decisions made at consecutive road junctions over the duration of a single journey [Conroy, 2003]. The study involved a virtual urban environment containing a variety of urban block shapes and involved 30 participants, 20 males and 10 females with a mean age of 28. The geometry was the equivalent of 650 m x 650 m and would take approximately 8.5 min to cross diagonally walking at an average pace. Participants spent on average 10 minutes immersed in the virtual world. The participants were instructed to enter the geometry at the top corner and make their way to the diagonally opposite bottom corner. From an analysis of the paths chosen, Conroy concludes that route selection is a competition between the desire to select the simplest route (i.e. straightest route to the destination) and the desire to maintain a heading closest to the direction of the destination from the origin (most direct route). Conroy goes on to suggest that the finding of Golledge in which people prefer to select the longest leg first (i.e. starting the journey by selecting the route option that has the longest line of sight) over the shortest leg first, is a result of the most direct route winning over the simplest route. The surveys carried out in this thesis tests this hypothesis by comparing longest leg first paths, shortest leg first paths and the most direct path amongst other factors.

A drawback of Conroy's experiment is that the destination was not clearly defined. The participants all started from the same location and were instructed to walk the opposite corner by the most direct route possible. The 'opposite corner' is not a specific location and from the routes taken by the participants it was observed that different participants had different final locations which sometimes were not very close to the opposite corner. Another drawback is that the participants were specifically asked to take the most direct route. It is therefore no surprise that the results show the participants taking the most direct path! In the surveys carried out for this thesis the start and finish locations are clearly indicated. Also very minimal information is provided to the participants so as to not influence their route choice decision.

The study of Scharine and McBeath [Scharine and McBeath, 2002] investigated the choice people make in taking a left or right turn when all other conditions were equal. Their experiment involved 112 participants who were library patrons, 82 from the USA and 30 from the UK. The sample consisted of 87% right-handed people. Participants were asked to retrieve an object which was hidden at the end of an aisle formed by a shelf of books. The participants had to walk down a 10 m long corridor formed by book shelves and then turn either into the left aisle or the right aisle to retrieve the object. They found that 66% of the right-handed sample preferred to turn right while only 33.3% of the left-handed sample preferred to turn right. This indicates that the handedness of the participant is a strong indicator of the direction in which the person is likely to turn. In addition, 67.1% of the sample who drive on the right-side preferred to turn right while 46.7% of the sample who drive on the left-side prefer to turn right. This indicates that while the side of the road that you drive on has an influence, it is not as strong as the handedness. Furthermore, it appears that handedness and driving side are additive factors, with approximately 70% of right-handed, right-side driving sample preferring to turn right, while approximately 48% of the right-handed, left-driving sample prefer to turn right. The sample size of left-side drivers was considered too small to draw definitive conclusions. This study would suggest that there is both a genetic component to wayfinding (handedness) and a cultural component (driving side). These factors have also been tested with a larger sample size in this research.

Christenfeld [Christenfeld, 1995] carried out 6 experiments involving human selection of items from a list of identical options. The first three experiments involved selecting a product from a supermarket shelf, deciding which toilet cubicle to use and selecting one circle from a list of circles drawn on paper. In these studies it was found that people had a tendency to choose the object in the middle than the objects at the end. For e.g. people in the supermarket tend to take the product from the centre row when the same product is in three or more rows; people choosing to use the middle toilet cubicle more than the ones at the ends; people choosing the middle circle in the case of the questionnaires.

Christenfeld then carried out 3 experiments which were route choice experiments. Unlike the previous three experiments the route choice experiments produced completely different trends. In the first route choice experiment, people were given a maze and were asked to choose one of the possible routes from X to Y. A simplified version of the maze used by Christenfeld is shown in Figure 2-3. All the three paths A, B and C are similar in terms of distance and number of turns. The only difference is the time at which people decide to make the inevitable turn to reach Y. Taking path A would imply that people prefer to take a turn at the earliest possible opportunity. Taking path B would imply that they prefer to take a turn at a slightly later opportunity. Taking path C would imply that they prefer to take the turn at the last possible opportunity. Later, Christenfeld also carried out variations of this experiment where the number of options or route choices was varied from 3 to 10. In all the mazes people preferred to take the end routes (A or C) than the ones in the middle. So people when they know that they need to turn, they either turn immediately or wait till the last possible turning point and avoid the routes in the middle.

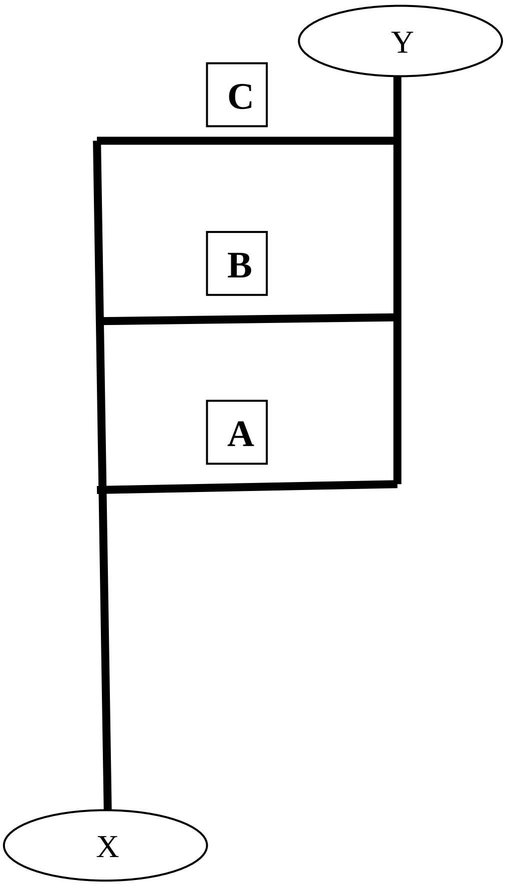


Figure 2-3: Wayfinding experiment used by Christenfeld

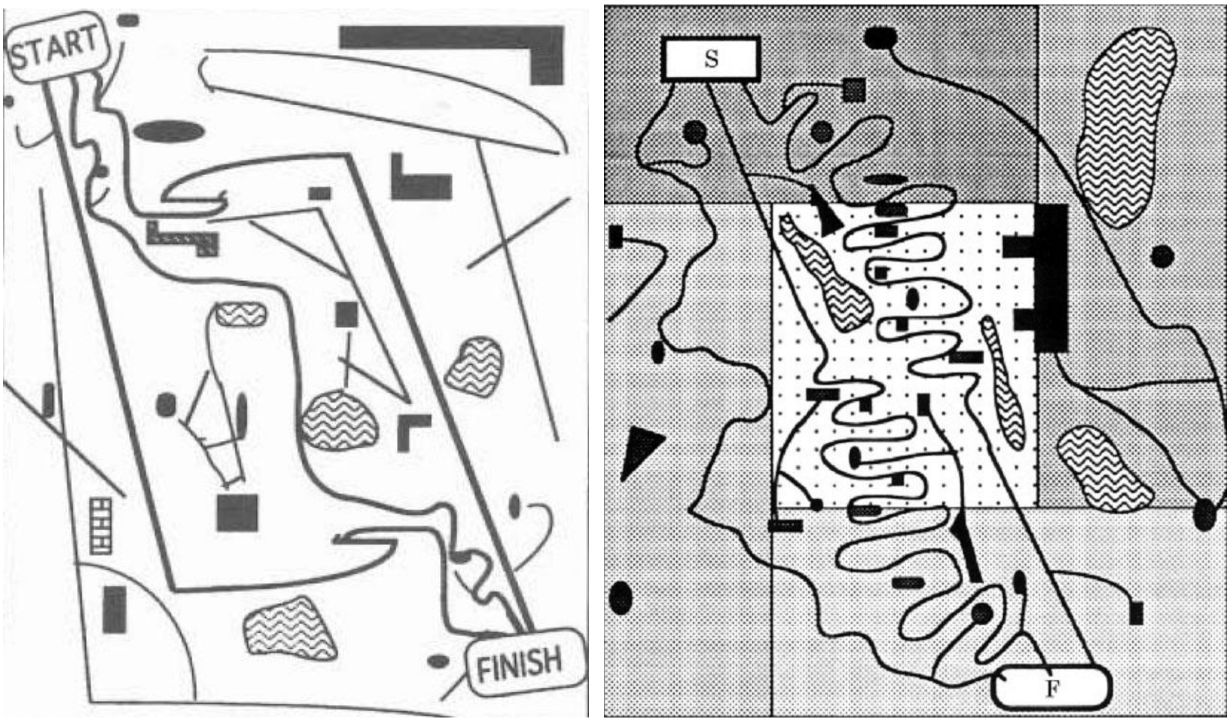
The last route choice experiment by Christenfeld involved two real world tasks where the action taken at a decision point involving three possible routes were studied. The trend of the results in this experiment differed slightly from the last 2 route choice experiments, where majority of the participants tried to avoid making a turn till the last possible decision point.

This is probably because people try to travel as straight as possible and since they have a dislike to turns in the routes, try to make a turn at the last possible moment. This could also be a preference for the longest leg first paths which is a factor that has been studied in the questionnaires carried out in this thesis.

Bailenson, et al [Bailenson, et al., 1998] conducted a series of experiments to provide an alternative theory to why people delay making a turn till the last possible opportunity. According to them people use a heuristic such as preferring paths which have initially straight segments. They say that this heuristic can be more important than taking the shortest distance routes. In [Bailenson, et al., 1998], subjects were given maps consisting of 3 possible routes from the start to the finish (see Figure 2-4a). One path was initially straight and had a few detours towards the end of the route. The second path initially had a few detours and then straightened up. The length of the straight part of the first and second paths was equal. The third path which started and ended with many turns was the shortest path going almost diagonally from the start to the finish. In the maps that were given to the subjects the location of the start and finish were interchanged and also the relative lengths of the first and second path with the third were changed as well. The maps were tested on twenty four Northwestern University students. The results show that subjects prefer routes with initial straight segments even when these routes are substantially longer overall than the other alternatives. It was also found that subjects chose the initial straight segments route more often when the maps were regionalised than when they were not. It was only when the initially straight route was twice as long as the shortest route that subjects preferred the shortest route regardless of the presence or absence of regions. This suggests that there may be an upper limit at which subjects will switch their preference for the route with initially straight segments to the shortest route.

[Bailenson, et al., 2000] conducted four experiments to explain why people choose asymmetric routes. Asymmetric routes in terms of choosing one path from the origin to the destination and another from the destination to the origin. In the first experiment, they created map templates where there was an origin and a destination joined by two possible equal distance routes. The goal was to analyse the hypothesis that people prefer routes with less turns. One of the routes contained a single turn and the other contained two or more turns. In all maps the single turn path was the same but the alternative path differed in the number of turns as two, three, four and five turns. The results of this experiment clearly showed that people preferred the route with the single turn in all cases. There was also a linear trend observed in people preferring the route with single turn more as the alternative route had more and more turns.

In the second experiment, maps were given to check people's preference for initially straight routes over the initially circuitous routes. The results showed that people had a high preference for the initially straight routes and it did not matter if the route later became circuitous.



(a) (b)

Figure 2-4: Maps used by Bailenson, et al [Bailenson, et al., 1998] in thier route choice experiments. (a) Map with no regions and (b) Map with regions

In the third experiment, the effect of regions on the selection of initially straight routes was tested (see Figure 2-4b). In this case the maps consisted of 2 routes from start to finish. One of the routes did not contain a turn in the initial region while the other route with almost the same initially straight segment length did contain a turn in the initial region. The results of this experiment suggest that people prefer to take the route which does not contain a turn in the initial region.

The fourth experiment was performed to check if people can identify shortest routes and how time influences the choice of initially straight routes and the initially circuitous routes. The results of this experiment shows that subjects selected the shortest routes less often when they had less time than when they had unlimited time. When they were given a specific goal of choosing the shortest route, more subjects chose the shortest routes even under the timed condition. The results in the fourth experiment in all cases show that the shortest routes are more preferred. Bailenson, et al [Bailenson, et al., 2000] conclude that route asymmetries can be explained by the importance of the initially straight segment heuristic. For example in Figure 2-4, depending on whether people travel from start to finish or finish to start people will prefer the initially straight route leading to an asymmetric route choice.

These experiments were carried out with sample size as low as twenty four subjects. Also the experiments contained an additional parameter handedness which was ignored as being an insignificant factor – handedness of routes. The authors did perform a test to prove that the handedness of the route was not a factor since in one of the experiments they found that all factors being similar, subjects chose the left and right handed paths equally. But the results in the questionnaires carried out in this thesis which will be presented in Chapters 5 and 6 show that people certainly have a bias for the left and right handed routes based on whether they are right or left handed and which side of the road they drive on as well.

Christenfeld [Christenfeld, 1995] concluded that people avoid making a turn for as long as possible. He concludes that this is an important result that should be taken into account while designing streets. The end routes should lead in the correct direction and should be of greater capacity than the preceding ones. Bailenson, et al [Bailenson, et al., 2000] is his experiments tries to prove that the behaviour of taking end routes is as a result of people preferring the initially straight segment. In this thesis it is assumed that an initially straight segment can also be considered to the longest leg first path. Hence rather than considering the 'initially straight segment' as another wayfinding factor it will suffice to consider the 'longest leg first' criterion alone as both factors are similar.

Kobes, et al [Kobes, et al., 2008] [Kobes, et al., 2009] [Kobes, et al., 2010] have conducted wayfinding experiments in virtual environments and have compared these results in real evacuation experiments of the same building. The Advanced Disaster Management Simulator (ADMS) is a virtual reality simulation used for training command and vehicle operation. An

ADMS based research instrument called the Behavioural Assessment and Research Tool (BART) was developed for the Netherlands Institute for Safety. The goal of the research was to validate the use of simulation for fire prevention modelling and to research methods for improvement of building evacuation. A virtual representation of an existing hotel in Netherlands was created in ADMS. The paths chosen by the participant's is automatically collected and saved by ADMS, and presented as visual and statistical reports for the researchers. Participants were recruited to take part in both the real evacuation trails and also a simulated one in ADMS. Kobes, et al have used ADMS to compare the performance of people in the hotel represented in BART and in the actual hotel. Kobes, et al claim that initial results seem to suggest that there is a good co-relation between the wayfinding results in BART and the real hotel. They seem to make this conclusion based on 1) in both the BART trials and the real hotel similar number of participants did not choose the shortest route and 2) no major difference was noticed in the rating for the feeling of an emergency. However, a closer analysis of the results seems to suggest that in the virtual environment more participants seem to choose emergency exits than in the real evacuation. Among the participants in the BART trails seven out of eight people (87.5%) have chosen the emergency exits. In the real evacuation only five out of nine people (55.6%) chose the emergency exits. The sample size (eight and nine) is again relatively small; however, the results do seem to strongly suggest that people in a virtual environment might be more willing to take risks and try new routes than in a real situation. In a real situation people are more likely to prefer familiar routes and exits.

Benthorn and Frantzich [Benthorn and Frantzich, 1999] carried out experiments on the customers at an IKEA warehouse in Sweden. The aim of this experiment was to investigate which exit people choose on hearing a fire alarm. The factors that were tested were familiarity of the exit, distance to the exit and the condition (open or closed) of the emergency exits. The results suggest that people prefer the (familiar) main exit when the main exit and the emergency exits are at the same distance and the emergency exits are closed. The main exit was chosen by 87 percent of the people in this scenario. All conditions remaining as previous but with the emergency exit being open instead of closed, the main exit is still preferred but is not as popular as previous with 56 percent of the people choosing the main exit. If the main exit is double the distance of the emergency exit and the emergency exit is closed, the main exit is still preferred with almost the same popularity as the previous case with 59 percent of the people choosing the main exit. All conditions remaining the same as previous if the emergency exit is open then the emergency exit becomes more popular with only 5.8 percent of people choosing the main exit in this case. In other words the main or familiar exit is the most preferred exit even when it is at a greater distance than the emergency exit or if the emergency exit is closed. However, if the emergency exit is open and is closer than the main exit, then the emergency exit will be preferred over the main exit.

Shields and Boyce [Shields and Boyce, 2000] have carried out unannounced evacuations of four Marks and Spencer retail stores. Two of these stores were single floor and two were three floor stores. The results of a questionnaire survey administered to the evacuees of the stores suggest that evacuees in the three storey stores chose the nearest exit more than the evacuees in the single storey stores who mostly followed the directions of the staff or other people. A study of the actual exit usage from the evacuations however suggests that there is no significant difference between the single floor stores and the three floor stores. So the mean results of the four stores suggest that customers are most likely to use the familiar or commonly used exits except in one of the stores where an emergency exit opened automatically when the fire alarm rang. In this case majority of the people chose the emergency exit which was closer than the main exit. This supports the conclusion made by Benthorn and Frantzich [Benthorn and Frantzich, 1999] that when the emergency exit is open and is closer than the familiar exit, the emergency exit will be the most popular.

Nilsson, et al [Nilsson, et al., 2008], carried out two unannounced evacuations in an office building and in a cinema theatre to determine if green flashing lights at exits can influence exit choice. It was found that in the office setting the introduction of flashing lights at the emergency exits did not make a significant impact which has been attributed by the authors to two factors: the green flashing lights going unnoticed as they were not bright and most of the people in the office were familiar with the exits. An interesting outcome of the experiment was that people chose the exits mainly based on the proximity and size of the exits. The other set of experiments were carried out in a cinema theatre with/without the flashing lights on the emergency exit. In this case a majority of the evacuees chose the emergency exit with the flashing lights to exit from the cinema theatre. These two experiments seem to suggest that although flashing lights may be used to attract more people towards emergency exits, when people are very familiar with a building the flashing lights may not have an effect. Also, the brightness of the flashing lights and the colour used are an important factor. For example in the United Kingdom green flashing lights may be used as the emergency signs are green in the UK, whereas in the United States red flashing lights may be used as the exit signs in the US are in red. The authors also suggest that changing the state of the lights to flashing only in emergency conditions will improve the affordance of the exits.

Table 2-1: Methodologies used in wayfinding experiments

Methodology	Procedure
Map based questionnaires	[Bailenson, et al., 2000] [Christenfeld, 1995] [Golledge, 1995a]
Virtual Environment	[Kobes, et al., 2008]
Real-World Experiments	[Shields and Boyce, 2000] [Benthorn and Frantzich, 1999] [Nilsson, et al., 2008] [Kobes, et al., 2008] [Christenfeld, 1995] [Golledge, 1995a]

It is interesting to observe from this section that the wayfinding studies have used different methodologies as summarised in Table 2-1. Each methodology has benefits and drawbacks. Map based questionnaires are the simplest, having a wide reach especially when posted online. The disadvantage of this method is that the participant's base their decision on a map of the building which may not be a true indicator of their behaviour in the actual building. Virtual environment techniques are a step forward providing more realistic immersive conditions. However, a disadvantage of virtual experiments is that they are game like and the decisions taken by the participants in imagined emergency conditions cannot be relied upon [Kobes, et al., 2008]. Real world experiments are probably the best; however, it involves a lot of preparation to hide unwanted features or environmental clutter which needs to be camouflaged before the experiment. They are also expensive and consume a lot of time. Given the limited scope of this thesis and the international nature of the surveys conducted (See Chapter 5) the map based questionnaire approach has been used.

2.5 Signage and Wayfinding

Exit signs provide a useful means of information in buildings providing directional cues to exit from a building [Arthur and Passini., 1992]. Some evacuation/circulation models like buildingEXODUS, PEDROUTE, Legion, ALLSAFE and E-scape have incorporated interaction of occupants with signage. The agents in these models are either forced to follow the signage or are affected by the signage depending on whether they fall within the visibility catchment area (VCA) [Xie, et al., 2007] of the sign and the probability that they notice the sign upon falling within the VCA. Instead of modelling the visibility of the agent, buildingEXODUS makes use of a circular VCA around a sign to determine if the agent is capable of noticing the sign.

Hajibabai, et al [Hajibabai, et al., 2007] have developed an unnamed model capable of representing human spatial cognition and exploration with the help of signs. Three different configurations of signage of an actual hospital building have been simulated. The evacuation/circulation simulation was performed in NetLogo [Wilensky, 1999] which is a cross-platform multi-agent programmable modelling environment. The agents in the simulation can move straight, left, right, back or in one of the intermediate positions between these directions. It is assumed that people would mostly prefer to travel straight with this direction being the most preferred; left and right is the next most preferred direction with left being more preferable than right. (Contrary to this the results of the questionnaire's carried out in this thesis shows that most people would prefer to choose the right handed direction rather than the left, see Chapter 5). The agents in the simulation are capable of perceiving fire and signs in the building to update their initial route dynamically. Though the research carried out by Hajibabai, et al [Hajibabai, et al., 2007] is not based on empirical data, they show how evacuation time of buildings may be reduced by modifying the placement and quantity of signage.

In the buildingEXODUS model, Filippidis, et al [Filippidis, et al., 2008] have implemented a sophisticated interaction with signage systems introducing the searching behaviour, backtracking behaviour, lost behaviour and fail safe. Zero order signs are the signs which are located directly on top of an exit. First order signs are the signs that directly point to the target exit and higher order signs are those that point to other signs in a chain of signs leading to the exit. The evacuees on falling within the VCA of a higher order sign are directed towards the exit pointed by the sign. The evacuees walk along this direction which is called the "searching behaviour" till they encounter the VCA of the next sign in the chain or until they travel double the "Expected Distance between the signs" which is initially 15m and is regularly updated to the distance between the last two detected signs. The occupant is said to have reached the "backtracking behaviour" when they have travelled twice the "expected distance between signs" and have failed to detect the next sign or target exit. This stage represents the verification process where the occupant goes back to the last seen sign to verify the direction of the sign and have another chance at finding the next sign in the chain. The occupant after backtracking and returning to the last seen sign enters into the "lost behaviour" if they fail to obtain any new information regarding their target. In this stage they will try to communicate with building staff or other building occupants. If they manage to obtain the necessary information they head directly towards the target ignoring the signage system. If the occupants travel four times the “expected distance between” signs and have still failed to find the target or obtain reliable information regarding the route to the target they then enter into the “fail safe behaviour”. During this stage (depending on whether it is a circulation or evacuation situation), the occupants will either choose to follow the next task in their itinerary list or exit via their nearest known exit which may be the exit that they used to enter the building.

In all the signage related work discussed above the probability of people detecting a sign and taking an appropriate action based on the sign was either 100% or based on the angle of approach. Xie, et al [Xie, et al., 2009] performed experiments to determine the probability of familiar and unfamiliar occupants detecting a sign and after detecting following the instruction in the sign which is to travel along the direction pointed to by the sign. The authors found that people who are unfamiliar with a building are more likely to notice a sign than people who are familiar with the building. People who are familiar with a building would know the route to the exit and hence may not need the information from the signs and hence may not be actively looking for a sign and hence have a lesser probability of noticing signs. This study also confirms that after detecting a sign people are likely (97%) to follow the sign.

While the signage based studies deal mostly with how people wayfind with very little or no building knowledge, the work in this thesis deals with how people with a slightly better building knowledge choose a route from a list of options available to them. However, agent interaction with signage has been included in this research. The calculation of the VCA of signs is taken from Xie, et al [Xie, et al., 2007] and the probability of occupants noticing the sign is taken from Filippidis, et al [Filippidis, et al., 2006]. More detail on the use of signage within the wayfinding model is provided in Chapter 7, Section 7.5.4.

2.6 Wayfinding Models

Gopal, et al [Gopal, et al., 1989], have developed a computational process model (Navigator) of spatial learning incorporating cognitive processes relating to spatial learning and navigation. This includes a hierarchical information storage model, sensitivity to the importance of environmental features and usage of heuristics to find the path when the spatial information in memory is inadequate.

The Traveller is a computational model of spatial network learning developed by Leiser and Zilbershatz [Leiser and Zilbershatz, 1989]. For each task, the agent attempts to plan a route. If successful, they remember the route. The integrated system of memorised routes forms a cognitive map. In this model the agents start with the knowledge of the links between neighbouring locations. During the exploration phase the agents are not aware of the structure of the environment. They do not have knowledge of what paths they will encounter later. However, they have the capability to memorise the local connections that they have traversed. The memorised routes form the cognitive map of the agents.

In the Tour model developed by Kuipers [Kuipers, 1978], the spatial knowledge or cognitive map of the agents are represented in terms of route instructions, knowledge of the topological structure of the street network, paths between landmarks, boundaries of the environment and regions in the environment like rooms. Each trip of an agent teaches them a new part of their environment and at the end they know the whole network. Unlike the Traveller model the order of learning exerts no influence on the resulting representation in the Tour model.

The wayfinding models discussed in this section Navigator, Traveller and Tour try to mimic human spatial learning, cognitive mapping and wayfinding behaviour. Their attempt is to model agents who learn to navigate in an unfamiliar environment finding routes with the help of their spatial knowledge. These models would be more useful for robotic applications where a robot perceives an environment with its sensors, builds a cognitive map and navigates with the help of the newly acquired map. Attempting to develop such a wayfinding model for evacuation/circulation models based on this assumption would result in the application consuming a lot of computational resources. For instance, imagine a scenario with 10,000 agents, each possessing a cognitive map and navigating using this cognitive map. This process can be simplified by providing a common cognitive map to the entire population and assigning a sub set of the paths to each agent based on their familiarity with the environment; i.e. a single map that is interpreted rather than a multitude of slightly different maps. Instead of letting the agents find their path, it would be more efficient to pre determine the choice set of routes before the start of the simulation. The emphasis of this thesis is more on how people familiar with a building plan/choose routes.

2.7 Wayfinding in Evacuation Models

The spatial-grid model (SGEM) [Lo, et al., 2004] [Lo and Fang, 2000] uses a graphical representation of a building by modelling the regions such as rooms, corridors, stairs, etc as nodes or zones and the connectivity between them represented as links or arcs. However, the zones are then divided into a number of cells of size 0.4m X 0.4m. The agents in the simulation move from "unprotected zones" to "partially protected" zones to "fully protected" zones. The movement within zones is a combined effect of minimising the distance between the current cell position to the exits within the zone and the probability of moving to the next cell which is determined by the weighting of each stimulus and the stimulation level of the personal/environmental attributes such as familiarity, signage, visual accessibility and illumination level. Thus, the exit selection within a cell is made taking into consideration the weights assigned to each agent for the different stimuli and the strength of each stimulus. Factors such as fire, furniture, obstacles or location of other people may also affect the movement of the agents. Thus, the wayfinding strategy in SGEM is to move the agents directly to an exit taking into consideration the environmental factors along the route. The route selection strategy assigns the final exit to take while the wayfinding function assigns a direction to the agent at each time step and guides the agent along a direct route to the target exit. The wayfinding features in SGEM are thus limited to a long term goal such as the exit choice and short term decisions such as obstacle avoidance. The consideration of the various routes to the exits is not evident.

In the PathFinder model [Pathfinder, 2009a] [Pathfinder, 2009b], the A* search algorithm and the triangulated navigation mesh is used by each agent to generate a path from their initial position to the exit. The path thus generated is zigzag. A variation of the string pulling algorithm [Johnson, 2006] is used to smooth the paths. PathFinder, like most other evacuation/circulation modelling tools, assigns the shortest paths for the agents in the simulation. There is a provision to provide user-defined routes to the agents as well.

The SIMULEX model [Thompson and Marchant, 1995] uses algorithms such as "distance mapping, wayfinding, overtaking, route deviation" to represent agent movement. Distance mapping is a technique that is used by many computer models to assign the shortest distance path to the agents. The 'wayfinding' technique employed in SIMULEX determines the optimal (shortest) route to an exit. This route is generated by using the distance map and calculating the 'immediate angle of travel' from start to finish in linear steps of 0.25m. On encountering an obstructing person along the path, the agent is capable of overtaking through an alternate optimal path avoiding the obstruction (route deviation).

The GridFlow model [Bensilum and Purser, 2003] [Purser, 2009] uses the distance mapping technique to generate a map for each exit in the building. There are three methods of exit assignment in this model: optimal exit assignment where agents are assigned exits that minimise the overall evacuation time; random exit assignment where agents randomly choose an exit; and 'weighting or user specification' where agents choose an exit based on a preference value attached to the exit or the user specifies the exits to be taken by the agents.

The SimWalk [Steiner and Schmid, 2007] model uses a combination of a social force [Helbing and Molnar, 1995] and a shortest path algorithm. The pedestrian routes are determined by their goals, interactions with other pedestrians and the obstacles in their paths. SimWalk uses the potential field algorithm [Hwang and Ahuja., 1994] to drive the motion of the agents. Three forces act on the agent, the first force leads the agent towards its destination by using the potential force; a second force regulates the interactions between agents ensuring that agents do not walk into other pedestrians and try to keep a certain distance from each other. The third force guarantees that agents do not walk into walls and that they try to keep a certain distance from walls.

The magnetic model [Okazaki and Matsushita, 2004], uses the social forces model as well which they call "the movement of a magnetic object within a magnetic field". The occupants have the following walking options

- Indicated route: User specifies a series of target points and the agents follow them
- Shortest route: The agents take the shortest route to the exit.
- Wayfinding: The agent walks in search of the goal following the forces acting on it due to the artificially created magnetic or potential field.

Legion [Still, 2000] which is a collection of programmes developed to analyse the dynamics of crowds utilises the ant algorithm to find all shortest routes in a given environment. The ants make use of pheromones which is a chemical substance to mark a trail [Panait and Luke, 2004a] [Parunak, et al., 2002]. They wander randomly until they sense the effect of pheromones, when they decide to either follow the trail or continue to roam randomly. Veeraswamy, et al [Veeraswamy, et al., 2006] have shown that these ant based pheromone techniques are at times more efficient or quicker than graph search algorithms like the A* algorithm.

In the ASERI model [Kuligowski, 2008], the egress route mechanism has three modes: shortest path mode, prescriptive egress mode and dynamic exit choice mode. The shortest path mode is the simplest with all agents choosing the shortest path to the exit. In the prescriptive egress mode, agents follow the path prescribed by signs. The dynamic exit mode considers factors such as the usage of less occupied routes, selection criteria in case of similar route sections and the effect of smoke or heat on egress route choice. The agents score each exit based on these factors and choose the one with the lowest score. If more than one exit has the same score then the occupants choose one of the exits randomly.

In the buildingEXODUS [Galea, et al., 2006] model, the exits chosen by people can be controlled in several ways:

- The occupants can choose the nearest exit
- The exits potential or attractiveness can be modified to attract or repel occupants
- Occupants can learn the exits when they fall within the catchment area of an exit sign pointing to that exit
- Occupants can also learn about exits by interacting with other occupants.

The occupants in buildingEXODUS are also capable of redirecting to another exit depending on the congestion around their present exit. The redirection of the occupant to another exit can only happen once. First, the physical possibility of the redirection is considered i.e. whether the occupant is surrounded by other occupants making it impossible for him to redirect. If this is not the case then the time taken to reach the end of the queue is compared against the time taken to walk to the other visible exits and the congestion time at the other exits. If the time taken to reach the other exit is less than the time taken to reach the present target exit, then the occupant will redirect to the other exit. This redirection can presently take place only once. If visible exits are not available then non visible exits are considered. In the case of the non visible exit, only the travel distance is considered and congestion around this exit is not considered. This may lead to non-optimal exit selection. Also the decision to redirect depends on the time that the occupants have spent queuing at the present exit and their patience levels. The signage features in buildingEXODUS have been discussed in Section 2.5.

Southworth [Southworth, 1991] has described four possible modelling strategies for exit selection: agents could be made to choose the exit at the shortest distance and/or taking the least time; agents could be modelled to choose the exits for social reasons such as the location of family or friends; agents could be assumed to choose the designated exits; and finally agents could choose exits based on the congestion along the routes leading to the exits.

In the STEPS model [Waterson and Pellissier, 2009], the following factors are taken into account in assigning scores to the exits: time needed to reach the target, queuing/congestion at the target and the patience level of the agent. The STEPS model makes use of paths, junctions and checkpoints to introduce path/route choice. The agents use the term ‘paths’ to create unidirectional flows in the geometry. For example path objects are used to model ticket gates in a station. Junction objects are used when more than one path meet at a particular location and helps agents to decide which path to choose next. There are three options to choose at junctions: fixing the number of people in a population to use the paths; agents can be made to use only those paths that are free i.e. paths that do not have a queue; and lastly agents can be made to use the path with the least queue size. Checkpoint objects are used to specify target locations and tags are used to group checkpoints together. For example if there are three ticket gates in the same direction at a station, all three gates can be modelled as checkpoint objects with the same tag number and the agents targeting the checkpoints with the same tag number will choose the best one based on distance and queuing.

Finally, routes can be created by specifying a list of targets. The targets that can be specified in the route are exits, checkpoints, lifts, vehicles and tag numbers. There are two kind of routes that can be specified ‘main routes’ and ‘sub routes’. A main route is made up of more than one sub routes. The agents in the STEPS model first decide which target to move to and then can either take the shortest route to the target or randomness can be introduced where each possible move is given a certain probability of being chosen based on how close it gets the agent to the target.

The MassMotion model uses a graph or network whose nodes are formed by the rooms, plazas, corridors, etc and arcs are formed by the doorways, stairs, elevators, etc [Edwards, et al., 2011]. Each node is assigned a value which represents the shortest distance to the exits determined using the Dijkstra's algorithm. The routes available to the agent are the shortest paths to each exit in the building. Each agent has his own attributes such as speed, distance weight, queue weight and link traversal weight. The distance weight represents the preference for a shortest distance path; the queue weight represents the preference to choose a path with fewer queues along it; the link traversal weight represents the agent's preference of the links such as stairs, escalators, etc. At each junction, the agents calculate the cost of each available route which is a function of their personal attributes, the distance of the routes and the type of links in the route.

At least two evacuation/circulation models make use of game theory [Rasmusen, 2001] to model exit selection of the agents in the simulation. The game theoretic approach used in the SGEM model is outlined by Lo, et al [Lo, et al., 2006]. Game theory is a branch of applied mathematics which has been used to study many real life phenomena in political sciences, economics, international relations, evolutionary economics, social interactions and other fields. Lo, et al have proposed a game theory approach to model the exit selection of agents which can be applied to any evacuation/circulation model. A two player non-cooperative zero sum game [Fudenberg and Tirole, 1991] [Rasmusen, 2001] is envisaged between the crowd of evacuees seeking an exit to minimise the expected travel time and the environment representing a virtual entity imposing a blockage influence to maximise the expected travel time. Therefore, the agents choose the exit based on the crowd density, exit width and the distance to the exit.

Ehtamo, et al [Ehtamo, et al., 2008] model the evacuees exit selection as a 'best response dynamic' which is a concept in game theory where players choose the best response for the next iteration based on the decisions of the players in the previous iteration. Initially all evacuees choose an exit based on familiarity, visibility and conditions around the exits. They then calculate the time to travel to the exit and predict the congestion at that exit based on the other player's strategies to choose the best exit to go to. The authors claim that with large populations the system converges to a Nash Equilibrium [Rasmusen, 2001] within a few iterations. This methodology for exit selection has been used in the FDS+Evac model [Hostikka, et al., 2007].

Heliovaara [Heliovaara, 2007] has proposed another game theoretic exit selection technique for the FDS+EVAC fire and evacuation/circulation simulation model [Hostikka, et al., 2007]. There are two optimization problems that need to be solved by the agents in this model. Each agent takes into consideration the other agents heading to the exits, their walking speed and the exit width to determine the shortest exit with respect to time. Agents also consider three other factors while deciding which exit to take i.e. familiarity of the exit, hazardous conditions around the exit and the visibility of the exit.

SGEM and FDS+EVAC models only deal with wayfinding aspects through the exit selection process and specify which exits occupants are likely to choose. This approach may be good enough to model small buildings where there exists only a single route to each exit. These models do not deal with the problem of what routes people choose when there is more than 1 route to a single exit. If there exist more than one route to the same exit the agents in these models may still be taking the shortest route to that exit.

In the ZET model [Dressler, et al., 2009], network flow techniques [Ahuja et al., 1993] are used to find optimal exit selections for evacuees. Network flow techniques are usually used to solve transportation problems where people and material need to be transported from source nodes to sink nodes. These problems can also be solved through linear programming but are more efficiently solved by some of the network flow algorithms [Heineman, et al., 2008]. Dressler, et al [Dressler, et al., 2009] make use of the preflow-push algorithm with the highest-label selection rule and the global- and gap-heuristics [Cherkassky and Goldberg, 1997] to compute maximum flow which is used to identify bottlenecks in a building. They also make use of 'maximum flows' and 'minimum cost flow' network flow techniques to assign exits to the evacuees for an optimal evacuation scenario. The network flow techniques are usually used to optimise the flow through a network which has more useful applications in industries; where there are multiple production units producing commodities to be transferred to goal locations. These techniques are used in the ZET model by considering the locations where a group of evacuees exist to be source regions and the exits to be sink regions.

The MASSEgress [Pan, et al., 2005a, 2005b, 2005c, 2006a, 2006b] model is a multi-agent based computational framework to simulate human and social behaviours for egress analysis. In MASSEgress the K-Means clustering algorithm [MacQueen, 1967] is utilised to identify the potential congested areas in a building. They thus provide the facility for a designer to modify the geometry and signs to facilitate faster and efficient evacuation systems.

The evacuation/circulation models discussed so far have incorporated certain route choice, exit choice behaviours. However, most of these models provide the shortest routes to the different exits as the route options and some have confused navigation of the agents to be wayfinding features. The EVACSIM model [Poon, 1994] is more advanced than any other existing evacuation/circulation model and comes closest to the wayfinding model developed in this thesis. However, the EVACSIM model is no longer in use with there being no peer reviewed article on this model since 2000 [Kuligowski, et al., 2010].

A walkway network has been employed to model buildings in the EVACSIM model. Figure 2-5b shows the walkway network of the actual building in Figure 2-5a [Lovas, 1998]. The walkway network is actually the traversable path within the building with a node placed at each decision point (junctions). The final graph of the same building is shown in Figure 2-5c. The walkways have been replaced by links connecting the nodes or decision points with each link possessing a length attribute based on the walkway network. The exit of the building is represented by the triangle at the end. The position of the decision points in Figure 2-5c do not seem to be sufficient. For example the manner in which decision points 1 and 2 are connected, does not reflect the fact that there are three turns to reach from 1 to 2. However, number of turns is not a factor considered in EVACSIM.

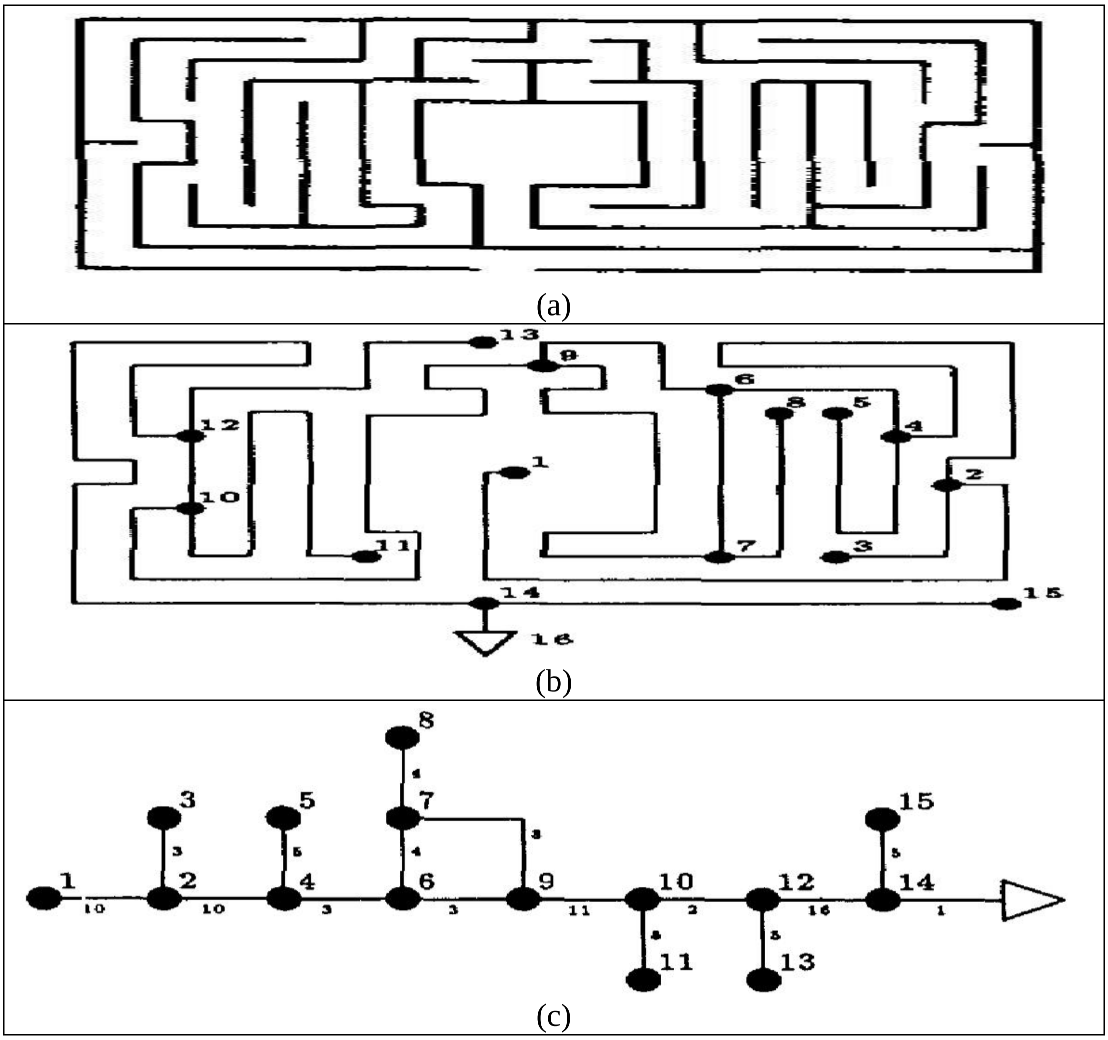


Figure 2-5: Representation of a building space shown in (a) as a walkway network in (b) and in terms of a graph in (c) [Lovas, 1998].

In EVACSIM the agents are assigned a cognitive map based on their personal attributes like building familiarity, level of queuing which forms the basis of a route choice model [Poon, 1994]. At each step the agent is assigned a probability P_K (i, j, X) as the probability that a person k, with his personal attributes, will move from node 'i' to node 'j' when the whole system is in state 'X'. Lovas, then goes on to introduce several models such as the random choice model where $P_K(i, j, X) = 1 / \partial(i)$, where $\partial(i)$ is the number of walkways connected to node 'i'. The route choice model in EVACSIM is based on the "Modified Shortest Local Path", "Shortest Global Path" and "Frequently used paths" models developed by Lovas. Each model has its own formulation for P_K (i, j, X).

The wayfinding model developed in this thesis is similar to and differs from the route choice model in EVACSIM in the following ways:

- While it is not known how cognitive maps are generated in EVACSIM, three sub optimal path planning algorithms have been developed in this thesis and agents in the simulation are assigned knowledge of these routes in terms of their exit and building familiarity. The details of the sub optimal path planning algorithms have been discussed in Chapter 4.
- The route choice model in EVACSIM is a step by step process where at each node the agent decides the next node to take. In the wayfinding model developed for this thesis, the agents make a route choice at each decision point instead of deciding the next node to take. Route choice considers the overall route, whereas node choice only considers the next node to take. People who are familiar with a building are more likely to follow a route choice model since they will have knowledge of various routes in the building. Whereas, people who are unfamiliar with a building are more likely to follow the node choice model. Therefore, the ideal model should perhaps have few agents using the route choice model and the rest using the node choice model.
- Unlike in EVACSIM where each connected node is assigned a probability, in the wayfinding model the agents assign a probability to the routes in their cognitive map. The personal attributes possessed by the agents are their preference to the different wayfinding criteria like distance, time, angle, turns, length of the first leg, decision points etc. More detail about these criteria and the methodology used to assign probabilities to the paths will be given in Chapter 7.

Table 2-2 shows a review of the wayfinding features in existing evacuation models discussed in this section and what additional features are being added in the wayfinding model developed in this thesis. The ticks represent that the evacuation model incorporates the respective feature while the cross represents that the evacuation model does not incorporate the feature. A summary of each wayfinding feature is provided below:

1. Spatial representation: Most evacuation models have a navigational graph which is more suitable for the navigation of the agents. In this thesis the connectivity graph (see Chapter 4, Section 4.2.3) is used which is more suitable for a higher route level planning.

2. Cognitive maps: In most evacuation models agents only possess knowledge of the shortest route. In the wayfinding model, agents possess knowledge of sub optimal routes.

3. Route choice: Most evacuation models use formulas, probabilistic or conditional methods to assign routes to the agents. The route choice method used in this thesis is based on multi criteria decision analysis methods (see Chapter 7, Section 7.2.3.2).

4. Wayfinding Criteria: Existing evacuation models only consider distance and time as factors influencing route choice whereas in this thesis other factors (see Chapter 7, Section 7.2.3.1) are considered as well.

5. Empirical data: The wayfinding model in this thesis is based on empirical data provided by two surveys (see Chapters 5 and 6).

6. Suboptimal paths: Whereas other evacuation models only provide the shortest paths to each exit, in this thesis route choice set generation algorithms have been implemented to provide suboptimal routes (see Chapter 4).

7. Normalisation of wayfinding criteria: Though mass motion uses the weighted sum method as well, it does not normalise the different wayfinding criteria as performed in this thesis. It is very important to normalise values when different units are used.

8. Route refinement: In most evacuation models route refinement consists of choosing alternative exits, whereas in this thesis alternate routes are chosen by the agents.

9. Unfamiliarity: This thesis does not model the wayfinding behaviour of people who are completely unfamiliar with the building.

The main goal of this thesis is to develop a wayfinding model and integrate it with buildingEXODUS. The wayfinding model developed will include spatial representation, cognitive mapping, path finding, route selection, movement or route execution and route refinement. The existing capabilities of buildingEXODUS will be used by the wayfinding model. For example spatial representation and route execution features already exist in buildingEXODUS which will be made use of by the wayfinding model. There will be constant communication between buildingEXODUS and the wayfinding model. For example, buildingEXODUS needs to pass the spatial information to the wayfinding model. The wayfinding model assigns paths to the agents in the buildingEXODUS simulation. The agents in the buildingEXODUS simulation make use of the MOVEMENT sub model [see Chapter 3, Section 3.3] buildingEXODUS to move to the target node specified by the wayfinding model. If the agent encounters an obstacle in his path, the wayfinding model is called upon to assign a new path. More detail on the integration of the wayfinding model in buildingEXODUS is discussed in Chapter 7, Section 7.3.

Table 2-2: A review of the wayfinding features in existing evacuation models compared to those introduced in the wayfinding model developed in this thesis.

	EVACSIM	Steps	Mass Motion	SGEM, FDS+EVAC	Path Finder	EXODUS	Wayfinding features identified for implementation in this thesis
Spatial Representation	✓	✓	✓	✓	✓	✓	✓
Cognitive Maps	✓	✗	✗	✗	✗	✗	✓
Route choice	✓	✓	✓	✓	✓	✓	✓
Wayfinding Criteria other than distance and time	✗	✗	✗	✗	✗	✗	✓
Empirical data	✗	✗	✗	✗	✗	✗	✓
Sub Optimal Paths	✗	✗	✗	✗	✗	✗	✓
Normalisation of wayfinding criteria	✗	✗	✗	✗	✗	✗	✓
Route Refinement	✓	✓	✓	✓	✗	✓	✓
Unfamiliarity	✓	✗	✗	✗	✗	✗	✗

2.8 Conclusion

This chapter started with a review of state of the art graph search and path planning techniques. The main topic of this thesis, wayfinding, was then introduced. The various steps involved in wayfinding which are spatial representation, cognitive mapping, path finding, route selection, route execution and route refinement were illustrated. Urban and building wayfinding experiments conducted studies were then analysed. Signage which is an aspect of wayfinding and its implementation in evacuation/circulation models was examined. Wayfinding features in other evacuation/circulation models were analysed in Section 2.7. Though most evacuation/circulation models have the nearest exit as the default option, some of them have slightly more advanced wayfinding features like exit selection, signage, etc.

The wayfinding models Tour, Traveller and Navigator (see Section2.6) make use of complex cognitive mapping abilities which are useful in robot path planning applications. These models were considered to be very complex focussing more on cognitive mapping and less on wayfinding. The urban wayfinding factors determined by Golledge form a good basis for the wayfinding model to be integrated into evacuation/circulation models. However, his work was based on urban wayfinding studies. Thus, it is necessary to determine if the urban wayfinding factors apply to building wayfinding as well. Questionnaires were developed in this thesis to determine what wayfinding factors affect building wayfinding which are described in Chapters 5 and 6.

Most of the wayfinding behaviour incorporated in evacuation/circulation models as discussed in Section 2.7 makes use of exit selection procedure. The wayfinding model developed in this thesis will incorporate not only agents choosing different exits but also agents choosing among the different paths available to the exits. Such a wayfinding model would be the first of its kind to have been developed for evacuation/circulation models. While the wayfinding model developed in this thesis can be integrated within any evacuation/circulation model, it has been integrated within the buildingEXODUS model as it was readily available and has sophisticated features (spatial graph generation, agent based behavioural model and agent navigation) that are useful for implementing a wayfinding model. Integration of the wayfinding model in the buildingEXODUS evacuation/circulation modelling tool is expected to give more realistic simulation results.

In the next chapter the Station Disco fire, a real incident is analysed. The events that occurred are recreated in buildingEXODUS along with the fire simulation generated by SMARTFIRE [Jia, et al., 2006] [Wang, et al., 2007]. The buildingEXODUS evacuation/circulation modelling features like signage, redirection due to signage, exit selection, response times and integration of fire data are demonstrated on the Station Disco building. This will enable a base setting of the EXODUS capabilities to be established, aiding in the identification of the model developments that are required.

3 The Case Study – The Station Nightclub Fire

3.1 Introduction

Chapter 2 provided a brief overview of the wayfinding features in current evacuation models. Since the wayfinding model developed in this thesis needs to be implemented within the buildingEXODUS model, this chapter provides an analysis of the circulation/evacuation features of the buildingEXODUS model by reconstructing a real life evacuation incident known as The Station nightclub fire [Grosshandler, et al., 2005]. The wayfinding behaviour of the occupants involved has been studied. The effect of the building design, smoke, hazards on the evacuating population has been analysed. Question 2 (see Chapter 1) namely “How do the existing evacuation models represent human wayfinding” was answered in Chapter 2 by looking at the wayfinding features in the current evacuation models. However, the main purpose of this Chapter is to determine the wayfinding features existing in buildingEXODUS and to perform a requirements analysis for the wayfinding model to be developed in this thesis.

In Section 3.2, The Station nightclub incident is briefly described. Section 3.3 provides a general overview of the important features of the buildingEXODUS model. The evacuation modelling assumptions used in modelling The Station nightclub incident is then described in Section 3.5. The key simulation results of The Station nightclub and their analysis is then provided in Section 3.6. The limitations of the buildingEXODUS model from a wayfinding perspective are then described in Section 3.7.

3.2 The Incident

On the night of February 20, 2003, a deadly fire occurred in The Station nightclub at 211 Cowesett Avenue, West Warwick, Rhode Island, USA [Grosshandler, et al., 2005]. One hundred people lost their lives in the fire with more than two hundred people being hurt from burn, respiratory insult and physical trauma. The National Institute of Standards and Technology (NIST) established a National Construction Safety Team (NCST) to determine the likely technical cause or causes of the building failure that led to the high number of casualties in the nightclub fire.

The Pyrotechnic devices used by a band performing that night ignited the polyurethane foam lining portions of the wall and ceiling of the platform which started a quick spreading fire fed further by the wood from the wooden frame building. Even though the first fire crew arrived at the scene at about 5 minutes and 21 seconds [Grosshandler, et al., 2005] after the start of the fire, 100 people out of the total 462 in the nightclub lost their lives.

The main causes of such a large number of causalities were the lack of a water sprinkler system, the hazardous mixture of building materials, bad building design and inability of the evacuees to find certain exits in the building. This incident brought about a number of changes to the building codes. A Massachusetts law [Ford, 2007] was passed forcing all nightclubs and bars with an occupancy limit of more than 100 people to install sprinklers. Indoor fireworks were banned in Boston, Massachusetts. The National Fire Protection Association (NFPA) adopted a new standard which recommended sprinklers in new clubs with 50 or more occupants and existing clubs with 100 or more occupants [Arnold, 2005]. A few months after the incident Rhode Island enforced the following regulations: banned pyrotechnics in assembly facilities with less than 1000 person occupancy limit; required sprinklers for nightclubs with more than 150 occupants; eliminated the exemption for older buildings from new code compliance; required the installation of low-level exit signs for all nightclubs and the local fire officials were given the authority to inspect nightclubs during operating hours and close those violating fire codes.

The layout of The Station nightclub is shown in Figure 3-1. There was 1 main exit and 3 emergency exits in the nightclub. The double door of the main exit leads into a corridor at the end of which is a single door. Further from the single door is the ticket taker area from which there are 2 openings, one leading to the bar room and the other leading to the dance floor. While this design was ideally suited for the general operation of the night club, wherein people queue to buy the tickets and then branch out to the bar room or the dance floor, this design proved to be a deadly trap for the people involved in the evacuation of the club under fire on the night of the incident. According to the NIST report there was a crowd crush at the main door within less than 100 seconds after ignition.

The fire started at the platform area (stage) located in the north-eastern side of the nightclub. People were slow to respond initially since they thought that the fire was part of the pyrotechnic show. Some people did not want to give up their places and hence did not start evacuating immediately. The fact that the band continued with the show up till 30 seconds after the start of the fire may also be a key factor for the late reaction of the people. The fire alarm sounds and strobes flashed only at 41 seconds [Grosshandler, 2005] after the start of the fire by which time most of the people had already started evacuating. On the other hand the fire spread very rapidly with smoke seen at the entrance doorways within less than 5 minutes [Grosshandler, 2005].

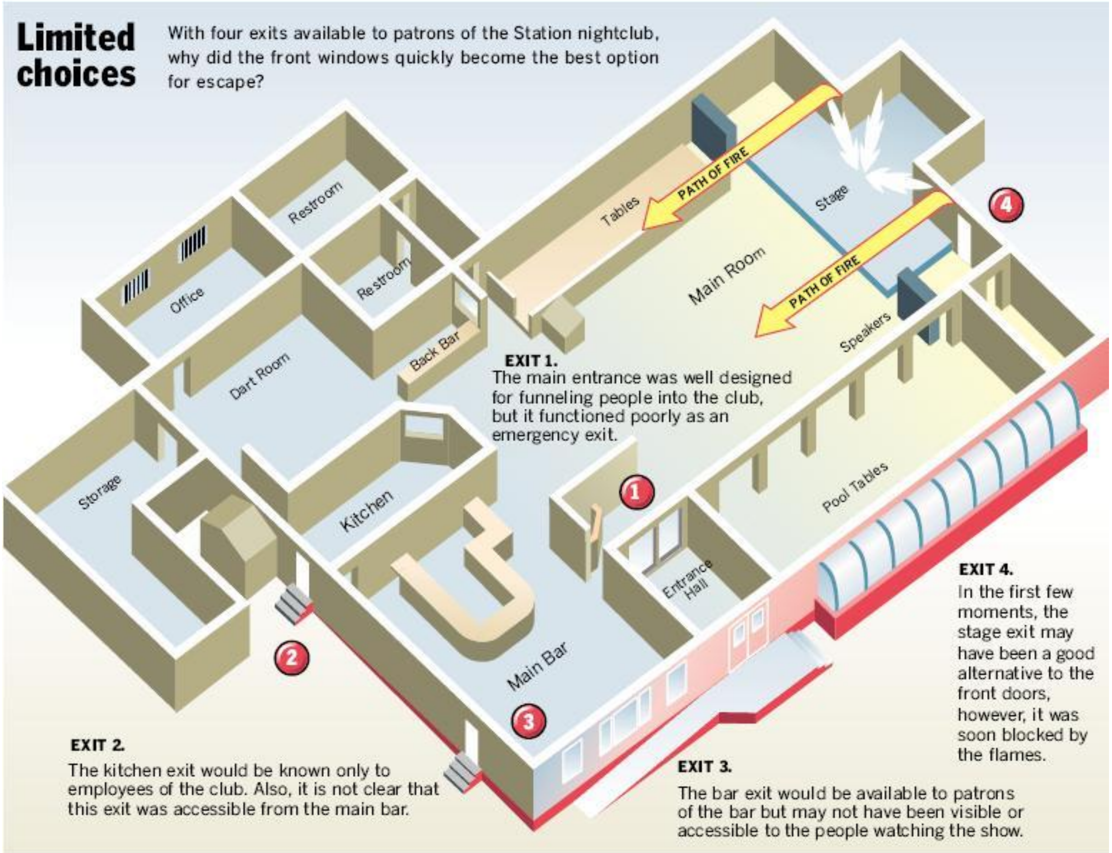


Figure 3-1: **Layout of The Station nightclub [Providence Journal, 2003a].**

In August 2002, the Rhode Island Attorney General, released a picture (Figure 3-2) of the approximate locations of the 96 people found dead in the nightclub in the aftermath of the incident. 34% of the fatalities occurred in the corridor leading to the main exit which is where a crowd crush occurred. The factors that lead to the crowd crush are: the usual tendency of people to go out the same way they came in; the tendency of people to use the main exits more than the emergency exits; and also the configuration of the ticket desk (while the actual main door was a double door the door from inside the building leading to the main exit was a single door).

About 19% of the fatalities occurred in the sunroom area. Since the fire started in the platform area it would be expected that the areas around the platform and the sunroom would quickly get hazardous. The escaping evacuees experiencing severe congestion at the main exit may have chosen to exit through the sun room windows which might explain why there were so many fatalities in the sunroom area.

28% of the fatalities were found in the rear bar, storage, office and restrooms which is quite surprising as there were no exits nearby. The possible reasons for this are: once the main exit was highly congested and most of the front part of the nightclub were untenable, people might have moved to less hazardous regions at the rear of the nightclub; people may have thought it to be a good idea to stay in less hazardous areas and wait for help; due to the thick smoke levels people may have got lost and wandered aimlessly. A very low number of fatalities (3%) in the bar room area would suggest that the bar room windows provided a quick and less hazardous exit option.

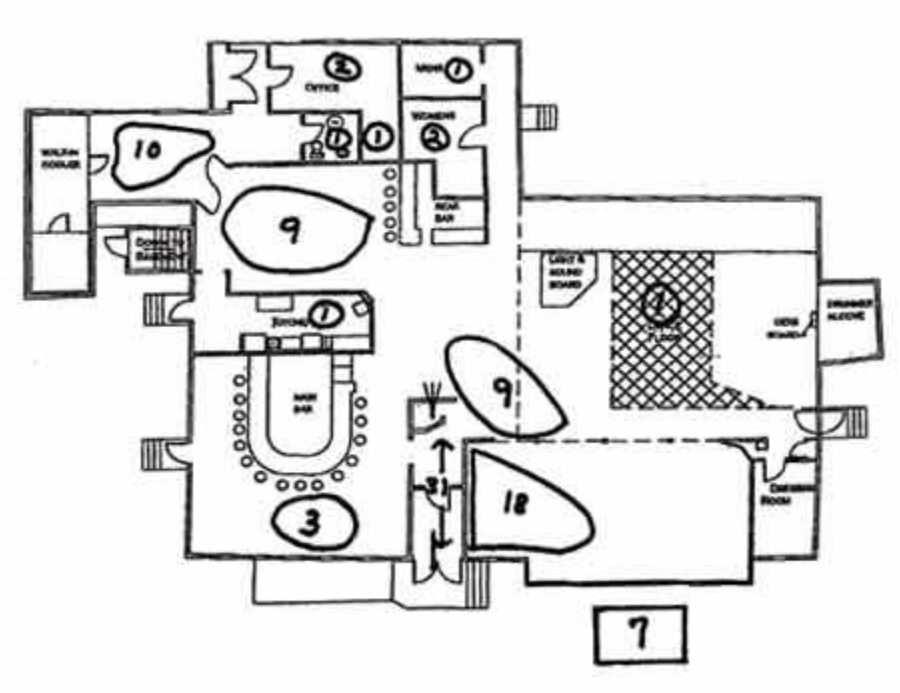


Figure 3-2: Approximate locations of the fatalities in The Station Fire incident [Providence Journal, 2003b].

3.3 The buildingEXODUS Model

EXODUS is a suite of software tools designed to simulate the evacuation and movement of large numbers of individuals within complex structures [Galea, et al., 2006]. The EXODUS software has been written using C++ and object oriented techniques. The buildingEXODUS model is the part of EXODUS which deals with evacuation and circulation modelling within buildings. The buildingEXODUS model is capable of modelling people-people, people-fire and people-structure interactions. People-people interactions involve overtaking or following other people. People-fire interactions involve the effect of fire on the occupants such as inhalation of toxic gases, exposure to heat and crawling due to smoke. People-structure interactions involve the response of the occupants to structural elements such as signage.

The buildingEXODUS model consists of five interacting sub-models: the occupant, movement, behaviour, toxicity and hazard sub-models as shown in Figure 3-3.

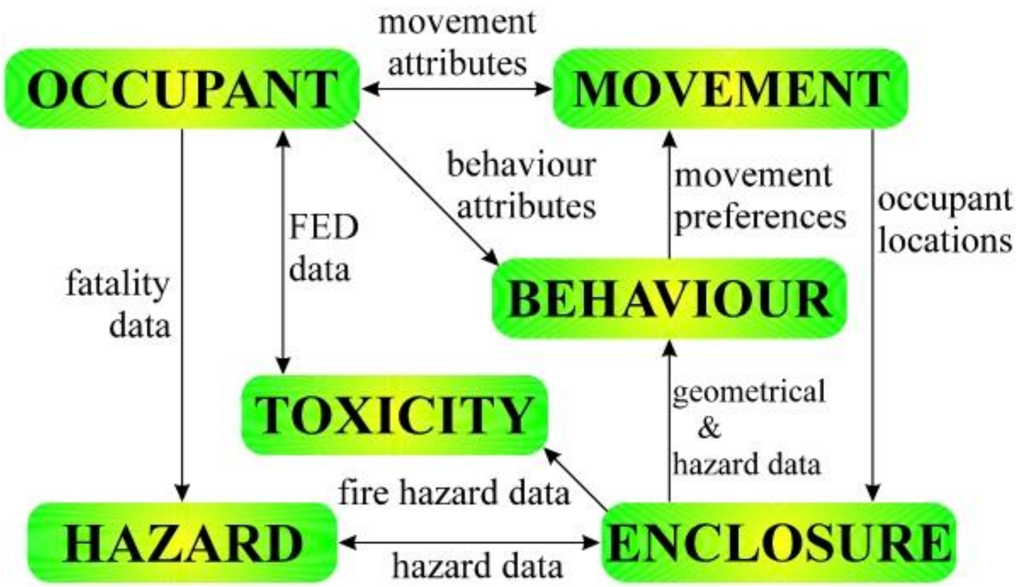


Figure 3-3: The sub-models in buildingEXODUS [Galea, et al., 2006].

3.3.1 The Enclosure (Geometry) sub-model

The geometry sub-model in buildingEXODUS deals with the spatial representation process. The space is represented by means of a fine node model where it is divided into equal sized grids each of size 0.5 meter X 0.5 meter. The geometry can either be constructed using the tools provided in the model or it can also be read from a CAD DXF file. A DXF of The Station nightclub was used to construct the geometry in buildingEXODUS. The *Node Flood* tool available in buildingEXODUS was then used to fill the space with nodes thus creating a nodal mesh. The exits in the geometry were created using the *Door* object. Two nodes of combined width 1 metre was used to represent the single doors in the geometry and four nodes of combined width 2 meters was used to represent the double doors. However, the actual widths of the doors in The Station nightclub building were 0.91m for the single doors and 1.71m for the double door. Hence, the flow rates of the doors were accordingly adjusted to accommodate the difference in the door widths. The geometry of The Station nightclub as modelled in buildingEXODUS is shown in Figure 3-4. The emergency exits are shown in green and the main exit is shown in red.

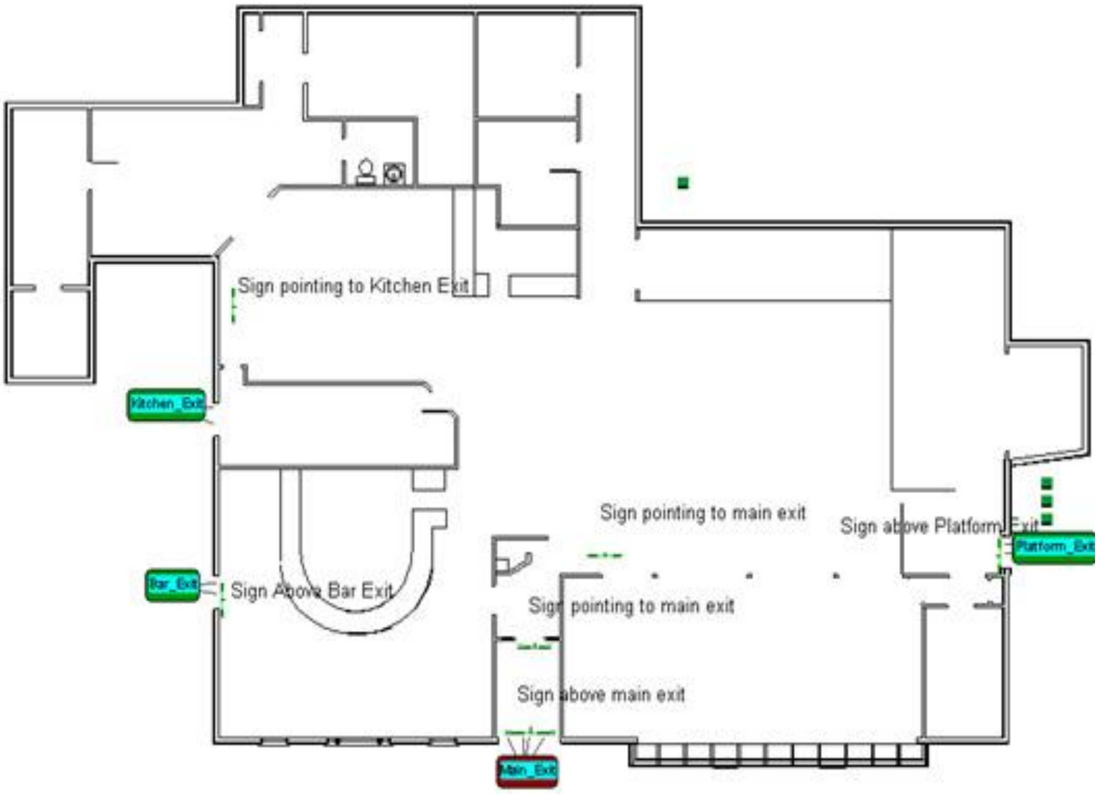


Figure 3-4: **Exit signs in The Station Disco Nightclub modelled in buildingEXODUS.**

The signage in The Station nightclub geometry was represented by placing Sign objects in buildingEXODUS. The six Sign objects placed in the geometry are represented by green lines (see Figure 3-4) and match with the location and size of the actual signs that were existing in The Station nightclub building on the night of the incident.

The geometry initially used as shown in Figure 3-4 consists of the four standard exits in The Station nightclub. However, during the actual incident, the windows in the sun room and bar room were broken by the evacuees to provide a faster escape route or due to the inability to find the actual exits. In the scenarios trying to reconstruct the incident additional exits were added (Figure 3-6) matching the number, size and locations of the windows used by the occupants as specified in the official report [Grosshandler, et al., 2005]. The flow rates and open/close times were also assigned based on the incident.

3.3.2 The Movement Sub-model

The movement sub-model corresponds to the movement or route execution process in wayfinding as described in Chapter 2, Section 2.2.6. The movement sub-model deals with the actual physical movement of the agents through the geometry. The agents move from the centre of one node to the centre of another node. The distance or potential map is used to navigate the agents to the target nodes such as exits or itinerary nodes (nodes where agents are assigned a task) through the shortest possible route. There are three navigation methods used in buildingEXODUS: local potentials, local familiarity and exit signs.

3.3.2.1 Local Potential

Each node in the buildingEXODUS model possesses an attribute called the ‘potential’ which is a measure based on distance from the nearest exit. The combined potentials of the nodes in the geometry form the potential map of the geometry. When the local potential option is chosen the agents move according to the potential map generated choosing the node with the lowest potential at each step.

3.3.2.2 Local Familiarity

The ‘local familiarity’ option can be used as an alternative to the ‘local potential’ in which case the agent chooses the shortest path to the nearest exit that they are familiar with. Each agent has a list of exits called the ‘Occupant Exit Knowledge’ which represents the exits that they have knowledge of. The local familiarity option is more complex than the local potential option as in the latter agents are assumed to have full knowledge of the building and take the shortest route to the nearest exit. However, if all agents are familiar with all exits then both local potential and local familiarity options could produce similar results.

3.3.2.3 Signage Visibility

This mode is similar to the local familiarity mode except that now agents can gain new exit knowledge on falling within the VCA of a sign. They can then decide to either continue along thier original target or choose the newly perceived exit if it is better in terms of distance and time. The agent could also choose an alternative exit if they encounter a lot of congestion around the present target.

3.3.3 The Behaviour Sub-model

The behaviour sub model determines the response of the agent to external stimuli such as crowd following, group movement, hazards, etc. Some of the behavioural attributes available in the buildingEXODUS model will be discussed next.

3.3.3.1 Avoid Congestion

This is an option that can be chosen in the buildingEXODUS model that enables the agents in the simulation to avoid congested areas. Choosing this option along with the ‘local familiarity’ and ‘signage visibility’ options enables agents to redirect to other exits in their ‘Occupant Exit Knowledge’ if the other exit is less congested than the current exit they are heading to.

3.3.3.2 Extreme Behaviour

There are two main operational regimes in the buildingEXODUS model: extreme and normal behaviour. In the normal behaviour regime the agents will prefer to use the main or normal exits in the building whereas in the extreme behaviour regime the agents assign equal importance for normal and emergency exits. The exits in buildingEXODUS have an important attribute called ‘attractiveness’. If the attractiveness attribute of an exit is 100, then all occupants have knowledge of that exit whereas if the attractiveness attribute of an exit is 0 then no occupant has knowledge of it. Therefore in the scenarios involving signage, along with local familiarity and signage visibility options, the extreme behaviour mode is also chosen. The main exits are assigned an attractiveness of 100 and the emergency exits are assigned an attractiveness of zero. Thus, when the simulation starts all the agents are aware of the main exit(s) but none are aware of the emergency exits. All agents start moving towards the main exit. However, if they fall under the VCA of a sign pointing to another (emergency) exit, then the agents can gain knowledge of this exit and if the ‘avoid congestion’ option is chosen they can redirect to the other exit based on the congestion around the exits.

3.3.3.3 Social Influence

The agents in the buildingEXODUS model are capable of interacting with other agents using the *gene* attribute. Agents who share a common gene value can share spatial awareness such as exit knowledge. Inactive agents (those who have not started to evacuate) will respond when another agent with a common gene passes within 2 meters [Galea, et al., 2006].

3.3.3.4 Patience Attribute

Each agent is given a patience value which is a measure of the time they are willing to wait before considering an alternative action such as moving away from a queue or jumping over a row of seats, etc. The higher the value the more patient the agent is and the lower the value the less patient the agent is.

3.3.3.5 Impatient Flag

The patience value of the agents can be overridden by enabling the impatient flag. This guarantees that the agent will exhibit 'extreme behaviour' on waiting for a certain amount of time.

3.3.4 The Occupant Sub-Model

The attributes of the agent such as location, height, speed, agility, exit knowledge, etc is defined in this sub-model. The buildingEXODUS is a microscopic model which means that each agent has his/her own attributes and is capable of behaving independently.

3.3.5 The Hazard Sub-Model

This sub-model deals with the distribution of fire hazards. The hazards can be created within buildingEXODUS by manually entering data or can be imported from CFAST or SMARTFIRE data files [Galea, et al., 2006]. In order to use the data files, a consistent set of zones have to be created in the geometries used by buildingEXODUS and the model generating the fire hazards. The hazard data within SMARTFIRE was averaged over these zones to produce two values, a hazard value at an upper height of 1.7m and at a lower height of 0.5m. When occupants are standing they are exposed to the hazards at the upper height and when they are forced to crawl they are exposed to the hazards at the lower height. In buildingEXODUS, occupants crawl when the smoke concentration at head height exceed a critical value of 0.5/m [Gwynne, et al., 2001a]. The walk speed of the occupant is also reduced when occupants are forced to move through smoke [Galea, et al., 2006].

3.3.6 The Toxicity Sub-model

This sub-model deals with the effects that environmental conditions such as exposure to heat, hazardous gases have on the agent. The agent's walk speed can reduce due to exposure to hazards. The agents are capable of crawling if the smoke concentration increases beyond a certain level. There are two toxicity models implemented within buildingEXODUS which are the FED models of Purser [Purser, 2008] and Speitel [Speitel, 1995]. Purser's model considers the toxic and physical hazards associated with elevated temperature, HCN, CO, CO_2 and low O_2 and estimates the time to incapacitation [Galea, et al., 2006]. For the effects of heat Purser proposes a "time to pain" heat model for design purposes. This is considered to represent intolerable conditions that could affect escape capability (for example occupants may be willing or unable to enter an escape route under these conditions) at a radiant heat exposure dose of $1.33(kW.m^{-2})^{1.33}\cdot$min [Purser, 2008]. Other models are presented for "time to serious injury or severe incapacitation" representing more extreme conditions likely to prevent escape, and time to fatal exposures with extensive third degree burns at a radiant heat exposure dose of 16.7 $(kW.m^{-2})^{1.33}\cdot$min [Purser, 2008]. For example, Speitel has developed an alternative heat exposure model. The "time to pain" Purser model was considered too conservative for the prediction of failure to escape for The Station nightclub case. Therefore, the Speitel model was used to predict the incapacitation of people shown in this chapter. However, in practice, especially in the sunroom, conditions became extreme after 90 seconds in terms of both heat and toxic gases, so that both models predict incapacitation at this time [Galea, et al., 2009].

3.4 The SMARTFIRE Model

A research version of the SMARTFIRE V4.0 [Jia, et al., 2006] [Wang, et al., 2007] software was used by [Galea, et al., 2009] to generate the fire data that was used in this thesis to simulate The Station nightclub evacuation. SMARTFIRE uses a flame spread model [Jia, et al., 2006]. Because of the size of the computational domain, the fire simulation was carried out using the parallel version of SMARTFIRE [Grandison, 2007]. The predicted early burning locations in the full scale fire simulation modelled using SMARTFIRE is in good agreement with the photographic evidence of the actual fire and the predicted onset of flashover is similar to that produced by NIST [Grosshandler, et al., 2005]. The FDS simulation of the fire by NIST used a single ignition criterion (surface temperature) and predicted oxygen concentrations alone. The SMARTFIRE simulation of the fire used a three ignition criteria (ignition temperature, flame spread rate and the heat flux) and predicted concentrations of toxic gases such as CO, CO_2 and HCN. The analysis of The Station nightclub evacuation performed in this thesis differs from that performed by NIST in three main areas; (1) usage of an enhanced flame spread model, (2) usage of a toxicity generation model and (3) the evacuation is coupled to the fire simulation.

3.5 Evacuation Modelling Assumptions

The assumptions made in the evacuation simulations performed in this chapter are described in this section.

3.5.1 Population

Providence journal [Providence Journal., 2003c] published a list of the 440 people supposed to have been in the building during the incident. However, a recent press report has published the names of 462 people [Parker, 2007] supposed to have been in the nightclub during the incident. The simulations for this chapter were performed before the recent press release and hence all the simulations in this chapter only involve 440 occupants. Most of the simulated population are situated on or around the dance floor (see Figure 3-5) as there was a live band performance during the incident. The population density varied from 2.8 persons/m^2 on the dance floor to 0.72 persons/m^2 in the bar area. About 21 people were distributed in the storage, office, restrooms and dressing room areas. This distribution is very close to the safe occupant limits according to the building code regulations at the time [Grosshandler, et al., 2005].

3.5.2 Tenability

Untenable conditions are said to be reached when the temperature and heat flux raise beyond 120^{0}C and 2.5kW/m^2 or when the oxygen volume drops below 12% [Purser, 2008]. The probability of people getting out at untenable conditions is low and if they do manage to escape from the building they would probably get out with minor or serious injuries depending on the time they spend in the hazardous environment. The Available Safe Egress Time (ASET) for a building is the time that is available for occupants to safely exit the building. There are various ways in which the ASET can be calculated [Galea, et al., 2008] but for the simulations carried out in this chapter, 90 seconds which is the time it takes for most parts of the nightclub to become untenable [Galea, et al., 2009] [Grosshandler, et al., 2005] is considered to be the ASET.

3.5.3 Exits in the Building

There were three single door emergency exits and one double door main exit in The Station nightclub. One of the emergency exits, the kitchen exit, in The Station nightclub was however not considered for egress of patrons by the building codes existing at the time of the incident [Galea, et al., 2008]. During the incident less than 5% of the evacuees exited out of the kitchen exit. Hence in the simulations carried out in this chapter the kitchen exit is used only in those scenarios which depict the real incident and is not used otherwise.

The platform exit was blocked by flames and was unusable within 85 seconds after the start of fire. In the scenarios which depict the real incident the platform door is closed at 85 seconds. The bar exit would have been the least hazardous exit as this is the exit which is furthest from the start location of the fire. The main exit was the only double door exit in The Station nightclub. However, exit through the main door was hampered by a single door along the corridor leading to the main exit. This has been taken into account by modelling a double door (2m) for the main exit and having an opening of about 0.5m internally leading to the main door [see Figure 3-4].There was a crowd crush at the main exit by about 1 minute and 42 seconds.

3.5.3.1 Exit Usage

The Providence Journal interviewed 247 out of the 340 survivors. The escape route of these 247 survivors has been published in [Providence Journal, 2003c]. The first row of Table 3-1 shows the number of people using the different exits according to this report. The second row shows the same statistics interpolated to the actual number of survivors (340). The data in this row is considered to be the best estimate of how all the survivors in The Station nightclub escaped. The third row shows the same statistics interpolated to the actual population of 440 who were in The Station nightclub on the night of the incident.

The kitchen exit has been the least used exit as not many knew the existence of this exit and the sign pointing to the kitchen exit was not well placed. The platform or stage exit has been used by very less people as the fire started at the stage and the areas around this exit was quickly engulfed in flames. The staff in The Station nightclub did not realise the magnitude of the disaster and initially prevented patrons from using this exit. The band members alone were allowed to use it during the initial phase of the evacuation. Considering that the main exit was almost double the size of the bar exit it seems natural that the main door was used by almost double the number of occupants than the bar exit.

Table 3-1: Exit usage of the 247 survivors and interpolation of the usage to 340 and 440 people.

No of Survivors	Main Door (36%)	Bar Exit (19%)	Platform Exit (8%)	Kitchen Exit (5%)	Bar-room Windows (22%)	Sun-room Windows (10%)
247(Interviewed)	90	46	20	12	54	25
340(Interpolated to the number of survivors)	124	63	27	17	74	34
440(Interpolated to the actual population)	160	82	36	21	96	45

3.5.3.2 Exit Times

Table 3-2 shows the times at which the different exits opened and closed during the incident. This data is taken from the observations made in the official report [Grosshandler, et al., 2005] who used the evidence gathered from the WPRI video of the incident.

Table 3-2 : Opening and closing times of the different doors and windows in the nightclub.

Exits	Opening Time (seconds)	Closing Time (seconds)
Kitchen Exit	60	Open all through
Bar Exit	45	Open all through
Main Exit	30	< 102 seconds(Crowd Crush)
Platform Exit	29	< 85 seconds(Blockage due to flames)
Sunroom Windows(4)	78, 100, 110, 120	Open all through
Barroom windows(3)	80, 80, 80	Open all through

3.5.4 Signage

NIST has published photographs of the six exit signs located in the nightclub from the video captured on that night [Grosshandler, et al., 2005] just before the incident. The location of the six exit signs in the nightclub as represented in Exodus is shown in Figure 3-4.

3.5.4.1 Signage Features in Exodus

In the scenarios which implement signage, the main exit is assigned an attractiveness of 100 which implies that all agents have knowledge of this exit. Considering that all the occupants entered the nightclub through the main door it is reasonable to assume that all the occupants have knowledge about the main exit. The other three exits (including the kitchen exit in some of the scenarios) are modelled as emergency exits and are assigned an attractiveness of zero.

Occupant interaction with signage can either be modelled as agents having a cone of vision to check if the sign objects fall within this cone or by creating a Visibility Catchment Area (VCA) for the signs to determine whether the agent falls within the VCA. The latter approach has been used in the buildingEXODUS model as it is more computationally efficient. The original approach was to represent the VCA by a semicircular region around the sign [Filippidis, et al., 2004]. The revised approach, based on empirical evidence is to use a circular VCA as described in [Xie, et al., 2007] which has been used in the simulations described in this chapter.

According to Xie, et al [Xie, et al., 2009] agent interaction with signage needs to take into account three factors: 1) given that the agent is within the VCA what is the probability that they can physically see the sign which depends on the orientation of the agent with respect to the sign 2) given that they are physically able to see the sign what is the probability that they actually see it? and 3) given that the agent sees the sign, what is the probability they act on the information provided by the sign? The version of the buildingEXODUS model used in this chapter to model agent interaction with signage is based on [Filippidis, et al., 2006] which only takes the first factor into account – the orientation of the agent with respect to the sign. The second and third factors have been studied through real world experiments and the data has been incorporated into a research version of the buildingEXODUS model [Xie, et al., 2009]. The analysis of the simulations using the agent signage interaction model proposed by Xie, et al could be considered for future work.

The agent on noticing the sign may deviate to the newly learnt exit or may continue to his initial target exit based on the distance to reach the exits and the congestion around the exits [Gwynne, et al., 2001b].

During the actual incident, the visibility range of the signs would have varied over time. According to Xie [Xie, 2011], the visibility range of the signs in The Station nightclub would have been about 30m from 0 – 66 seconds after the start of fire covering about 70% of the geometry. At 81 seconds the coverage area of the signs drop to as low as 5% of the building. At 86 seconds the exit signs are hardly visible (approximately 1 – 4 m range). The influence of smoke on the visibility of signs has been implemented in a research version of buildingEXODUS [Xie, 2011]. However, this version was unavailable when the simulations presented in this chapter were performed. There was no provision to change the visibility range of the signs during the simulations in the version of buildingEXODUS used to carry out the simulations presented in this chapter. Therefore, an average visibility range of 10 meters has been assumed and only the simulation results using 10m visibility range has been presented in this chapter.

3.5.5 Response Times

All the scenarios in this work either make use of instant response times or real response times. Instant response times imply that occupants react immediately as soon as the simulation starts. Real response times means that the occupants in different areas of the nightclub react at approximately the same times as deduced from the real incident. The timeline of events published by NIST and video recordings of the incident was used to estimate the actual response times of the people in various regions of the nightclub. The distribution of the response times within the nightclub is as shown in Figure 3-5.

According to NIST the first patrons recognised the fire at 24 seconds, the band stopped playing and majority of the crowd started evacuating at 30 seconds. Hence in Figure 3-5 the people in red who are in the vicinity of the stage are assigned lowest response times ranging from 25 to 30 seconds at random. The green coloured people in the main bar, side bar and dining hall who are slightly away from the origin of fire are given a response time ranging from 30 to 35 seconds. Finally the yellow coloured people in the remote regions of the nightclub are given a response time of 35 to 41 seconds. This is due to the fact that the fire alarm sounded at 41 seconds.

Figure 3-5: **People in red have response times ranging from 25-30 seconds, people in green have response times ranging from 30-35 seconds and people in yellow have response times ranging from 35-41 seconds.**

3.5.6 Inclusion of Hazards

In the reconstruction scenarios (see Section 0) and the *what-if* scenarios (see Section 3.6.5) the fire simulation results produced by SMARTFIRE [Galea, et al., 2009] were used for coupled fire and evacuation analysis. The physiological effects on an individual exposed to the toxic and thermal environment are determined using the Fractional Effective Dose (FED) concept [Purser, 2008].Within buildingEXODUS two models are provided for the determination of FIHr (an individual's cumulative exposure to radiative heat), the so-called Pain Threshold model (in which the dose required to cause effect (Dr) is 80, which is the equivalent to an exposure of 2.5 kW/m2 for 24 sec) and the Incapacitation model (in which Dr = 1000, the equivalent to an exposure to 2.6 kW/m2 for 5 min which can result in a 1% mortality) [see Appendix C for more information]. Given the severe nature of the fire and that the occupants could not exercise exposure choice; the latter less conservative value is used here. The Speitel model has been used for the calculation of FIHc (an individual's cumulative exposure to convected heat). The VCO_2, 1.0 option has been used for the calculation of the FIN attribute [see Appendix C].

3.6 Evacuation Simulation Results

The complete set of results carried out during this research has been presented in Appendix B. In this section, three set of scenarios are presented – optimal scenarios, event reconstruction scenarios and *what-if* scenarios. The optimal scenarios assume ideal conditions without the coupling of fire. The event reconstruction scenarios and the *what-if* scenarios discuss the coupled fire/evacuation simulations of The Station Nightclub fire. Details of the fire simulation have been provided in [Galea, et al., 2009] (see Appendix A.1).

Prior to this research NIST conducted evacuation simulations of The Station nightclub [Grosshandler, et al., 2005] using buildingEXODUS and SIMULEX. The total population used in the NIST study was 420 people, which was the maximum allowable occupancy according to the building codes existing then. The simulations in this chapter use 440 occupants which is the actual number of occupants in the building during the incident [Providence Journal., 2003c]. A major difference between this research and the NIST report is that they did not couple the fire with the evacuation which has been performed in this thesis. The NIST report used only the nearest exit method to model the exit selection behaviour of people whereas in this chapter more complex exit selection methodology such as exit potentials and signage has been used. The differences in the fire modelling methodology used in this thesis and the NIST report have been described in Section 3.4.

3.6.1 Simulation Setup

The important experimental setup for carrying out the simulations in this chapter will be described in this section.

3.6.1.1 Population distribution

On the night of the fire there was a performance by the Great White band and hence it is assumed that most people were concentrated in the dance floor area and the areas near the platform. The distributions of the 440 occupants are shown in Figure 3-5, with a population density varying from 2.8 persons/m^2 at the dance floor to 0.72 persons/m^2 at the bar area. About 21 people were distributed in the storage, office, restrooms and dressing room. This distribution is very close to the safe occupant limits according to the building code regulations at the time [Grosshandler, et al., 2005].

3.6.1.2 Response times

In the *optimal scenarios* (see Section 3.6.3) OS1, OS2 and OS3, instant or zero response times are used. In the *event reconstruction* and *what if* scenarios, the actual response times as shown in Figure 3-5 were used.

3.6.1.3 Exit widths and flow rates

The width of the exits in The Station Nightclub taken from the NIST report [Grosshandler, et al., 2005] is shown in Table 3-3. Though the main exit is slightly less than 2 meters and the other exits are less than 1 meter, they have been represented as being exactly 2 meters and 1 meter respectively. This is as a result of the nodal spacing in buildingEXODUS being of 0.5 meters [Galea, et al., 2006]. However, the HMSO flow rates of the exits (1.33 occupants/m/s) have been accordingly modified and the values used are shown in the third column of Table 3-3.

Table 3-3: The widths and flow rates of the exits used in the simulations.

Exit	**Width mm(in)**	**Flow rate (occupants/m/s)**
Main exit	1829 (72)	1.21
Bar exit	914 (36)	1.22
Platform exit	914 (36)	1.22
Kitchen exit	914 (36)	1.22

3.6.1.4 Exit signs

The usage of signs in the building was described in Section 3.5.4. Scenario OS2, ER1 and all scenarios in the '*what if'* scenarios make use of the signs to represent agents exit selection. In these scenarios where signs are used, all agents initially start with knowledge of the main exit alone. There are two circumstances under which the agents could redirect:

1. On falling within the Visibility Catchment Area (VCA)
2. On encountering congestion around the exit

In the first instance agents redirect to the nearest exit when they fall within the VCA of a sign pointing to a new exit they were unaware of. In the second instance, when they encounter congestion at their target exit, agents would choose the exit that takes the least time. The changes introduced with the implementation of the wayfinding model in this thesis have been described in Chapter 7, Section 7.5.4.

3.6.1.5 Exit open/close times

In the Optimal Scenarios, all exits except the kitchen exit are open all the time. The Kitchen exit in these scenarios is kept closed as the codes existing then prohibited its usage by patrons [Grosshandler, et al., 2005]. However, during the actual incident, this exit was used by 5% of the survivors and hence it has been used in the *event reconstruction* and *what if* scenarios. In these scenarios windows have been introduced as exits and the close/open times of all exits match the actual open/close times during the incident based on the NIST report (see Table 3-2).

3.6.1.6 Hazard settings

The inclusion of the SMARTFIRE data providing details on the hazards produced was described in Section 3.3.5. The simulations in this section make use of the Speitel model as specified in Section 3.3.6. The incapacitation model has been used to model an individual's cumulative exposure to radiative heat (see Section 3.3.6). The VCO_2, 1.0 option has been used for the calculation of the FIN attribute (see Appendix C).

3.6.2 Summary of the Simulation Settings

Table 3-4: Simulation settings.

Scenarios		**Exit Selection**	**Redirection due to congestion**	**Exit open/close Times**	**Response Times**	**Hazards**	**Population**
Group	**Scen-ario**						
OS	**OS1**	Nearest	No	Kitchen exit closed. Other exits open all time	Zero or instan-taneous	No	Maximum population density as defined by building Codes (See Chapter 3, Section 3.6.1.1).
	OS2	Optimal	No				
	OS3	Signage	Yes				
ER	**ER1**	Signage	Yes	All exits open/close times match the actual opening times during the incident (See Table 3-2).	Real response times observed during the incident (see Figure 3-5).	SMART-FIRE data file is used. (see Section 3.5.6 for more details).	
	ER2	Optimal	No				
WI	**WI1**	Signage	Yes				
	WI2	Signage	Yes				
	WI3	Signage	Yes				
	WI4	Signage	Yes				
	WI5	Signage	Yes				

Table 3-4 provides a summary of the simulation settings used in all the scenarios described in this chapter. There are three main set of scenarios – OS refers to the *optimal scenarios* where optimal conditions are assumed such as instant response times, all exits open all time, no inclusion of hazards; ER refers to *event reconstruction* scenarios where the main aim is to reconstruct the real incident in buildingEXODUS which therefore assigns response times, exit open/close times and hazards from information gathered during the actual incident; WI scenarios are used to determine what would have happened if a few alterations had been performed in The Station nightclub. More information on these scenarios will be provided in the following sections.

3.6.3 Optimal Scenarios

The scenarios in this section assume ideal conditions; for instance all occupants responding instantly, all exits are functioning perfectly. The scenarios performed in this section may be typically considered by the building designers for evaluating the Required Safe Egress Time (RSET). RSET is the time it takes for a population to exit safely from an enclosure. Scenario OS1 makes use of nearest exit usage which is the default option in most evacuation models. Scenario OS2 makes use of optimal exit usage where agents are given target exits in such way as to obtain the least possible evacuation time. Scenario OS3 makes use of signs to direct the exit usage of the agents.

OS1: Nearest Exit Usage

OS2: Optimal Exit Usage

OS3: Exit Usage based on Signage

Table 3-5: Average of the evacuation statistics of 20 repeat simulations of the optimal case scenarios.

Scenarios	Kitchen Door	Bar Door	Main Door	Platform Door	Total Evacuation time (seconds)	Evacuation time for 420 people (seconds)	People Left after 90 seconds
OS1	0	23	211	206	188.92	170.48	158
OS2	0	113	214	113	115.15	105.20	80
OS3	0	56	301	83	163.50	153.37	160

Table 3-5 shows the average evacuation statistics of 20 repeat simulations of the optimal case scenarios. The evacuation time for 420 people is an important statistic as this denotes the RSET for the maximum allowed occupant load of The Station nightclub. The people left in the building after 90 seconds is also an important statistic as the ASET for The Station nightclub was 90 seconds according to [Galea, et al., 2009] [Grosshandler, et al., 2005]. Therefore, it is reasonable to assume that people left in the building after 90 seconds will either succumb to death or suffer serious injuries.

From the results of scenario OS1, it is seen that the main exit and platform exit were the nearest exits to most of the occupants in the building. The bar exit seems to be the furthest of the three exits. In scenario OS2, it is seen that the main exit with a double door has been used by about twice the number of people as those using one of the other single door exits. This scenario gives the lowest number of people remaining in the building after 90 seconds. It is tragic to note that the spread of the fire during the incident was so quick that even in the most ideal situation 80 people are still left behind after ASET.

In scenario OS3, all agents start with knowledge of the main exit. They gain knowledge of the emergency exits (platform and bar exits) during the simulation when they fall within the VCA of the signs. Though the number of people remaining in the building after 90 seconds is almost similar to the OS1 scenario, the total evacuation time has decreased by 19%. This is as a result of more people in OS3 using the main door (double door) which has more capacity than the platform exit door (single) door.

Table 3-6: First and last used times of each exit in the optimal case scenarios.

Scenarios	**Bar Door**		**Main Door**		**Platform Door**	
	First Used (seconds)	**Last Used (seconds)**	**First Used (seconds)**	**Last Used (seconds)**	**First Used (seconds)**	**Last Used (seconds)**
OS1	2.51	22.2	6.64	118.5	2.27	188.9
OS2	2.51	102.9	6.36	115.1	2.27	104.2
OS3	3.69	159.2	6.77	163.5	3.68	78.2

Table 3-5 shows the average evacuation statistics of 20 repeat simulations of the optimal case scenarios. The evacuation time for 420 people is an important statistic as this denotes the RSET for the maximum allowed occupant load of The Station nightclub. The people left in the building after 90 seconds is also an important statistic as the ASET for The Station nightclub was 90 seconds according to [Galea, et al., 2009] [Grosshandler, et al., 2005]. Therefore, it is reasonable to assume that people left in the building after 90 seconds will either succumb to death or suffer serious injuries.

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Table 3-5 shows the average evacuation statistics of 20 repeat simulations of the optimal case scenarios. The evacuation time for 420 people is an important statistic as this denotes the RSET for the maximum allowed occupant load of The Station nightclub. The people left in the building after 90 seconds is also an important statistic as the ASET for The Station nightclub was 90 seconds according to [Galea, et al., 2009] [Grosshandler, et al., 2005]. Therefore, it is reasonable to assume that people left in the building after 90 seconds will either succumb to death or suffer serious injuries.

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Table 3-6 shows the times of the first and last use of the three exits in the *Optimal scenarios*.

These provide useful information such as identify the exit that was last used and help calculate an estimate of the flow rates of exits assuming they were constantly used. In OS1 the main and the platform doors have been used almost equally as these exits are the two nearest exits for majority of the population. However, the main door is twice the size of the platform door and hence has been the last used exit. In OS2, an attempt was made to utilise all three exits equally by manipulating their potentials (see Section 3.3.2.1). The bar and platform doors have finished at about the same time. The main exit has finished 11 seconds later. In OS3, the main door is used more than the other doors and hence is the last to finish deciding the total evacuation time.

In OS3, the main door has been used for a total of 156.73 seconds with 301 people using it. Assuming that the main door was used continuously for this period the flow rate of this door is 1.92 occupants/second. From Table 3-3 it is seen that the maximum flow rate of the main exit is 2.42 occupants/second. Therefore the achieved flow rate is within the limits of the maximum flow rate. The platform door has been used for a total of 74.52 seconds with 83 people using it. The flow rate of this door is thus 1.11 occupants/second. This is within the maximum allowable flow rate of 1.22 occupants/second for the platform exit.

3.6.4 Event Reconstruction Scenarios

The scenarios in this section are an attempt to simulate the events of the actual incident in the buildingEXODUS model. Actual response time as specified in Figure 3-5 are used, windows are introduced as exits (see Figure 3-6) in the building with the open/close times of the windows as in Table 3-2. The development of the fire data used in these simulations has been described in [Galea, et al., 2009]. Two scenarios are discussed in this section:

ER1: Exit usage based on signage
ER2: Exit usage based on Exit Potentials

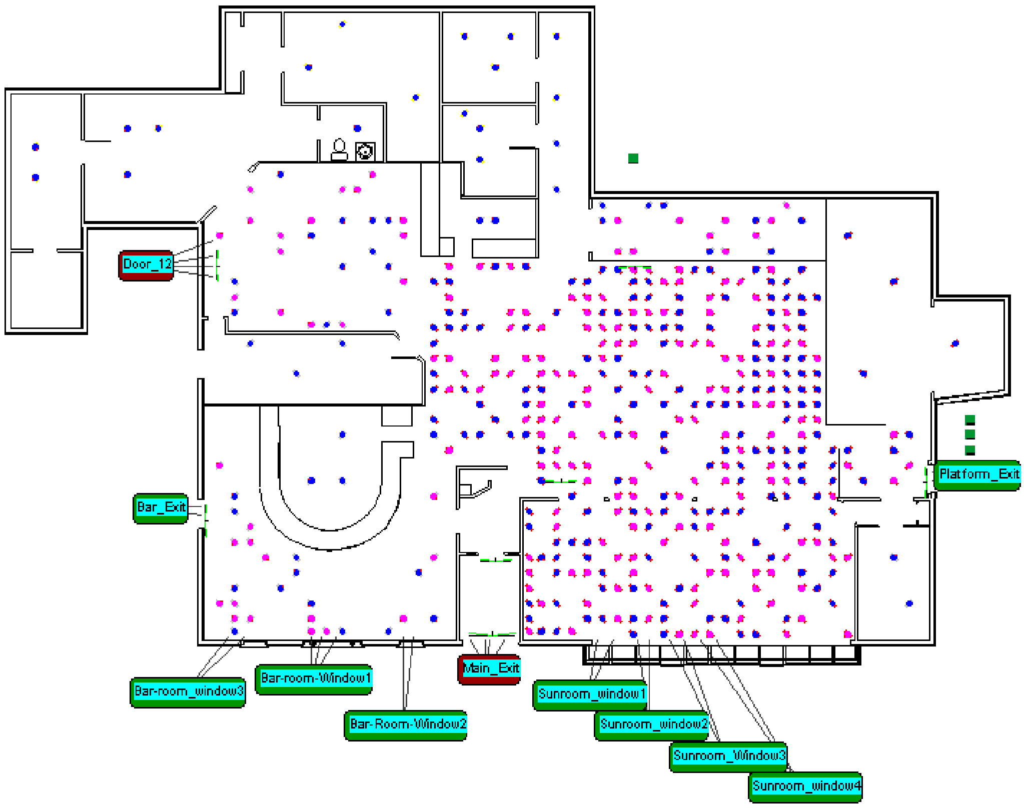


Figure 3-6: Door 12 is the additional door added for scenario WI3. The kitchen door has been removed. There are two signs for the extra door: one sign on top of the door and another on the wall of the dining area.

Table 3-7: Average of the evacuation statistics of 20 repeat simulations of the event reconstruction scenarios.

Scenario	Kitchen Door	Bar Door	Main Door	Platform Door	Bar-room Windows	Sun-room Windows	People left after 90 seconds	Total Evacuation time (seconds)	Fatalities
ER1	23	26	98	63	10	31	234	115.48	189
ER2	19	61	90	32	55	31	217	115.25	153

In scenario ER1 the exit usage is based on the exit signs which are similar to scenario OS3. However, the actual exit usage as shown in Table 3-1 was found to be very different from the exit usage in scenario ER1. Thus, in scenario ER2, the door potentials were manipulated to reflect the actual exit usage as close as possible. The results of the event reconstruction scenarios are shown in Table 3-7. In scenario ER1 the number of fatalities has been overestimated by 89% whereas in scenario ER2 the error rate has come down to 53%. The error rate in the estimation of the fatalities has been attributed to a slightly advanced prediction of the flash over in the fire analysis which has been described in more detail in [Galea, et al., 2009].

3.6.5 What-If Scenarios

In this section a number of alterations are performed to The Station nightclub building and the effect of these alterations are analysed. This is an accepted engineering approach which has been adopted in the past in the analysis of The Gothenburg Dance Hall Fire [NFPA, 1998], World Trade centre incidents [Galea, et al., 2004] and in the NIST analysis of the Rhode Island fire [Grosshandler, et al., 2005] as well. Five scenarios have been performed in this section:

WI1: The single door leading to the main exit removed.
WI2: The main door corridor removed.
WI3: Replacing the kitchen door with an additional door.
WI4: Combination of WI3 and WI1.
WI5: Combination of WI3 and WI2.
In scenario WI1, the single door leading to the main double door was removed. Though the main door was a double door, the exit through this door was hampered by the single door leading to the main door. In scenario WI2, the entire corridor leading to the main exit has been removed. The designers of the nightclub may have considered the existing design to have been a good one. The club patrons queue up to the ticket taker area, buy tickets and then can either go left to the bar room or right to the stage area. However, this design resulted in a severe crowd crush in the nightclub during the actual incident. Scenario WI2 thus examines the effect of removing this corridor. In scenario WI3, the single door kitchen exit is replaced by a double door of the same size as the main exit and two additional signs are placed to attract people to this exit (see Figure 3-6). In scenario WI4, along with replacing the kitchen exit by a double door as in WI3, the single door leading to the main double door is also removed as in WI1. In scenario WI5, along with replacing the kitchen door by a double door as in WI3, the main door corridor is also removed as in WI2.

All the *What-If* scenarios make use of signage to guide the agents to the exits. Thus, the effect of removing the single door leading to the main exit can be analysed by comparing the results of scenarios WI1 and ER1. In scenario WI1 there is a 12% decrease in the number of fatalities compared to scenario ER1. Removing the main door corridor altogether in scenario

WI2 has a more drastic effect bringing down the number of fatalities by 35% compared to scenario ER1. Adding an additional door has also brought about a similar reduction 33%. A combination of adding an additional exit and removing the corridor in scenario WI4 has almost halved the number of fatalities as in scenario ER1. Scenario WI5 produces the least number of fatalities with a 60% reduction in the number of fatalities compared to the original building design in scenario ER1.

Table 3-8: Average of the evacuation statistics of 20 repeat simulations of the *What-If* scenarios.

Scenarios	Kitchen Door	Bar Door	Main Door	Platform Door	Bar-room Windows	Sun-room Windows	People left after 90 seconds	Total Evacuation time (seconds)	Fatalities
WI1	22	24	123	63	10	32	219	114.82	167
WI2	22	23	149	62	27	34	193	116.75	122
WI3	101	23	89	63	5	31	158	115.25	126
WI4	115	22	122	62	6	23	137	115.25	91
WI5	68	28	149	62	21	35	138	116.92	76

3.7 Limitations of the buildingEXODUS model

Table 3-9: Summary of the wayfinding features in buildingEXODUS

Wayfinding features in buildingEXODUS	
Exit choice	Nearest exit usage
	Optimal exit usage
	Signage
Signage	Redirection due to new exit knowledge
	Redirection due to congestion
Social Interaction	Sharing of exit knowledge using the gene attribute (see Section 3.3.3.3)

Table 3-9 provides a list of the wayfinding features existing in buildingEXODUS. The wayfinding in buildingEXODUS is simply based on exit finding, not route selection. Occupant interaction with exit signs which are an important tool for wayfinding is the most advanced wayfinding feature existing in buildingEXODUS. The wayfinding research in this thesis addresses route choice instead of exit choice. The Station nightclub is a simple enclosure where modelling exit choice is sufficient. However, in complex enclosures where there is more than one possible route to the same exit, it is very important to model route choice in addition to exit choice. This is one of the main goals of this thesis.

Similar to many of the existing evacuation models, buildingEXODUS also uses simplistic wayfinding rules. The potential map method (default option) assumes that all agents have perfect knowledge of the structure and hence take the shortest paths to the exits. The local familiarity method leads to a more sophisticated model where agents have knowledge of only some of the exits. However, the agents still take the shortest path to the nearest exit in their 'Occupant Exit Knowledge'. If there exist two paths to the same exit then all agents will take the shortest path regardless of the congestion along that path. However, it is possible to specify the routes of the agent by manually assigning the 'Occupant Itinerary List' of the agents. However, itineraries were not really intended to represent wayfinding and results in a static model where the agents follow predefined routes and do not respond to the actual situation.

Signage and redirection due to congestion offer more complex wayfinding behaviour. When agents fall within the VCA of a sign they gain knowledge of the exit the sign points to and can redirect to this exit if they estimate that continuing along the present route will take a longer time. However, the rules determining the redirection are simplistic and consider only the distance and the queue at the exits. Similar to the other evacuation models, buildingEXODUS considers only distance and time as factors affecting wayfinding. Though distance and time are important there are other factors (see Chapter 2, Section 2.2.4) that need to be considered.

There are significant differences in the locations of the fatalities from the buildingEXODUS simulation shown in Figure 3-7 and in the actual locations of the fatalities shown in Figure 3-2. A major difference is noticed in the back bar, storage, rest rooms and office (see Figure 3-1). About 26 fatalities have occurred in these areas during the actual incident whereas there are no fatalities in these regions in any of the buildingEXODUS simulations. In reality the occupants in The Station nightclub may have reached these areas either because they were lost or because these areas would have been the least hazardous before flashover occurred. The main reason for the mismatch in the location of the fatalities may be attributed to: 1) buildingEXODUS does not model the redirection of agents due to hazardous conditions and 2) buildingEXODUS assumes that all agents are aware of at least one exit and does not model the possibility of the agents getting lost due to bad visibility. The buildingEXODUS model follows very simplistic rules where all agents have knowledge of at least one exit and hence no agent gets lost. The buildingEXODUS model consists of the hazard and toxicity sub-models which model the effect of hazards and smoke on the evacuating occupants. However, it does not model the wayfinding behaviour of people under these circumstances.

Figure 3-7: A snapshot showing the location of the fatalities in the ER2 scenario carried out using buildingEXODUS.

The buildingEXODUS model represents communication between agents by the sharing of exit knowledge with members of the same gene value (see Section 3.3.3.3). However, the model can be extended by allowing route knowledge to be shared as well. At times, in evacuation situations people just follow the person in front [Korhonen and Heliovaara, 2011]. Representation of group behaviour within buildingEXODUS could be considered for future work.

The agents in buildingEXODUS have physical attributes such as height, age, etc., behavioural attributes such as patience, drive, etc. However, for the wayfinding model more attributes need to be added such as their preference for shortest paths, least time paths, etc [Golledge, 1995a] [Golledge, 1995b]. The spatial knowledge of the agents is limited to exit knowledge. This needs to be modified to represent route knowledge as well.

There are a lot of useful features existing in the buildingEXODUS model such as the occupant sub-model, the movement sub-model and the behavioural sub-model features which can be utilised by the wayfinding model developed in this thesis. The buildingEXODUS model can also benefit from the introduction of the wayfinding model which should produce more realistic wayfinding characteristics and hence more realistic evacuation results.

3.8 Conclusions

The second major question posed in Chapter 1 "How do existing evacuation models represent human wayfinding" has been answered in this chapter by reconstructing a real incident in buildingEXODUS. The evacuation simulation results of The Station nightclub incident have been presented and analysed in Section 3.6. Several scenarios were carried out. The Optimal Scenarios considered optimal conditions such as no fire, no blockage, instant response times, etc. The Event Reconstruction Scenarios took a more pragmatic approach trying to match the actual events that took place on the night of the incident. The *What-If* scenarios analysed how the evacuation process of The Station nightclub could have been improved by making minor modifications to the design of the building.

The main purpose of analysing the Station nightclub incident in this chapter was to understand evacuation modelling concepts, study the existing wayfinding features in buildingEXODUS (see Table 3-9), to identify additional wayfinding features (see Section 3.7) to be included in this thesis and to explain the wayfinding difficulties people encountered in The Station nightclub. The cognitive map of the people in the building was limited to the knowledge of the main exit and the platform exit. Once the platform exit was blocked due to fire, people headed to the main exit thus causing a crowd crush at the main exit. The placement of the bar exit and the kitchen exit was such that very few occupants were aware of them. Even though the bar exit was close by, people still broke the windows in the bar room to exit the building. The kitchen exit was only used by the staff that was aware of its existence. More signs could have been placed to attract more people to this exit.

The limitations of the buildingEXODUS model and the wayfinding behaviour of the occupants during the actual incident have been analysed in Section 3.7. The main limitation of the buildingEXODUS model is that like other evacuation models, wayfinding is simplified as exit choice with the only influencing factors being distance and time. The Station nightclub geometry was a simple enclosure not containing many routes and hence buildingEXODUS was able to model it well. However, for large complex enclosures such as shopping malls, where there will exist many possible routes, more complex wayfinding strategies need to be implemented. More factors than just distance and time need to be considered as well.

In order to identify the wayfinding factors that need to be included in the wayfinding model past urban wayfinding studies were reviewed which is described in Chapter 2, Section 2.3.These factors will be used by the agents in the wayfinding model to choose between routes instead of exits. However, the agents require a set of routes in order to select one. In the next chapter, the spatial representation and generation of choice set of routes, two very important aspects of a wayfinding model are described.

4 Implementation of Route Choice Set Generation Algorithms

4.1 Introduction

The purpose of this chapter is to answer Questions 2 and 4 posed in Chapter 1 concerning the spatial representation techniques and route choice set generating algorithms. Existing evacuation models make use of optimal path planning algorithms such as the A*, Dijkstra or potential fields to assign the shortest routes to the agents in the simulation [Pathfinder, 2009a, b]. However, it is important to provide agents alternate routes or a choice set of routes to choose from [Daamen, 2004]. Multi Criteria Decision Analysis theory [Triantaphyllou, E., 2002] can then be applied by the agents to choose a route from the choice set. This chapter introduces the choice set generation techniques or algorithms developed in this thesis. Algorithm 1 makes use of a tree of paths to generate a large number of routes. Algorithm 2 quickly generates a limited number of routes. Algorithm 3 is a modification of the Yen's algorithm [Martins and Pascoal., 2003] to generate the K shortest paths between a given source and destination.

The choice set generation algorithms described in this chapter are all graph search algorithms and hence require a graph of the building. Therefore, spatial representation which is the conversion of a building geometry into a connectivity graph is first described in Section 4.2. The pseudo code of the three route choice set generation algorithms is described in Section 4.3. The working of the three algorithms is then tested by finding the routes in three hypothetical buildings. The paths found by the algorithms for these three test cases is analysed in Section 4.4. The computational complexity of the algorithms is then described in Section 4.5. The chapter ends with concluding remarks.

4.2 Spatial Representation

Spatial representational is generally done by means of graphs. The buildingEXODUS model is capable of producing two kinds of graphs: room graphs and route graphs. The room and route graphs are explained by considering the building 1 geometry shown in Figure 4-1. The good features of the room and route graphs have been combined to produce a connectivity graph which was found to be more suitable for the wayfinding model.

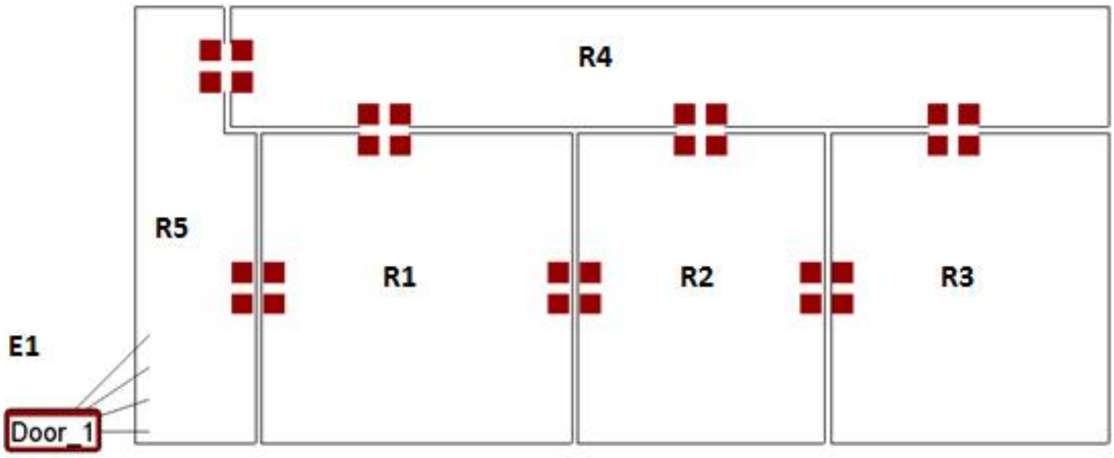


Figure 4-1: Building1 consisting of 3 rooms (R1 to R3), 2 corridors (R4 and R5) and an external exit E1.

4.2.1 Room Graph

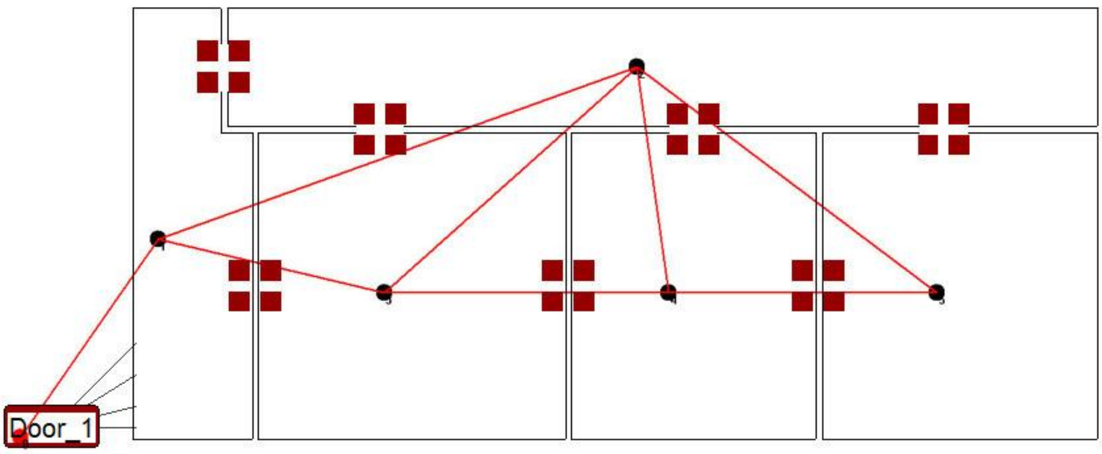


Figure 4-2: The room graph of Building 1 overlaid on the Building 1 geometry. The room nodes are represented by black circles and the external exit by a red circle.

The room graph for Building 1 is shown overlaid on the actual building in Figure 4-2. A room node is placed at the geometric centre or centroid of the room. Figure 4-2 was created by visually merging the room graph with the building geometry and hence the room nodes may not be exactly at the centre of the rooms. The room graph is thus a very simple representation of the connectivity of the rooms in the geometry. However it does not contain a lot of information such as the presence of the internal exits in the rooms. Also the distance between the rooms is not accurate. For example the distance between rooms R3 and R4 is the length of the arc connecting them whereas the actual traversal distance will be longer as the person has to go through an internal exit to reach room R4 from R3.

4.2.2 Route Graph

The route graph of Building 1 overlaid on the Building 1 geometry is shown in Figure 4-3. In addition to the room nodes, the internal exits are represented by grey circles and waypoint nodes are represented by cyan circles. The waypoint nodes generated by buildingEXODUS denote changes in direction according to the distance map (see Appendix [D]) and help in creating a smother path. The route graph is more complicated but overcomes the disadvantages mentioned regarding the room graphs. The distances between the nodes are more accurate. The waypoint nodes are useful for a short term movement model which is responsible for physically moving the agents. However, it was decided that the additional accuracy provided by the waypoint nodes was not required as the wayfinding model is only concerned with long and medium term goals (see chapter 1, Question 7.1). The more nodes in the graph the more time it takes to run the graph search algorithms described in this chapter. Hence the waypoint nodes were removed the result of which is the connectivity graph discussed in the next section.

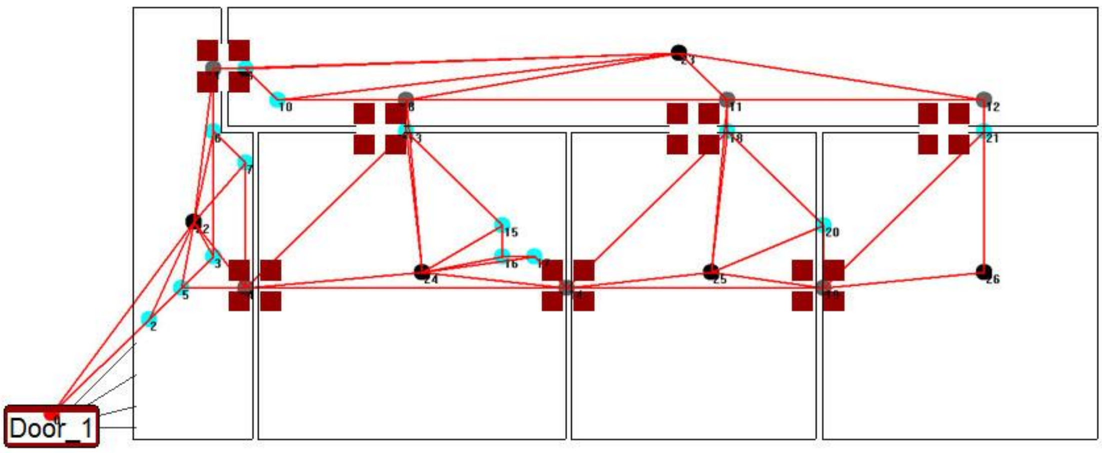


Figure 4-3: The route graph of Building 1 overlaid on the Building 1 geometry.

4.2.3 Connectivity Graph

The connectivity graph of Building 1 is shown in Figure 4-4 and is a result of removing the waypoint nodes from the route graph and re-establishing the connectivity between the other nodes. The connectivity graph is simply a mathematical graph, the connectivity of which is representative of the enclosure. The key elements of the enclosure are the rooms (and corridors), the internal exits and the external exits. Each of these elements is considered a node in the graph. These nodes are linked by arcs which represent the actual connectivity between the enclosure elements.

A room node is placed at approximately the centre of each room based on the average of the (x, y) values of all nodes in the room. An internal exit node is placed at the centre of the cluster of nodes forming the internal exit. The connectivity graph of Building 1 shown in Figure 4-4 is a schematic representation of the actual connectivity graph produced.

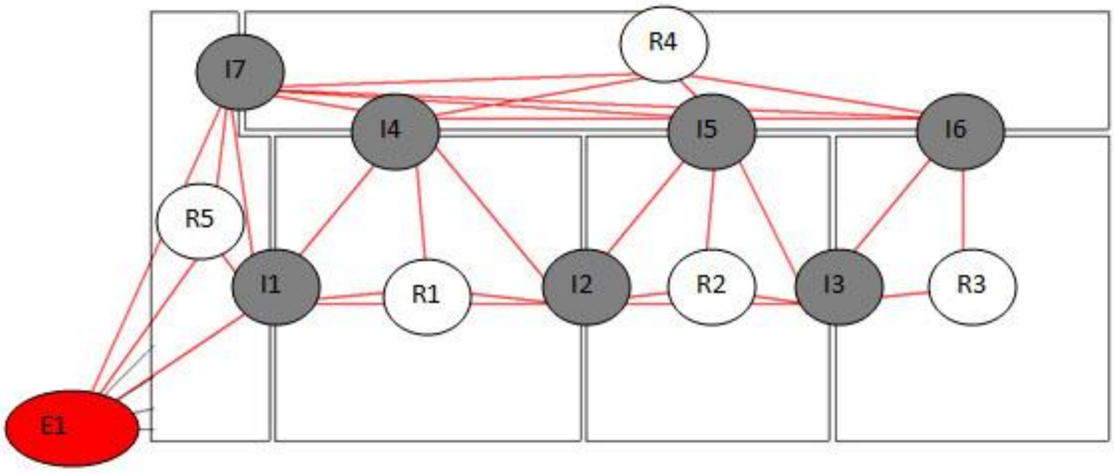


Figure 4-4: Connectivity graph of Building 1 overlaid on the Building 1 geometry. The internal exits are replaced by the grey nodes, the rooms are represented by the white nodes at the centre of each room and the external exit is represented by the red node.

4.3 Route Choice set Generating Algorithms

In this thesis, three algorithms or methodologies are proposed to generate route choice sets. The first algorithm is a brute force method which tries to create a tree giving all possible paths from all rooms in the geometry to all exits. The second algorithm gives the shortest path from all internal exits to all external exits in the building. The third algorithm modifies an implementation of the Yen's algorithm [Martins and Pascoal., 2003]. A more detailed description, the performance, advantages and disadvantages of each algorithm is given below.

4.3.1 Algorithm 1

The connectivity graph of the building is converted into a tree of paths. Tree of paths is the tree generated by Algorithms 1 and 2. The exit nodes form the root nodes of the tree. Nodes are then added in the following order: exit nodes, room nodes and then internal exits. This order is followed as people will tend to move from their present room to an internal exit to another room and so on until they are in the final room from which they exit the enclosure. Figure 4-5 shows the pseudo code of this algorithm.

In the tree created by algorithm 1 every node is connected to zero or any number of child nodes. Nodes at the same level are called siblings, while nodes below a given node are its children. At the top of the tree, there is a set of nodes which do not have any parents. These nodes are the root nodes or head nodes of the tree. A node can appear more than once in the tree, however in each branch of the tree a node can only appear once, thus avoiding loops. In Algorithm 1 line 1, the root nodes are the exit nodes of the geometry.

The maximum depth of the tree is two times the number of room nodes in the geometry. This can be proved as follows. Consider a branch of the tree. The root node of any branch is an exit node. This is followed by a room node, internal exit node, and room node and proceeds till there are no further nodes to add or adding a node will create a loop in the branch or an exit node has been reached. In other words any branch of the tree will have the exit node as the root node and a room node at every alternate position. Hence the maximum depth of any branch and hence the maximum depth of the tree cannot be more than two times the number of room nodes in the geometry, since adding a room node after this will mean adding the same room node twice which forms a cycle.

Hence the maximum depth of a tree is found at line 2 and the WHILE loop starting at Line 2 is limited to this maximum depth. In line 1, the exit nodes of the geometry are added as root nodes of the tree. Line 4 starts a FOR loop which loops through the leaf nodes in the tree. If the leaf node is an internal or external exit Lines 6-13 are executed else if the leaf node is a room node, then Lines 15 to 21 is executed.

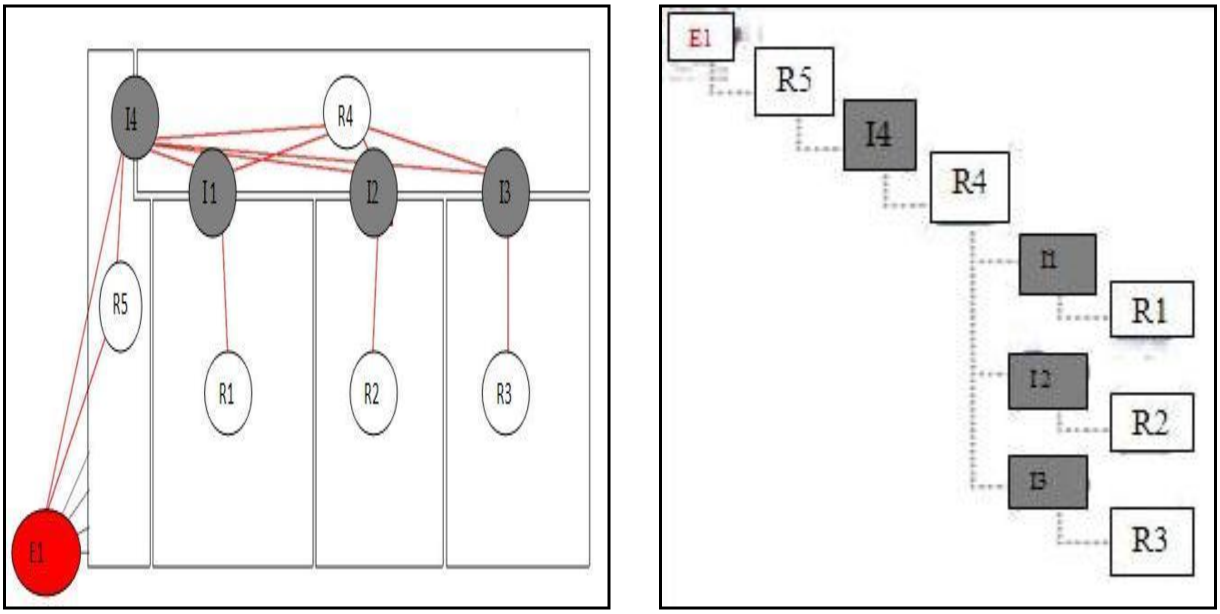
If the leaf node is an internal or external exit, then the room nodes connected to the leaf node are examined (Line 6). There can only exist one or a maximum of two room nodes connected to any exit node. If there are 2 room nodes connected, then one of the room nodes is the parent node and the other room node will be the child node. Since the parent node is already in the tree, it is ignored and only the child node is to be added. This is done in Line 7. In Line 8, a check is performed to see if the child node already exists in the tree. If the child node exists nothing needs to be done (Line 11), if it does not exist then the child node is added to the tree.

If the leaf node is a room node, then all the nodes connected to this leaf node are added to its neighbour list. The parent node of this leaf node is already in the tree and hence is removed from the neighbour list. The remaining nodes in the neighbour list are checked to see if it is already in the same branch. If the neighbour node has not appeared in the branch then it can be added as a child node of the leaf node (Line17).

1 Add the exit nodes of the building as the root nodes of the tree.
2 MaxTreeDepth = Number of room nodes * 2
3 WHILE tree depth is less than MaxTreeDepth
4 FOR each leaf node of the tree
5 IF leaf node is exit node or internal exit node THEN
6 Find room nodes connected to leaf node
7 Get room node which is not the parent node of the leaf node
8 *IF* this room node is not already in this branch of the tree *THEN*
9 Add this room node as the child node of the leaf node
10 *ELSE*
11 Do Nothing (End of branch)
12 *ENDIF*
13 ENDIF
14 IF leaf node is room node
15 Add all internal or external exits connected to the leaf node as the neighbours of this leaf node
16 Remove the parent node of the leaf node from the neighbours
17 Add each of the neighbour node as child of the leaf node if this neighbour node has not already appeared in this branch
18 *IF* leaf node is an exit node and not a root node of the tree *THEN*
19 Do Nothing (End of branch)
20 *ENDIF*
21 ENDIF
22 ENDFOR
23 ENDWHILE

Figure 4-5: Pseudocode of Algorithm 1

If the leaf node is an exit node and is not the root node of the tree then this marks the end of the branch and hence nothing needs to be done (Lines 18-19).



(a) *(b)*

Figure 4-6: (a) Connectivity graph of Building2 overlaid on its geometry. (b)Tree of paths Created for Building2 using Algorithm 1

Figure 4-6a shows the connectivity graph of building 2 overlaid on its actual geometry. Figure 4-6b shows the tree of paths created for Building 2 using Algorithm 1. The room nodes R1, R2 and R3 do not have any neighbours other than the internal exits I1, I2 and I3 respectively. Adding these internal exits will create a cycle and hence the room nodes R1, R2 and R3 form the leaf nodes of the tree.

4.3.1.1 Heuristics for Algorithm 1

Algorithm 1 is guaranteed to find all paths from any room to the exits in the geometry. But the disadvantage of this algorithm is that the space and time requirements are huge. For large geometries, heuristics similar to the author's previous work [Veeraswamy, et al., 2009] can be added to reduce the space and time taken by this algorithm. The heuristics that have been added are

Heuristic 1: The distance map algorithm (see Appendix [D]) needs to be run on the connectivity graph which assigns a cost to each node representing its shortest distance from an exit. Let P_{ij} represent the cost of node i to exit j. In Algorithm 1, any tree node which is added to the tree has a cost (distance) depending on how it was added to the tree which is different from the node's shortest distance to the exit. Let T_{ij} represent the tree cost of node 'i' to exit 'j'. The tree generated by Algorithm 1 finds all possible paths from each node in the connectivity graph to the exits in the building. This can lead to the generation of a very huge tree for a large complex building. The size of this tree can be controlled by adding a heuristic such as: add only those nodes in the tree which obeys the following constraint:

$T_{ij} < n * P_{ij}$ **Equation 1**

This constraint ensures that only those paths within n times the least cost path are found. For example if n equals two then only those paths that are two times the least cost path are found.

Heuristic 2: The number of routes calculated for each room in the geometry can be controlled by stopping the addition of a room node if it appears more than m times in the tree, where m is an integer that the end user can specify. Thus, only m paths are found for each room in the building to the exits.

4.3.1.2 Justification of heuristic 1 of Algorithm 1

A complicated building with many interconnections may have many possible combinations of routes. Consider a 1000 room geometry having hundred's of routes between a pair of nodes. It is not required to find all the possible routes. It may suffice to provide the routes which are within a certain distance of the shortest path. Another way of looking at this is that people will have a higher preference to choosing the shortest path and paths within a certain distance of the shortest path. They would have lesser preference to choosing paths that are considerably longer than the shortest path. Theoretically, there should a certain range beyond which the length of a path is so high that it becomes highly unlikely to be used. Therefore, as the length of a path increases the probability of usage of the path tends towards zero. There should exist a certain value of n [see Equation 1] at which the probability of usage of a path becomes zero. In this thesis it is assumed that a 'n' value of 2.0 should suffice for most buildings. However, a provision could be provided for the end user to increase or decrease this value. The end user should be made aware that choosing to determine a very high number of paths for a large and complex building could slow down the simulation.

4.3.1.3 Justification of heuristic 2 of Algorithm 1

A highly interconnected geometry could have hundreds of routes from a room to the exits in the geometry. By allowing the end user to control the number of routes per room, they can choose between efficiency or speed. If they choose a large number of routes per room for a large and highly interconnected geometry they would have to wait a long time to get the results. In this thesis an assumption is being made that 10 routes per room should suffice for most buildings.

4.3.2 Algorithm 2

Evacuation modelling tools do not require the agents to know all possible paths in any given geometry. It may suffice if the agents know a few good paths. The agents' route knowledge can improve as they travel to the exit. Algorithm 1 is a brute force method to determine all the routes in a building whereas Algorithm 2 limits the number of routes being found thus decreasing the space and time complexity required.

In Algorithm 2, the exit nodes again form the root nodes of the tree. For all internal exits in the connectivity graph, the shortest distance to each exit node is found using the distance map (see Appendix [D]) for that exit. These paths are added as branches to that exit node. Thus, the tree created by algorithm 2 contains the shortest distance route from all internal exits in the geometry to all external exits in the geometry. In other words using this tree it should be possible to find the shortest distance path from any room in the geometry through all internal exits of that room to all the external exits in the geometry.

Figure 4-7 shows the geometry of a second hypothetical building, Building 3. Figure 4-8 shows the connectivity graph of this building overlaid on its geometry. The room nodes on the connectivity graph have been omitted in Figure 4-8 for the sake of clarity. Algorithm 2 does not involve room nodes when creating the tree of paths and hence it is not required to show the room nodes in the connectivity graph.

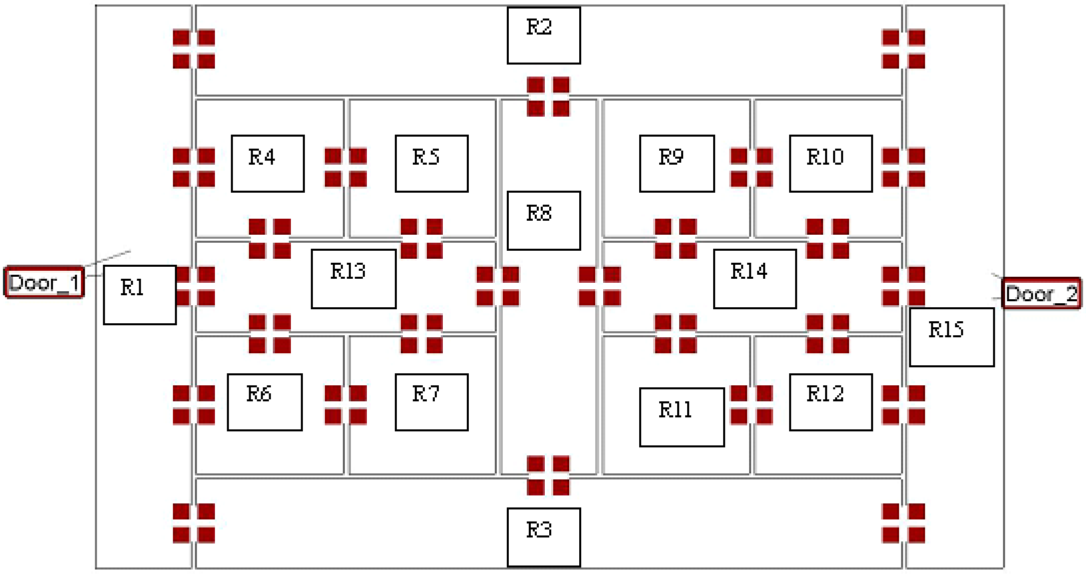


Figure 4-7: Building 3 geometry consisting of 15 rooms (including corridors), 2 external exits Door_1, Door_2 and a few internal exits represented by the 4 red squares.

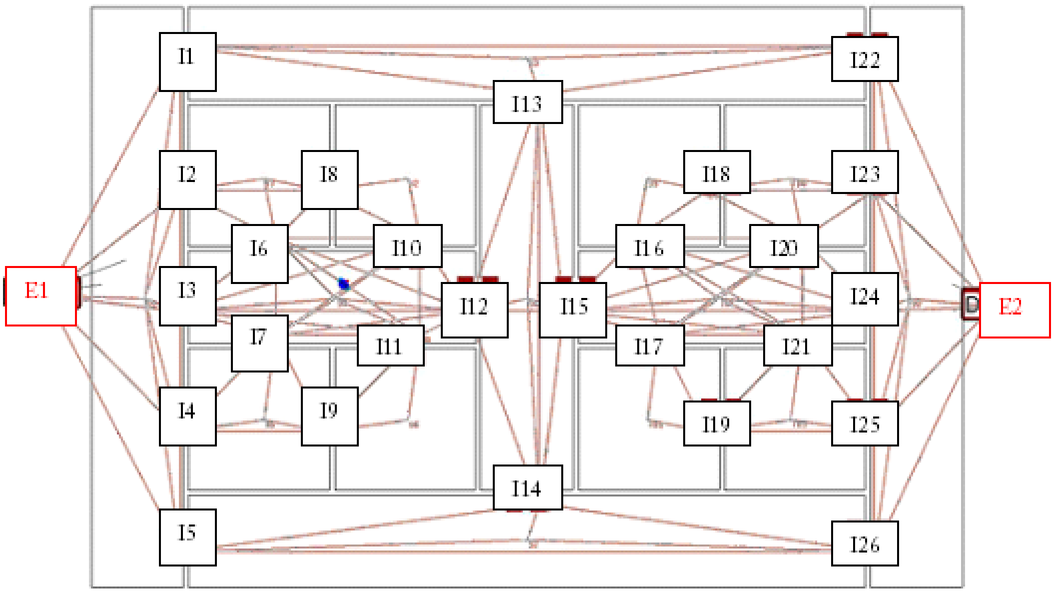


Figure 4-8: The building 3 geometry is overlaid on its connectivity graph.

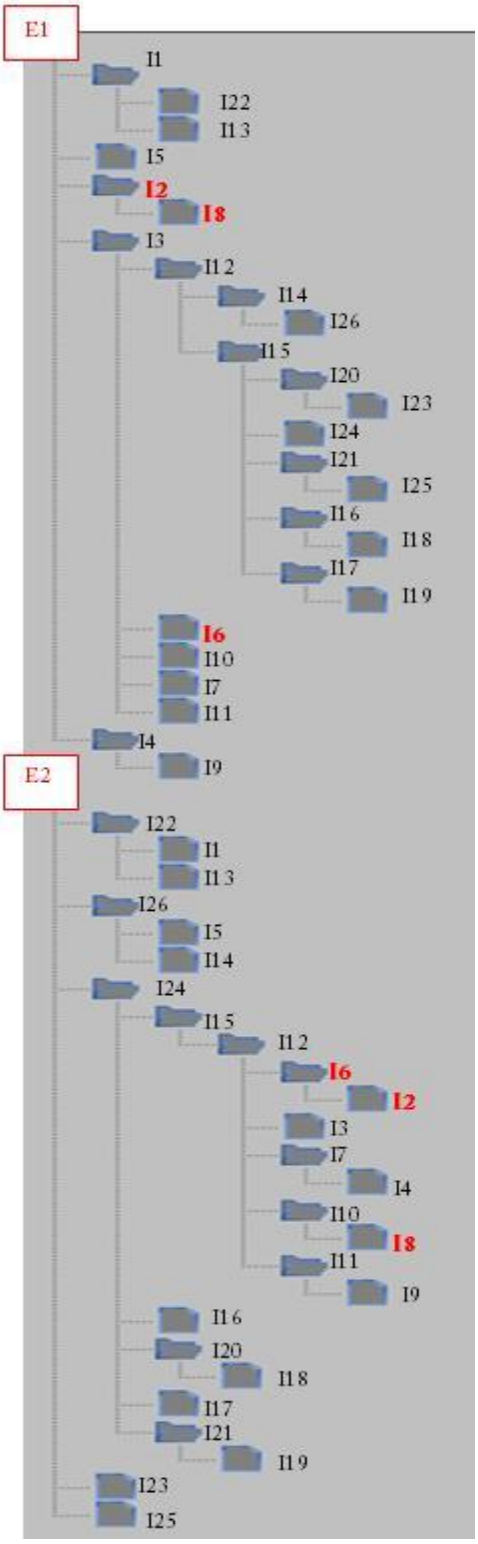


Figure 4-9: Tree of paths created by Algorithm 2 for Building 3

Consider an agent in room R4 (Figure 4-7). The agent consults the connectivity graph (Figure 4-8) and gains the knowledge that there are 3 internal exits (I2, I6 and I8) available in this room. Thus, he can choose any one of these internal exits. In order to help him to decide which internal exit of room R4 to use, he then consults the tree of paths shown in Figure 4-9. The agent needs to search for the internal exits I2, I6 and I8 in the tree. These nodes are shown in red in Figure 4-9. The paths from these nodes are found by recursively getting the parent node until an exit node is reached. The paths thus found are listed below

Path1: I2, E1

Path2: I8, I2, E1

Path3: I6, I3, E1

Path4: I6, I12, I15, I24, E2

Path5: I2, I6, I12, I15, I24, E2

Path6: I8, I10, I12, I15, I24, E2

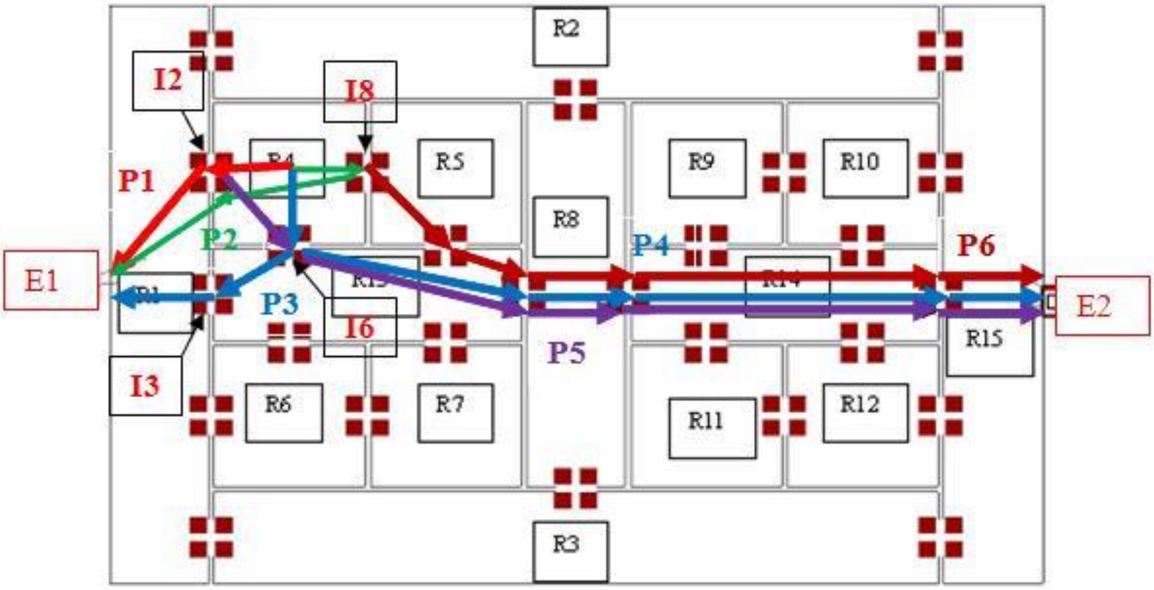


Figure 4-10: The paths from Room R4 found by Algorithm 2.

In Figure 4-10, Path P1 is the shortest path with the least number of internal exits along the path to the external exit E1. Path2 is not very useful, since it is meaningless to go to I8 and then to I2 rather than going to I2 directly. Path3 is a viable path which is slightly longer than Path1 and has 1 internal exit more than Path1. Path3 is a path which could be chosen by the agent if there was severe congestion or fire blocking the internal exit I2.

Therefore among the 6 paths, the only paths that may be chosen by a rational person are Path1 and Path3 with Path 1 being more preferable. Assuming that the occupants know both exits, Paths 4 to 6 which lead to exit E2 would not be chosen as exit E1 is much closer from Room R4.

Assume that the agents from Room R4 choose path3, pass through the internal exit I6 and enter into room R13. Here again assume that they come to know that exit E1 is blocked due to fire or severely congested due to many agents using it and that the agents become aware of it as soon as they enter into room R13. Depending on the severity of the fire or severity of the congestion, the agent may check for alternative routes which do not involve exit E1. In order to get alternative route agents need to check the connectivity graph and get the internal exits in room R13. The internal exits in room R13 are I3, I6, I10, I7, I11 and I12. They then need to check the tree for these internal exits. Since they are not interested in using exit E1, they could ignore the sub tree with E1 as the root node. The paths that they now find are

Path1: I6, I12, I15, I24, E2
Path2: I3, I12, I15, I24, E2
Path3: I7, I12, I15, I24, E2
Path4: I10, I12, I15, I24, E2
Path5: I11, I12, I15, I24, E2
Path6: I12, I15, I24, E2

Paths 1 to 5 above are not very useful since I12 can be reached directly without visiting the first nodes in these paths. Path 6 should be the most popular choice among Path1 to Path6. In Algorithm 2 more route options are presented as the agent moves into each room. Additional paths (not as optimal as Path 6) are

Path7: I12, I13, I22, E2
Path8: I12, I14, I26, E2

will not be known by the agents when they are in room R13. However, these paths will be available to the agents when they reach room R8.

A difference between Algorithm 1 and Algorithm 2 is that in Algorithm 1, the agents are initially given knowledge of all possible routes in a building but in Algorithm 2, the agents are given restricted route options which keep expanding as they exit.

4.3.3 Algorithm 3

The K-shortest loop less paths algorithm [Bock, et al., 1957] [Pollack, 1961] [Clarke, et al., 1963] was briefly described in Chapter 1, Section 2.2.3.2. Yen [Yen, 1971] provided a classical solution for finding the K shortest loop less paths between a pair of nodes in a graph. Yen's algorithm can be implemented with a worst case complexity of $O(Kn(m+n\log n))$ using the Dijkstra algorithm [Lawler, 1972]. K is the number paths to be determined, n is the total number of nodes in the graph and m is the total number of arcs. Another implementation of the Yen's algorithm [Martins and Pascoal., 2003] has the same worst case complexity but better average case complexity in practice. The original Yen's algorithm, the new implementation of the Yen's algorithm and the modifications performed to the new implementation to suit choice set generation suitable for building wayfinding has been described in this section.

The K shortest paths found between a pair of source (s) and target (t) nodes have the following characteristics:

- The paths found are loop less i.e., the paths do not contain repeated nodes
- The K shortest paths are a sub set of all the paths between the source and target nodes.
- The shortest path is found first, the second shortest next and so on until K paths are found, where K is a positive integer. In other words, any path in the K shortest paths list has a higher cost than the preceding one.
- Any path in the K shortest paths list has a lower cost than the other paths existing between the source and target nodes.

The Yen's algorithm has been described in detail in [Yen. 1971]. In this section, the working of the Yen's algorithm is explained by considering the connectivity graph of Building 4 shown in Figure 4-11. Building 4 is a simple geometry consisting of four rooms, five internal exits and one external exit. The connectivity graph of Building 4 along with the lengths of the arcs is shown in Figure 4-12. The decimal parts of the lengths are truncated to keep this discussion simple. The length of the arcs forms the edge weights or cost.

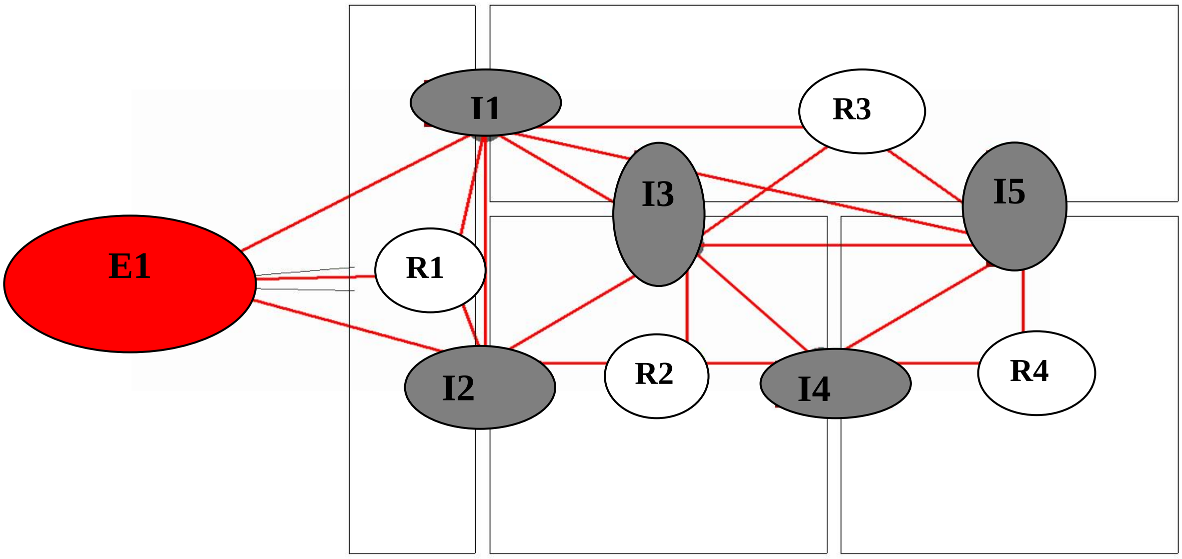


Figure 4-11: Connectivity graph of Building 4 overlaid on the Building 4 geometry. The internal exits are replaced by the grey nodes, the rooms are represented by the white nodes at the centre of each room and the external exit is represented by the red node.

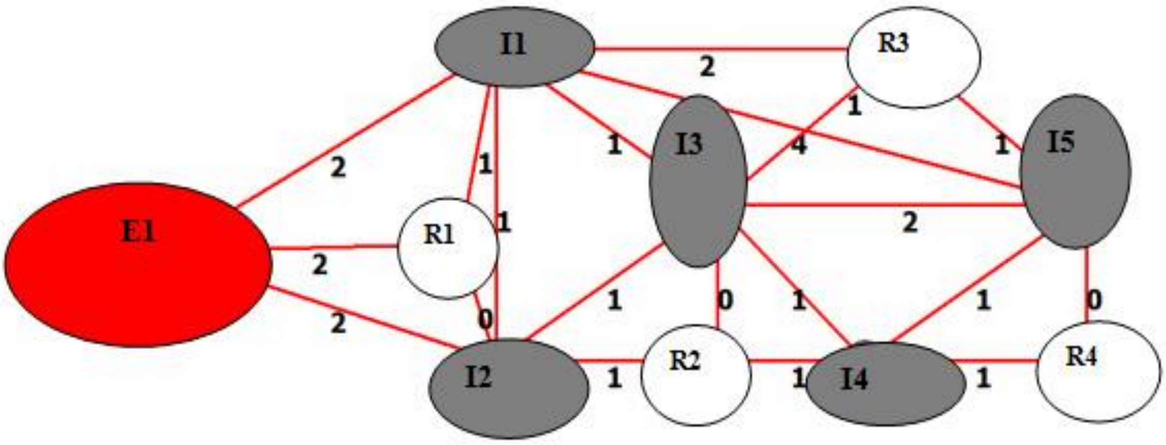


Figure 4-12: Connectivity graph of Building 4 with edge weights.

Consider the source node to be the room node R4 and the target node to be the exit node E1. The Yen's algorithm works by first determining the shortest path (P_1) between the source and the destination node using a shortest path algorithm such as the Dijkstra or the A* algorithms. The shortest path in this case found using the Dijkstra algorithm is:

P_1 = R4 – I4 – R2 – I2 – E1, Cp1 = 5

The cost of the paths are denoted by C_{pk}, where $k \in \{1,2,...,K\}$

In order to find the kth shortest path the following steps are followed:

The Yen's algorithm assumes that the next shortest path should be a deviation of the P_{k-1} path. Starting from the source node, deviations of the path P_{k-1} are then determined. The deviations of the path P_{k-1} are determined by considering each node in the path to be a deviation node starting from the first to the last node. However, some alterations need to be made before finding the alternate paths. The nodes in the path that are before the deviation node are deleted in order to avoid repeated nodes and the arc connecting the deviation node to the node succeeding it is deleted so that a different path is determined.

In order to find path P_2, path P_1 will be the P_{k-1} path. Node R4, the first node of path P_1, will be the first deviation node. There are no nodes before R4 and hence no nodes are deleted. The Arc(R4, I4) is deleted and the shortest path from the deviation node to the target node is determined. The deviation path (D_1) thus determined using Dijkstra's algorithm is:

D_1 = R4 – I5 – I4 – R2 – I2 – E1, C_{D1} = 5

The deleted nodes and arcs are then restored. The next deviation node is I4. The node R4 has to be deleted in order to avoid repetition of nodes and the arc (I4, R2) needs to be deleted as well. The shortest path from I4 to E1 is then determined. The nodes before the deviation node, which in this case is R4, needs to be added to the path. The deviation path (D2) thus determined using Dijkstra's algorithm is

D_2 = R4 – I4 – I3 – I2 – E1, C_{D2} = 5

At the end of the iteration k the following deviation or candidate paths are thus determined.

D_1 = R4 – I5 – I4 – R2 – I2 – E1, C_{D1} = 5

D_2 = R4 – I4 – I3 – I2 – E1, C_{D2} = 5

D_3 = R4 – I4 – R2 – I3 – I2 – E1, C_{D3} = 5

D_4 = R4 – I4 – R2 – I2 – R1 – E1, C_{D4} = 5

These paths are then stored in a list of candidate paths. For each iteration k the shortest path from this list is determined to be the k shortest path. If there is more than one shortest path, any one is chosen randomly. The Yen's algorithm terminates when k = K or when the list of candidate paths is empty.

The Dijkstra algorithm using binary heaps has a worst case run time complexity of O(m+nlogn) where m is the number of arcs and n is the number of nodes in a graph [Lawler, 1972]. In the Yen's algorithm the Dijkstra's algorithm is used n times (worst case) during each k iteration. Therefore the Yen's algorithm to solve the K-shortest paths problem has a worst case run time complexity of $\mathrm{O}(Kn(m+n\log n))$.

The new implementation [Martins and Pascoal., 2003] of the Yen's algorithm follows the same principle. However, there two important differences: In each k iteration, the order of the deviation node is from the last to the first node and instead of using the Dijkstra algorithm a tree is constructed with the last node as the root. Label correcting algorithms [Ahuja et al., 1993] are then used to find the candidate paths. The same number and order of paths are determined using both the original Yen's algorithm and the new one. The worst case complexity is the same as well. However, the average case complexity is lower than the original algorithm.

In this thesis an existing implementation [Google Project Hosting, 2011] of the new implementation of Yen's has been adapted to work with the connectivity graphs and the agent based wayfinding model. This algorithm found 33 paths from room node R4 to the exit node E1. The first four paths are:

P_1 = R4 – I4 – I2 – E1

P_2 = R4 – I5 – I4 – I2 – E1

P_3 = R4 – I4 – I2 – E1

P_4 = R4 – I4 – I3 – I2 – E1

There is a small issue with applying the Yen's algorithm as it is with the connectivity graphs. Some of the paths are a minor deviation from others. For example paths P1, P2 differ by just one node I5 and paths P3, P4 differ by just one node I3. Path P2 consists of internal exit nodes I5 followed by I4. Though this is a valid path without a loop, it is not a very useful path from a wayfinding perspective. It is meaningless to go from room node R4 to the internal exit I5 and then to I4. However, a person might follow this path under certain circumstances. For example, a person might change his/her mind / route at I5 and decide to take an alternate route. However, he/she will not at the outset decide to take such a circuitous path. The agents in the wayfinding model will be allowed to change their mind/route however they do not have to be given routes that involve moving around in the same room. Therefore, in this thesis an additional constraint has been added which forces the paths found to contain nodes in the following format:

P = { room node, exit node, room node, exit node}

The first room node is the source node, the last exit node is the external exit and the intermediate exit nodes are internal exits. Forcing paths to go from room node to internal exit node to room node prevents visiting two internal exit nodes in the same room consecutively thus preventing the issue described in the previous paragraph. Applying such a constraint produces more useful / manageable set of routes. The routes thus found from room node R4 to exit E1 for Building 4 are:

P_1 = R4 – I4 – R2 – I2 – R1 – E1

P_2 = R4 – I5 – R3 – I1 – R1 – E1

P_3 = R4 – I5 – R3 – I3 – R2 – I2 – R1 – E1

P_4 = R4 – I4 – R2 – I3 – R3 – I1 – R1 – E1

The additional constraint introduced has decreased the number of paths found from 33 to five for a simple four room geometry [see Figure 4-11]. If the connectivity graph is considered as just a graph 29 paths can be said to be lost in this particular case. However, if one considers the connectivity graph as a graph consisting of room nodes, internal exit nodes, and external exit nodes then the most useful paths have been determined.

The routes found are still the shortest routes between the source and target node but with the additional constraint that the paths go from room node to internal exit node to room node. Though the constraint introduced includes a room node between two internal exits, these room nodes need to be removed from the actual paths taken by the agent. For example, an agent can traverse directly from internal exit I5 to I1 without having to visit room node R3. Thus, all room nodes except the source room node R4 needs to be removed from the paths found. The routes thus determined from room node R4 to exit E1 for Building 4 are:

P_1 = R4 – I4– I2 – E1
P_2 = R4 – I5– I1 – E1
P_3 = R4 – I5 –I3 –I2 – E1
P_4 = R4 – I4 –I3 –I1 – E1

The additional constraint reduces the complexity of the algorithm 3 by decreasing the number of routes determined. However, it introduced a small error as now the shortest paths are found through the room nodes. The room nodes are placed at the centre of a room and it is not always required to visit it. This error can be rectified by correcting the cost function or by manipulating the nodes added in the tree of paths [Martins and Pascoal., 2003]. However, this has been left as work for the future.

4.4 ROUTES FOUND BY ALGORITHMS 1, 2 and 3

In this section some sample geometries and the routes found by the three path planning algorithms are presented.

4.4.1 Test Case 1

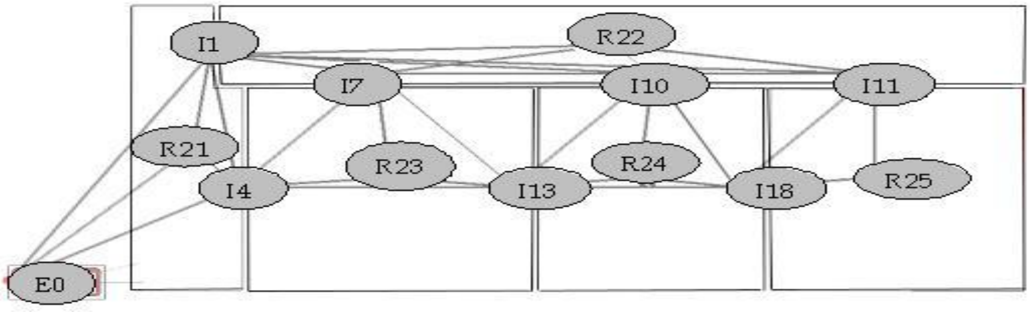


Figure 4-13: Test Case1 containing three rooms (R23, R24 and R25) and two corridors (R21 and R22) having an area of 108.50m^2.

4.4.1.1 Paths found by Algorithm 1 for case 1

Table 4-1 shows the paths found by algorithm 1. From Room R21 there is only one path

Path1: R21 E0

Algorithm 1 finds acyclic paths in a building and hence only one path has been found. The Paths P(R21, I1, E0) and P(R21,I4,E0) though valid are not considered as Path1: R21 E0 is more direct. Path 1 from room R22 is:

Path1: R22 I11 I18 I13 I4 E0.

The actual path found by Algorithm 1 is

R22 I11 R25 I18 R24 I13 R23 I4 E0

This path found by algorithm 1 is refined by removing all room nodes except the first (initial) room node. The room nodes are present in the graph to provide knowledge of the presence of a room. Though an agent moves from a "room to exit to room to exit" until the final external exit is reached, the agent does not have to visit the actual room node in the graph. Therefore, the room nodes are removed from the paths assigned to the agents.

Table 4-1: Paths found by Algorithm 1 for case 1

Path Number	**Path**
Paths From Room R21	
Path 1	R21 E0
Paths From Room R22	
Path 1	R22 I11 I18 I13 I4 E0
Path 2	R22 I10 I13 I4 E0
Path 3	R22 I7 I4 E0
Path 4	R22 I1 E0
Paths From Room R23	
Path 1	R23 I4 E0
Path 2	R23 I13 I18 I11 I1 E0
Path 3	R23 I13 I10 I1 E0
Path 4	R23 I7 I1 E0
Paths From Room R24	
Path 1	R24 I13 I4 E0
Path 2	R24 I18 I11 I7 I4 E0
Path 3	R24 I10 I7 I4 E0
Path 4	R24 I18 I11 I1 E0
Path 5	R24 I10 I1 E0
Path 6	R24 I13 I7 I1 E0
Paths From Room R25	
Path 1	R25 I18 I13 I4 E0
Path 2	R25 I11 I10 I13 I4 E0
Path 3	R25 I11 I7 I4 E0
Path 4	R25 I18 I10 I7 I4 E0
Path 5	R25 I11 I1 E0
Path 6	R25 I18 I10 I1 E0
Path 7	R25 I18 I13 I7 I1 E0

Considering the paths from room R22, a question may arise as to why the following path R22 I11 I18 I10 I1 E0 was left out as this refined path is acyclic. But the original path found by Algorithm 1 would be R22 I11 R25 I18 R24 I10 R22 I1 R21 E0. Since in the original path the Room R22 is visited twice this is considered to be a cyclic path and hence such paths are not found by Algorithm 1. Paths 1 – 7 computed from room R25 are shown in Figure 4-14.

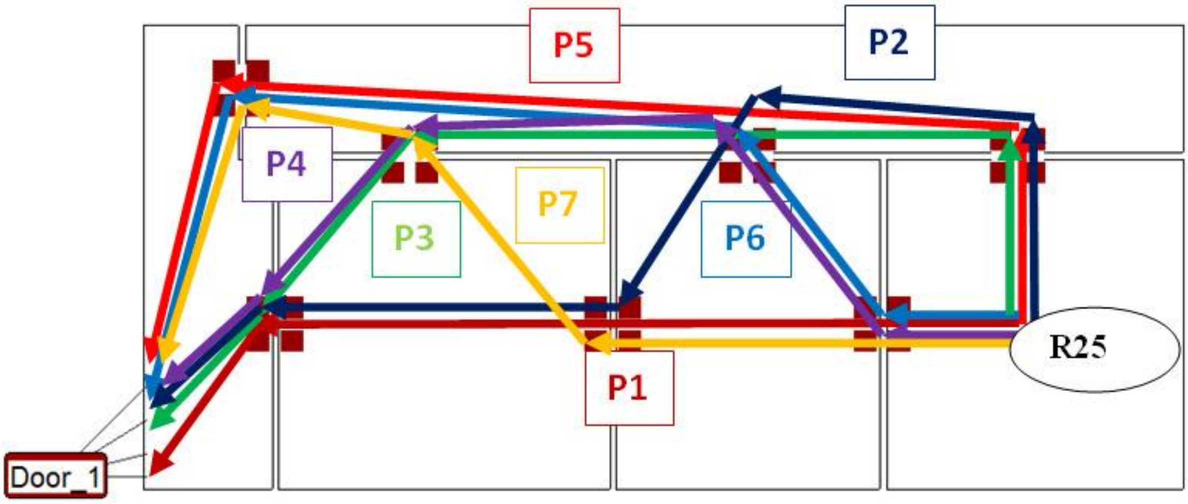


Figure 4-14: Paths P1 to P7 as computed by algorithm 1 from starting location R25.

4.4.1.2 Paths found by Algorithm 2 for Case 1

Comparing the routes found by Algorithm 1 (Table 4-1) and Algorithm 2 (Table 4-2), it is seen that more routes are found using Algorithm 1 than by Algorithm 2. But Algorithm 2 has an interesting feature which enables an agent to initially start with limited knowledge of routes and as he moves into adjoining rooms he gains knowledge of new routes from that room. For example, let us consider an agent in room R25. Using Algorithm2, the agent is initially assigned the Path 1 and Path 2 under Paths from Room R25 in Table 4-2 which are:

Path 1: R25 I11 I1 E0

Path 2: R25 I18 I13 I4 E0

Table 4-2: Paths found by Algorithm 2 for Case 1

Path Number	**Path**
Paths From Room R21	
Path 1	R21 E0
Paths From Room R22	
Path 1	R22 I7 I4 E0
Path 2	R22 I1 E0
Paths From Room R23	
Path 1	R23 I4 E0
Paths From Room R24	
Path 1	R24 I10 I1 E0
Path 2	R24 I13 I4 E0
Paths From Room R25	
Path 1	R25 I11 I1 E0
Path 2	R25 I18 I13 I4 E0

So this agent initially has no knowledge of the Path 3 under Paths from Room R25 in Table 4-1 which is

Path 3: R25 I11 I7 I4 E0.

Consider an agent decides to take Path 1 from Room R25. When he enters Room R22, he then gains knowledge of the Path 1 and Path 2 which are the paths determined from Room R22 (see Table 4-2). Path 1 from this room which is R22 I7 I4 E0 is the same as the Path 3: R25 I11 I7 I4 E0 found by Algorithm 1. Hence the agent has taken a path which was initially not planned at the start.

Consider an agent in room R23; Algorithm 2 has only one route for this agent which is R23 I4 E0. If the internal exit I4 were to be blocked for some reason due to a crowd crush or fire, this agent would not know of the alternative route R23 I7 I1 E0 which would be known by the agent using Algorithm 1. In this case an alternative search algorithm/technique may have to be used.

For the test case in consideration, if there was no fire blocking any of the routes, then the evacuation results using both Algorithm 1 and Algorithm 2 would be identical. Though

Algorithm 1 has found more routes than Algorithm 2, the paths falling within 10% of the best path has been found by algorithm 2 as well for all rooms except for Room R23.

4.4.1.3 Paths found by Algorithm 3 for Case 1

Algorithm 3 determined the same paths as those found by Algorithm 1 in Table 4-1.

4.4.2 Test Case 2

Figure 4-15a shows the test case 2 geometry and Figure 4-15b shows the connectivity graph of test case 2.

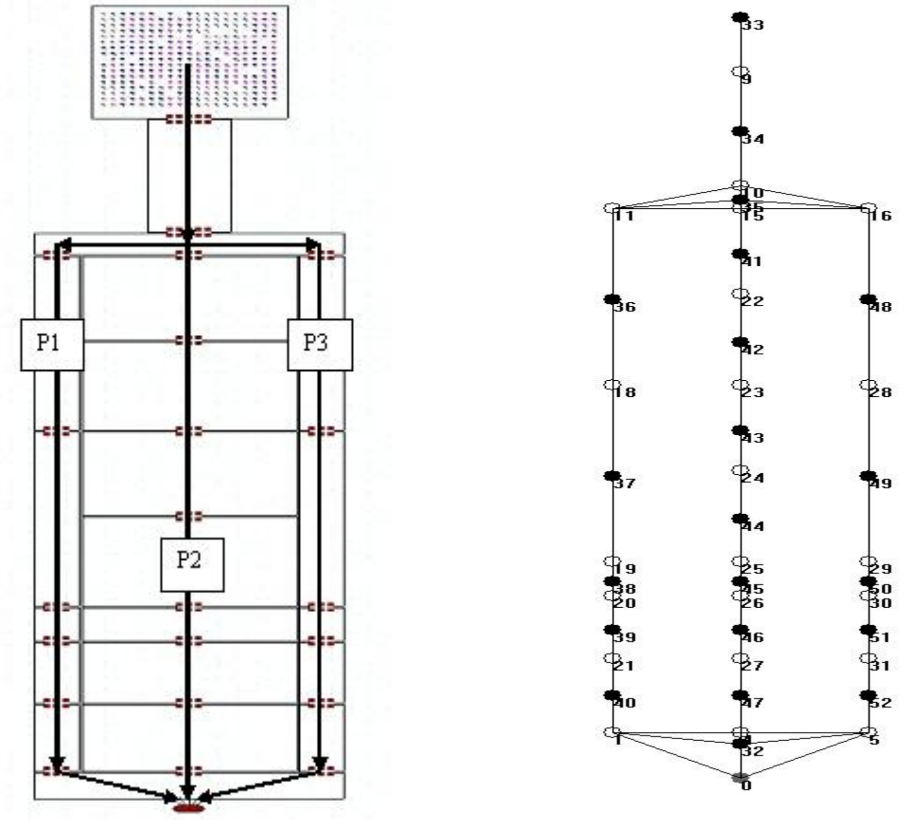


Figure 4-15: Geometry of test case 2 showing (a) three exit paths (P1, P2, P3) from assembly room and (b) connectivity graph for case 2 (filled black circles are room nodes, open circles are internal exits and the grey filled circle is the external exit).

4.4.2.1 Paths found by Algorithm 1 for Case 2

Since there are many rooms in this geometry, the routes from key points alone will be shown. The routes from room 33, room 35 and one route along each leg P1 (room 37), P2 (room 44) and P3 (room 49) will be shown (see Figure 4-15).

At each room there are 3 paths for the agents along each leg P1, P2 and P3. So even if an agent moving along path P1 finds that one of the internal exits along P1 is blocked he has the alternative of choosing one of the alternative paths along P2 or P3.

4.4.2.2 Paths found by Algorithm 2 for Case 2

Agents making use of Algorithm 2 have only one route option from room R33 which is

Path 1 : 33 9 10 11 18 19 20 21 1 0

This is the path labelled P1 in Figure 4-15a. Even though P2 is the shortest path, it has 2 additional internal exits and hence is the least cost path (in terms of distance and time) from Room R33 turns out to be P1.

Let us consider an agent using this Algorithm starting from Room 33, the top most room in test case 2, Figure 4-15a. This agent has knowledge of only the path P1 till he reaches Room 35. In this room he will have knowledge of all three routes P1, P2 and P3.

The agents using this algorithm regardless of which path they choose at Room 35 (P1, P2 or P3) after crossing one of the internal exits I1, I5 or I6 will then have knowledge of only one route that which proceeds along the initially chosen path. In case of the blockage of one of the internal exits along their chosen path, they will be unable to backtrack along their present path and choose another path at Room 35. An alternate search technique will have to be implemented on these agents using algorithm 2 for such situations.

Table 4-3: Paths found by Algorithm 1 for Case 2

Path Number	**Path**
Paths From Room R33	
Path 0	33 9 10 16 28 29 30 31 5 0
Path 1	33 9 10 15 22 23 24 25 26 27 4 0
Path 2	33 9 10 11 18 19 20 21 1 0
Paths From Room R35	
Path 0	35 16 28 29 30 31 5 0
Path 1	35 15 22 23 24 25 26 27 4 0
Path 2	35 11 18 19 20 21 1 0
Paths From Room R37	
Path 0	37 18 11 16 28 29 30 31 5 0
Path 1	37 18 11 15 22 23 24 25 26 27 4 0
Path 2	37 19 20 21 1 0
Paths From Room R44	
Path 0	44 24 23 22 15 16 28 29 30 31 5 0
Path 1	44 25 26 27 4 0
Path 2	44 24 23 22 15 11 18 19 20 21 1 0
Paths From Room R49	
Path 0	49 29 30 31 5 0
Path 1	49 28 16 15 22 23 24 25 26 27 4 0
Path 2	49 28 16 11 18 19 20 21 1 0

Table 4-4: Paths found by Algorithm 2 for Case 2

Path Number	**Path**
Paths From Room R33	
Path 1	33 9 10 11 18 19 20 21 1 0
Paths From Room R35	
Path 0	35 16 28 29 30 31 5 0
Path 1	35 15 22 23 24 25 26 27 4 0
Path 2	35 11 18 19 20 21 1 0
Paths From Room R37	
Path 1	37 19 20 21 1 0
Paths From Room R44	
Path 1	44 25 26 27 4 0
Paths From Room R49	
Path 0	49 29 30 31 5 0

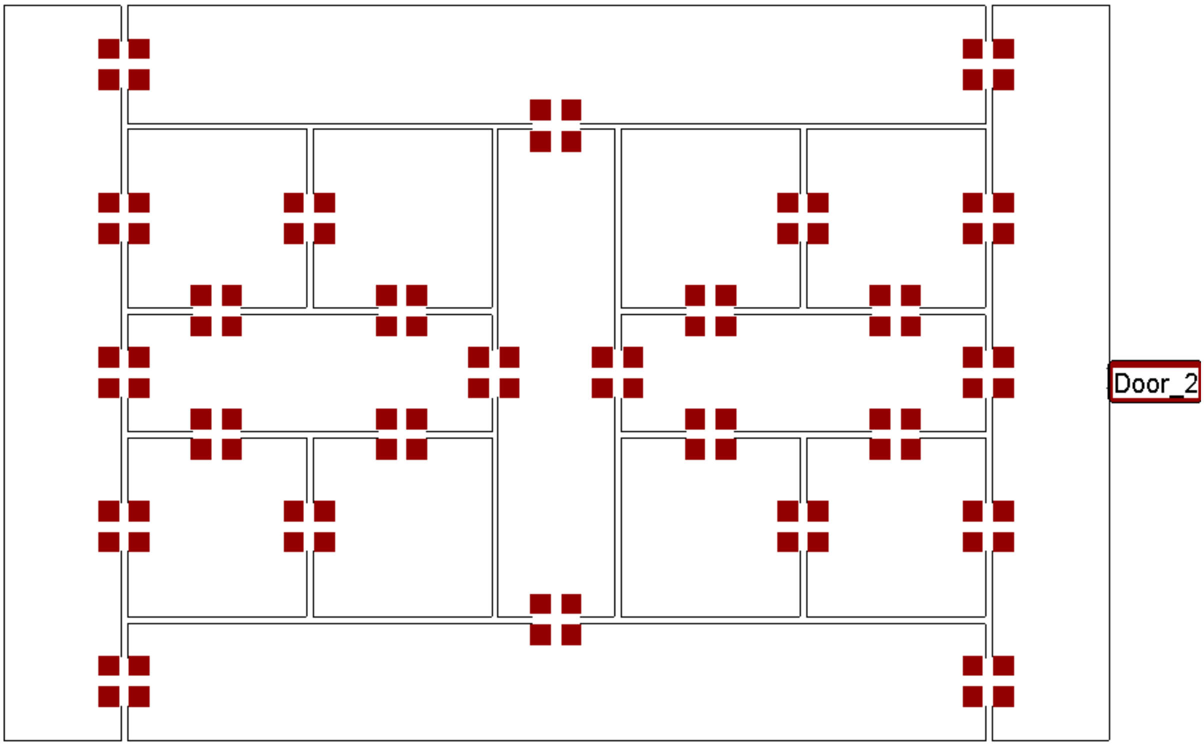


Figure 4-16: Test Case 3 geometry

4.4.2.3 Paths found by Algorithm 3 for Case 2

Algorithm 3 determined the same paths as Algorithm 1 in Table 4-3. The Yen's algorithm is guaranteed to find the k shortest loop paths between a pair of origin and destination nodes. In this case there are only 3 loop less paths from each room to the external exit. Therefore, Algorithm 3 computed the same paths as algorithm 1. The only difference is that algorithm 3 is guaranteed to find the paths in a non decreasing order whereas algorithm 1 is not.

4.4.3 Test Case 3

Figure 4-16 shows the geometry of the test case 3. Figure 4-17 shows the connectivity graph of the test case 3. Figure 4-18 shows the test case 3 connectivity graph overlaid on its geometry.

4.4.3.1 Paths found by Algorithms 1, 2 and 3 for Case 3

Table 4-5 shows the paths found by Algorithm 1 from Room 85 for test Case 3. Algorithm 1 actually found a total of 17 paths. But only the first 7 paths are shown. The distance to travel along the path in meters is shown along with the time taken in seconds to traverse this path. The time taken is not only the time taken to traverse this path but also includes the estimated time for a constant queue of 20 people at each internal exit to go through the exit which represents the estimated congestion around that exit. The "Percentage Difference From the Best Path" column shows the percentage difference of each path's score from the best path score. For example, in Table 4-5, the best path in terms of distance and time is Path 1 and hence its percentage difference is 0. The remaining paths have a percentage difference measured from the total score of Path 1.

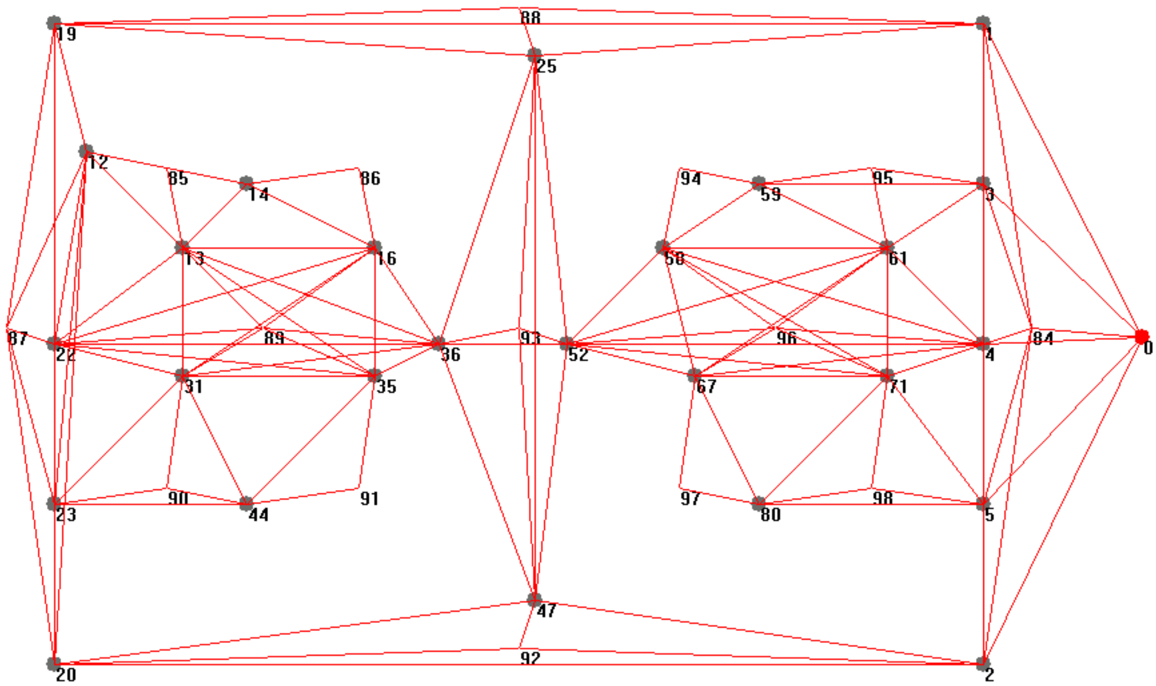


Figure 4-17: Test Case 3 Connectivity Graph. The internal exit nodes are in grey, the external exit nodes are red, the room nodes are just indicated by the node id alone.

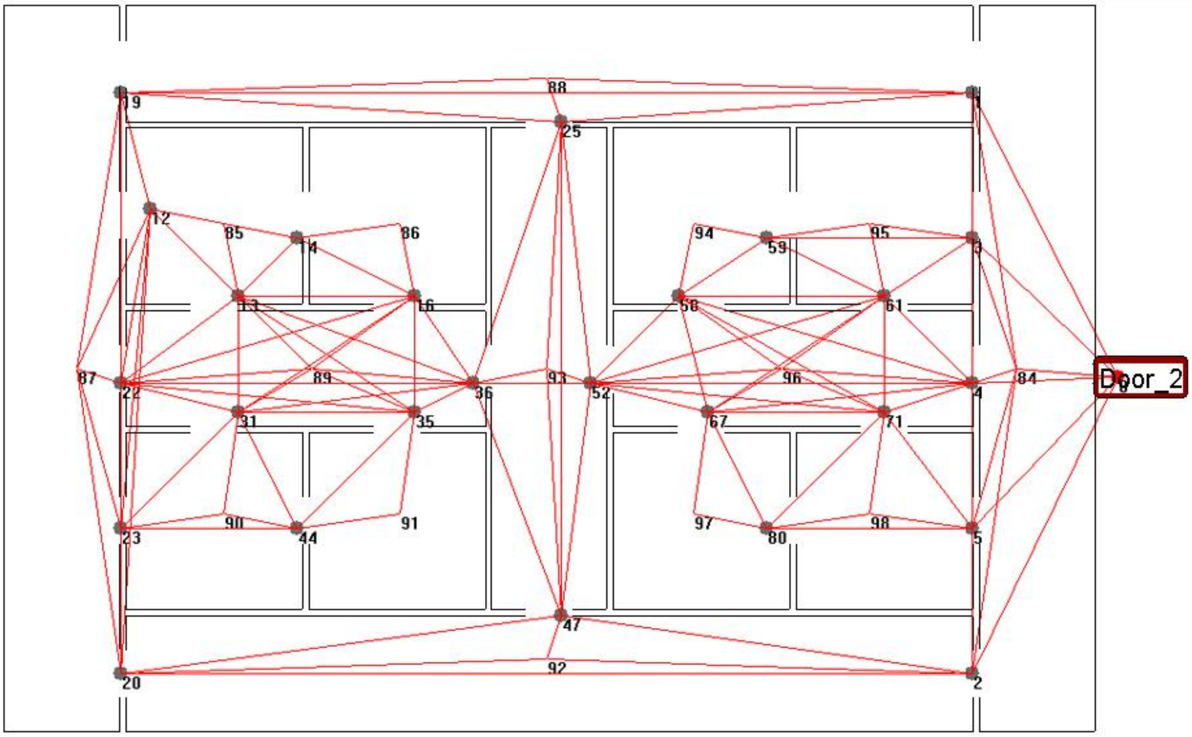


Figure 4-18: Test Case 3 connectivity graph overlaid on the geometry

Though only Path 1 has fallen within 10% of the best path score, other paths are quite close. For example if some of the internal exits along the other paths have more than 20 people blocking it, then Path 7 may become more optimal and get used during the simulation.

Table 4-5: Paths found by Algorithm 1 and 3 from Room 85 for Case 3

Algorithm 1				
Path Number	**Path**	**Distance (meters)**	**Time (seconds)**	**Percentage Difference from the Best Path**
Paths From Room 85				
Path 1	85 13 36 52 4 0	28.0345	42.2047	0
Path 2	85 13 36 47 2 0	38.2865	45.994	16.6602
Path 3	85 13 22 20 2 0	49.1248	50	29.1406
Path 4	85 12 20 2 0	50	43.955	25.2416
Path 5	85 13 36 25 1 0	38.6919	46.1438	17.2056
Path 6	85 13 22 19 1 0	48.8203	49.8875	28.8412
Path 7	85 12 19 1 0	39.5887	40.1068	11.8654

Table 4-6 shows the paths found by Algorithm 2 from Room 85 for test Case 3. The Paths 1 and 2 found by Algorithm 2 are the same as Paths 7 and 1 found by Algorithm 1. Though Algorithm 2 has found only 2 paths it has found the 2 best paths (in terms of distance and time) found by Algorithm1. The shaded path, Path 2 is the path with the best score. Though the paths found by Algorithm 2 from Room 85 are few with a sequential wayfinding algorithm the agents could actually find alternative routes on encountering congestion.

Table 4-6: Paths found by Algorithm 2 from Room 85 for Case 3

Algorithm 2	
Path Number	**Path**
Paths From Room 85	
Path 1	85 12 19 1 0
Path 2	85 13 36 52 4 0

Table 4-7 shows the paths found by Algorithm 3 from Room 85 for test Case 3. It is interesting to note that both Algorithms 1 and 3 have found the same set of routes. However, an important difference is the order of the routes found. Algorithm 1 found the routes in a random order with reference to the path cost whereas the cost of the routes found by Algorithm 3 are in an ascending order, due to the nature the Yen's algorithm.

Table 4-7: Paths found by Algorithm 3 from Room 85 for Case 3

Algorithm 3				
Path Number	**Path**	**Distance (meters)**	**Time (seconds)**	**Percentage Difference from the Best Path**
Paths From Room 85				
Path 1	85 13 36 52 4 0	28.0345	42.2047	0
Path 2	85 12 19 1 0	39.5887	40.1068	11.8654
Path 3	85 13 36 47 2 0	38.2865	45.994	16.6602
Path 4	85 13 36 25 1 0	38.6919	46.1438	17.2056
Path 5	85 12 20 2 0	50	43.955	25.2416
Path 7	85 13 22 19 1 0	48.8203	49.8875	28.8412
Path 8	85 13 22 20 2 0	49.1248	50	29.1406

4.4.4 Comparison of the routes found by the Choice set Generation Algorithms

Algorithm 1 without any heuristics applied is capable of finding all possible routes in a building. This is good as it provides many route options for the agents to choose and the agents could be made to choose the most realistic choice of routes from these options. However, Algorithm 1 can take a long time to run for large complex geometries. Therefore, the number of routes found can be reduced by adding additional heuristics as discussed in Section 4.6.1.1which decrease the space and time complexity of Algorithm 1.

Algorithm 2 gives minimal route options when the agent initially starts. The advantage of this Algorithm is that the route choice set increases or gets more accurate as the agent nears the goal. The disadvantage of this algorithm is that the agent given minimal route options may struggle to find a viable path if some of these paths is blocked (see Section 4.4.1.2). Therefore, Algorithm 2 is not suitable for a dynamic wayfinding model where paths could be blocked due to hazards.

Algorithm 3 provided identical routes as Algorithm 1 for the test cases considered in this section. However, in large complex buildings there is bound to be differences in the paths found by Algorithms 1 and 3. For example in the test case 3, Algorithm 3 found the paths in ascending order of path cost where as Algorithm 1 found the paths randomly. Since Algorithm 3 is guaranteed to find paths in a non decreasing order, in terms of the paths found, it can be considered to be the best of the three algorithms. The space and run time complexity of these algorithms will be considered in the next section.

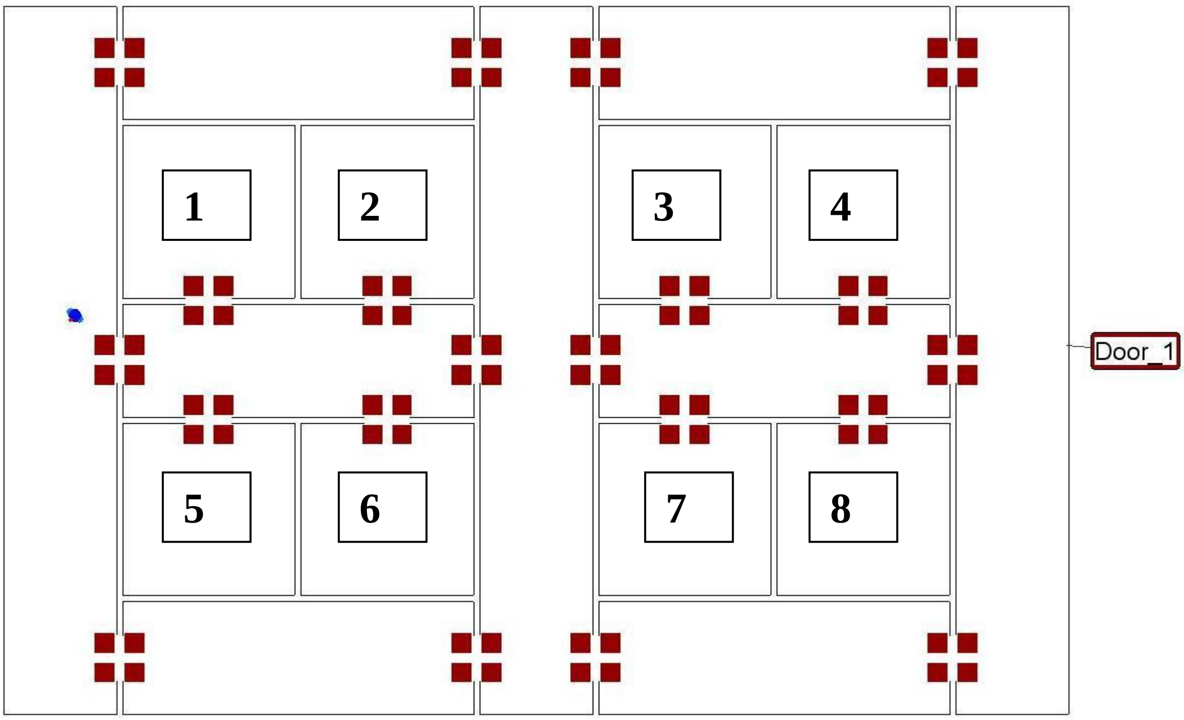


Figure 4-19: Base Case geometry (Connectivity1) for testing Algorithm 1, consisting of eight rooms and nine corridors.

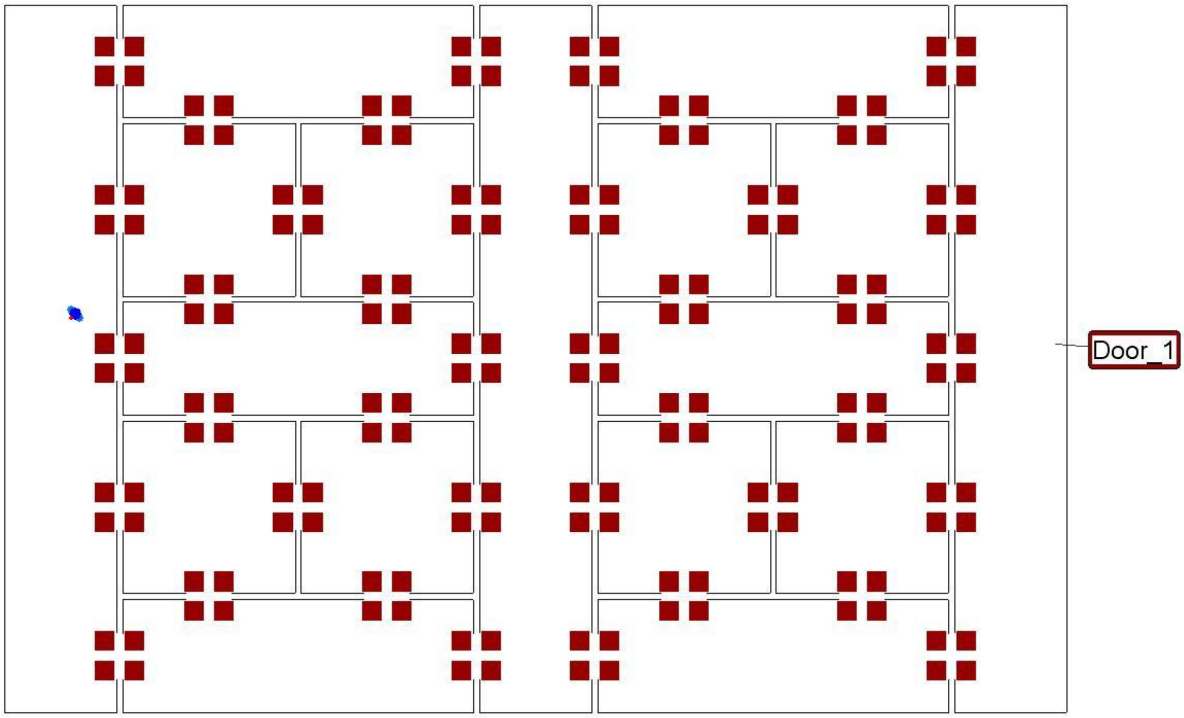


Figure 4-20: The (final) connectivity 11 geometry for testing Algorithm 1.

4.5 Performance of the Choice Set Generation Algorithms

In this section the performance of the three algorithms in terms of space and time complexity will be analysed. The complexities of algorithms are generally determined by varying one factor at a time such as the number of nodes or arcs. However, in the connectivity graph it is not possible to increase one factor at a time. For example, adding internal exits in the building will also increase the number of arcs as these internal exits will automatically have to be connected to the room nodes. The performance of the algorithms will be tested by increasing the density of the graph. The density or degree of a graph is the ratio of the number of arcs to the number of nodes [Martins and Pascoal., 2003].

$D = m / n$ **Equation 2**

Where m is the number of arcs and n is the number of nodes.

An important requirement of the choice set generation algorithms is their ability to be applied for large buildings. The complexity of the Algorithms 1 and 3 is a function of the number of rooms and exits in a building since paths need to be found for each combination of room and exit. The complexity of Algorithm 2 is a function of the number of internal and external exits in the building. Consider that there are 400 rooms and 4 exits in a building. Algorithm 1 will solve this problem by generating a tree with the exits forming the root nodes and the depth of this tree not exceeding 800 nodes (number of rooms x 2). Algorithm 2 does not consider the rooms in the building as it finds the shortest path from each internal exit to each external exit of a building. Algorithm 3, will solve this problem by running the modified Yen's algorithm 1600 times (number of rooms x number of exits). From initial testing of the algorithms it was confirmed that the size of the building or the number of rooms in the building did not pose a challenge to their performance.

The density of the graph (see Equation 2) posed a greater challenge to the performance of the algorithms. Increasing the density of a graph increases the connectivity of the nodes in the graph. Increasing the connectivity of the nodes lead to a large number of paths being found which increased the computational complexities of the algorithms. Therefore, in all the test cases considered in this section, the number of rooms remains the same. The number of internal exits are increased gradually thus increasing the interconnectivity or density of the graph.

4.5.1 Performance of Algorithm 1

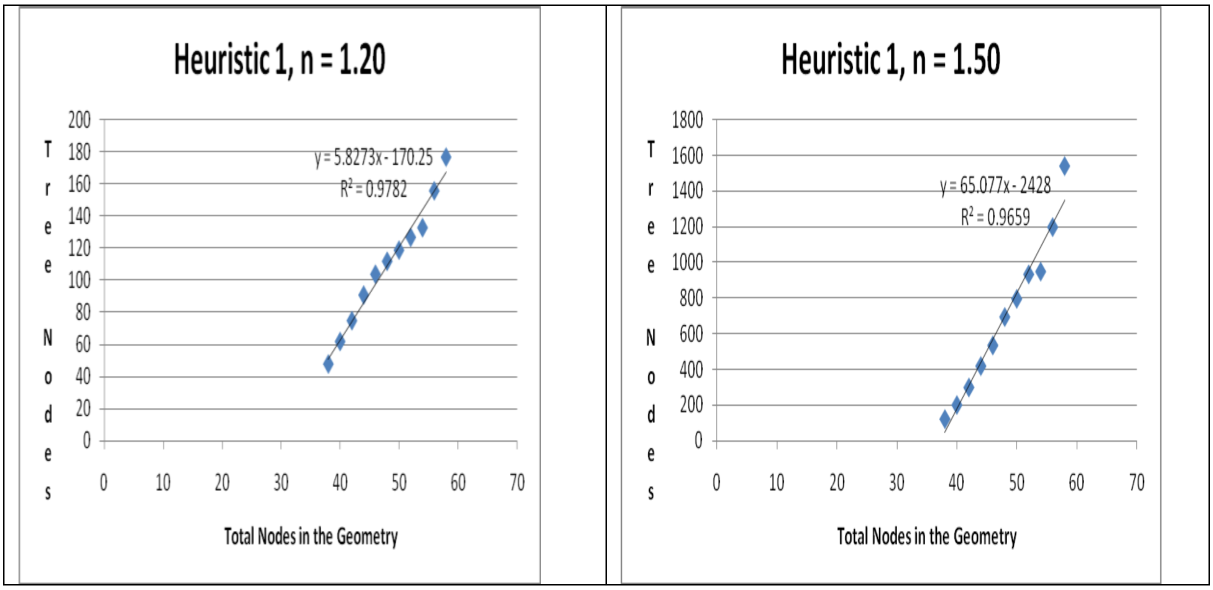
The base case geometry for testing Algorithm 1 is shown in Figure 4-19. The base case geometry consists of eight rooms and nine corridors. Each room has 4 walls but only 1 internal exit. This base case geometry forms the Connectivity1 geometry. In the subsequent connectivity scenarios the number of internal exits for each room is increased by 2 finally giving rise to Connectivity11 geometry shown in Figure 4-20. The performance of Algorithm 1 with no heuristic used and with the heuristics 1 and 2 used is analysed in this section.

Table 4-8: Space and Time complexity of Algorithm 1 with a varying distance heuristic.

Inter connectivity (Nodes, Arcs)	Algorithm 1 with distance heuristic (1.20)		Algorithm 1 with distance heuristic (1.30)		Algorithm 1 with distance heuristic (1.40)		Algorithm 1 with distance heuristic (1.50)		Algorithm 1 with distance heuristic (2.0)	
	Time (s)	Nodes	Time (s)	Nodes	Time (s)	Nodes	Time (s)	Nodes	Time (s)	Nodes
Connectivity1 (38, 99)	0.016	48	0.016	55	0.016	110	0.016	119	0.015	157
Connectivity2 (40, 111)	0.016	62	0.016	79	0.016	162	0.016	198	0.016	368
Connectivity3 (42, 127)	0.016	75	0.016	114	0.016	245	0.016	296	0.047	780
Connectivity4 (44, 140)	0.016	91	0.016	149	0.016	319	0.016	416	0.078	1526
Connectivity5 (46, 157)	0.016	104	0.016	188	0.016	404	0.016	532	0.125	2423
Connectivity6 (48, 174)	0.016	112	0.016	199	0.031	507	0.031	691	0.172	4041
Connectivity7 (50, 188)	0.016	119	0.016	211	0.031	523	0.031	793	0.266	6675
Connectivity8 (52, 206)	0.016	127	0.016	222	0.031	622	0.047	930	0.329	8602
Connectivity9 (54, 221)	0.016	133	0.016	234	0.031	638	0.047	946	0.406	11145
Connectivit10 (56, 237)	0.016	156	0.016	270	0.031	838	0.047	1195	0.657	16319
Connectivity11 (58, 253)	0.016	177	0.016	306	0.031	1044	0.062	1537	0.922	22520

Table 4-8 shows the time taken and the number of nodes expanded by Algorithm 1 using heuristic 1 with increasing n values: 1.2, 1.3, 1.4, 1.5 and 2.0. A 'n' value of 1.2 implies that all paths whose cost falls within 20% of the least cost path will be found. A 'n' value of 1.3 implies that all paths whose cost falls within 30% of the least cost path will be found. Finally a 'n' value of 2.0 implies that paths with costs within 2 times the least cost path will be found. The numbers in the brackets associated with the different connectivity levels are the total number of nodes and arcs in the geometry for that level. The number of nodes is increased by 2 for each successive connectivity level. The increase in the number of arcs could not be strictly controlled but is about 15 in average. The time taken is shown in seconds. The total nodes expanded are also shown which represents the space complexity or memory consumption of the algorithm.

Figure 4-21 shows the total nodes expanded by Algorithm 1 using heuristic 1 for connectivity 1 to 11 geometries. In Figure 4-21(a), a 'n' value of 1.20 is used and in Figure 4-21(b) a 'n' value of 1.50 is used. In both cases the curves suggest that the space complexity is almost linear. Figure 4-22 shows the total nodes expanded by Algorithm 1 for connectivity 1 to 11 geometries with a 'n' value of 2.0. This curve suggests that the space complexity of Algorithm 1 with heuristic 1, n=2.0 is almost exponential.



(a) (b)

Figure 4-21: Total nodes expanded by Algorithm 1 as a function of the total nodes in the building with (a) distance heuristic of 1.20 and (b) distance heuristic of 1.50.

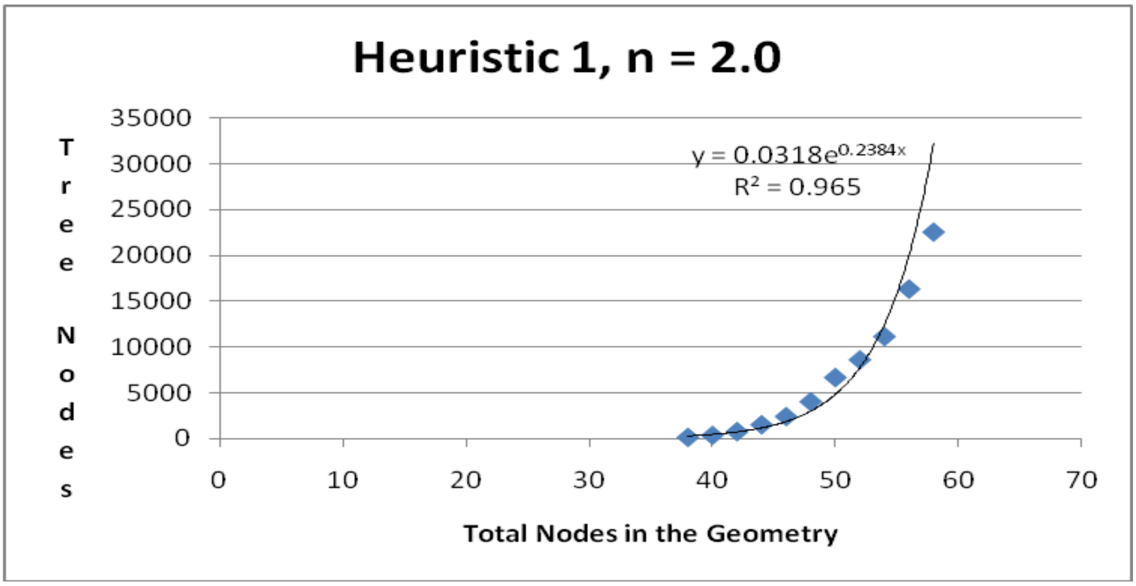


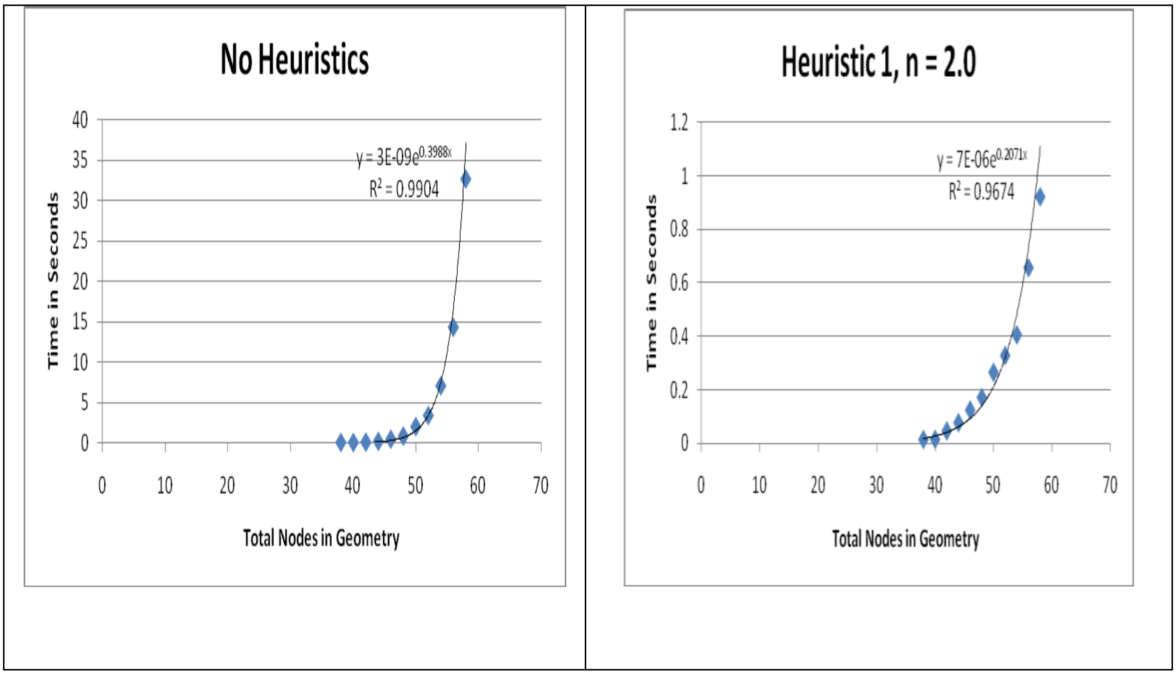
Figure 4-22: Total nodes expanded by Algorithm 1 as a function of the total nodes in the building with a distance heuristic of 2.0.

Table 4-9: Space and time complexity of Algorithm 1 with no heuristics, heuristic 1 (n=2.0), heuristic 2(m=10) and both heuristics.

Inter connectivity (nodes,arcs)	Algorithm 1 with no heuristics		Algorithm 1 with heuristic1 (n=2.0)		Algorithm 1 with heuristic 2 (m=10)		Algorithm 1 with both heuristics	
	Time	**Nodes**	**Time**	**Nodes**	**Time**	**Nodes**	**Time**	**Nodes**
Connectivity1 (38,99)	0.015	219	0.015	157	0.00	182	0.00	155
Connectivity2 (40,111)	0.015	561	0.016	368	0.00	198	0.00	176
Connectivity3 (42,127)	0.062	1293	0.047	780	0.00	246	0.015	224
Connectivity4 (44,140)	0.157	3303	0.078	1526	0.00	276	0.016	254
Connectivity5 (46,157)	0.422	6969	0.125	2423	0.015	303	0.016	281
Connectivity6 (48,174)	0.813	16299	0.172	4041	0.016	392	0.031	328
Connectivity7 (50,188)	1.985	39583	0.266	6675	0.016	405	0.031	363
Connectivity8 (52,206)	3.359	77117	0.329	8602	0.016	426	0.032	391
Connectivity9 (54,221)	7.032	147459	0.406	11145	0.016	440	0.032	412
Connectivit10 (56,237)	14.297	372677	0.657	16319	0.031	461	0.032	437
Connectivity11 (58,253)	32.656	945131	0.922	22520	0.031	491	0.032	468

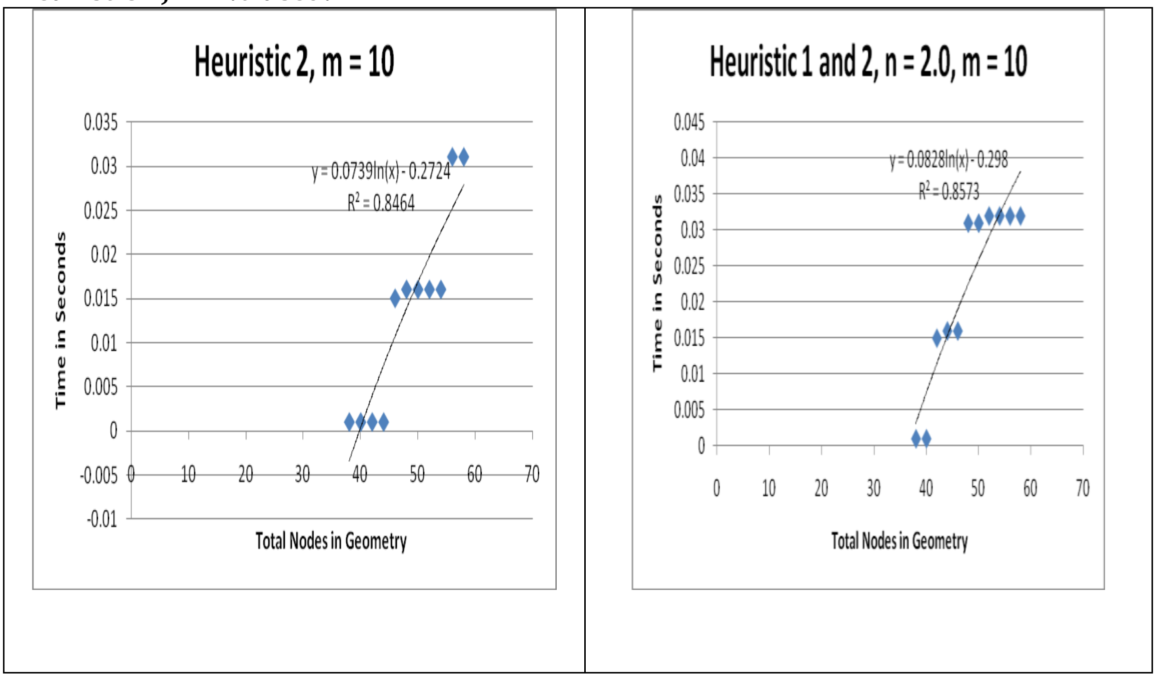
Figure 4-23(a) shows the time complexity of Algorithm 1 with no heuristics used and Figure 4-23(b) shows the time complexity of Algorithm 1 using the heuristic 1 with a 'n' value of 2.0. The time complexity of the Algorithm 1 for both cases suggests an exponential complexity.

Figure 4-24(a) shows the time complexity of Algorithm 1 with the 10 max routes heuristic used and Figure 4-24(b) shows the time complexity of Algorithm 1 with both heuristics 1 and 2 used. The heuristic 2 with a 'm' value of 10 limits the number of paths found for each room to a maximum of 10. Introduction of this heuristic makes the time complexity of Algorithm 1 to be linear. Using both heuristics as well makes the time complexity of Algorithm 1 to be linear. Therefore, the introduction of the heuristic 2 with a 'm' value of 10 has been the most effective. Combining both the heuristics has not made Algorithm 1 more efficient. In fact, the times have increased with the usage of both heuristics (see Table 4-9). Therefore, in the next section only the heuristic 2 with m=10 will be used.



(a) (b)

Figure 4-23: Time complexity of Algorithm 1 with (a) no heuristics used and (b) with heuristic 1, n=2.0 used.



(a) (b)

Figure 4-24: Time complexity of Algorithm 1 with (a) heuristic 2, m=10 used and (b) both heuristics used.

4.5.2 Performance of Algorithms 1, 2 and 3

A small 17 room geometry was considered to test the performance of the Algorithm 1 in the previous section, as Algorithm 1 without any heuristics has issues even with relatively large geometries like 100 rooms. The heuristic 2 is applied to the Algorithm 1 for the test cases in this section with a ‘m’ value of 10. Algorithm 3 similarly uses a K value of 10, implying that 10 shortest paths are found for each room. A larger 700 room geometry is considered for comparing the performance of all three route choice set generating algorithms. As it is difficult to visually present a 700 room geometry a simplified version of the geometry used is shown Figure 4-25. The simplified version has 7 blocks of 3X3 rooms with each block being separated by a corridor. The full version is similar but has 7 blocks of 10X10 rooms thus forming the 700 rooms not including the corridors. In Figure 4-25 it is noticed that for all the seven blocks the horizontal adjoining rooms are connected but the rooms in block1 are connected to the vertical adjoining rooms as well. The full scale version of Figure 4-25 forms the connectivity 1 test case used in this section. There are 7 test cases in this section. In the subsequent test cases 1 additional block of rooms are connected to the vertical adjoining rooms. So for the connectivity 2 test case block 1 and block 2 have rooms with vertical adjoining rooms connected. For connectivity 7 test case all the blocks 1-7 have the vertical and horizontal adjoining rooms connected by internal doors. These hypothetical test cases have been designed to check the performance of the three algorithms.

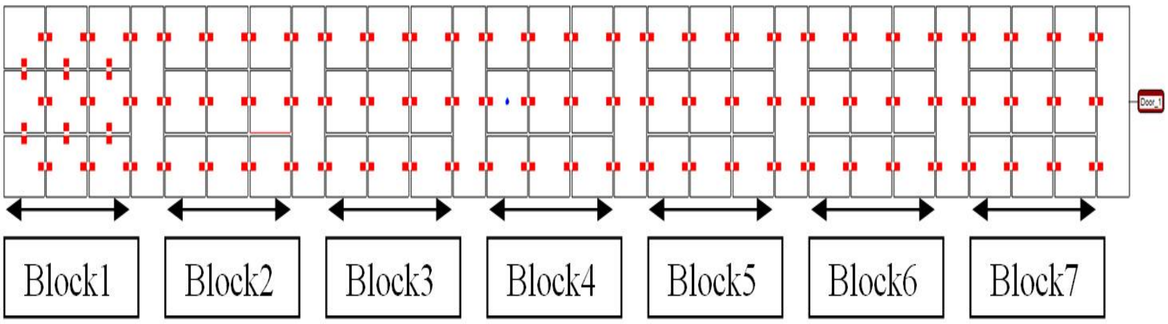


Figure 4-25: A simplified version of the 700 room geometry used to compare the performance of Algorithms 1, 2 and 3. The red blocks represent internal exits.

Table 4-10 shows the time taken by the three algorithms for connectivity test cases 1-7. All the algorithms have a linear run time complexity (see Figure 4-26 and Figure 4-27). Figure 4-28 shows the run time complexity of the three algorithms. Algorithm 2 takes the least time, Algorithm 3 takes the maximum time and the time taken by Algorithm 1 is in between the two. Yen's algorithm has a logarithmic run time as discussed in Section 4.3.3. However, it is interesting to note that Algorithm 3 which is a modification of the Yen's algorithm has a linear run time. The additional constraint introduced to the Yen's algorithm (see Section 4.3.3) has been responsible for the decrease in the times taken by Algorithm 3. The Algorithm 3, without this constraint crashes due to memory issues consuming more than 7 gigabytes of memory. However, the Yen's algorithm has been run by [Martins and Pascoal., 2003] on a computer with just 512 megabytes of memory taking just five minutes to calculate 1000 routes in a graph consisting of 10,000 nodes and 20,000 arcs. The reason for Algorithm 3 to crash with memory issues is either due to the usage of slightly more complex nodes and arcs carrying more information such as node/arc type, area, capacity and other attributes which are required for the wayfinding model or due to inefficient handling of memory. However, this investigation is considered for future research.

Table 4-10: Time taken by Algorithms 1-3 for connectivity test cases 1-6

Number of Interconnected Rooms (Total nodes, Total arcs)	Time taken by Algorithm1 (seconds),	Time Taken By Algorithm 2 (seconds)	Time Taken By Algorithm 3 (seconds)
Connectivity1 100(1558,4008)	12.68	0.431	30.90
Connectivity2 200(1648,4628)	21.86	0.5	36.63
Connectivity3 300(1738,5248)	28.89	0.552	44.28
Connectivity4 400(1828,5868)	34.093	0.625	54.62
Connectivity5 500(1918,6488)	38.65	0.735	64.57
Connectivity6 600(2008,7108)	40.93	0.812	70.89
Connectivity7 700(2098, 7728)	44.19	0.859	77.92

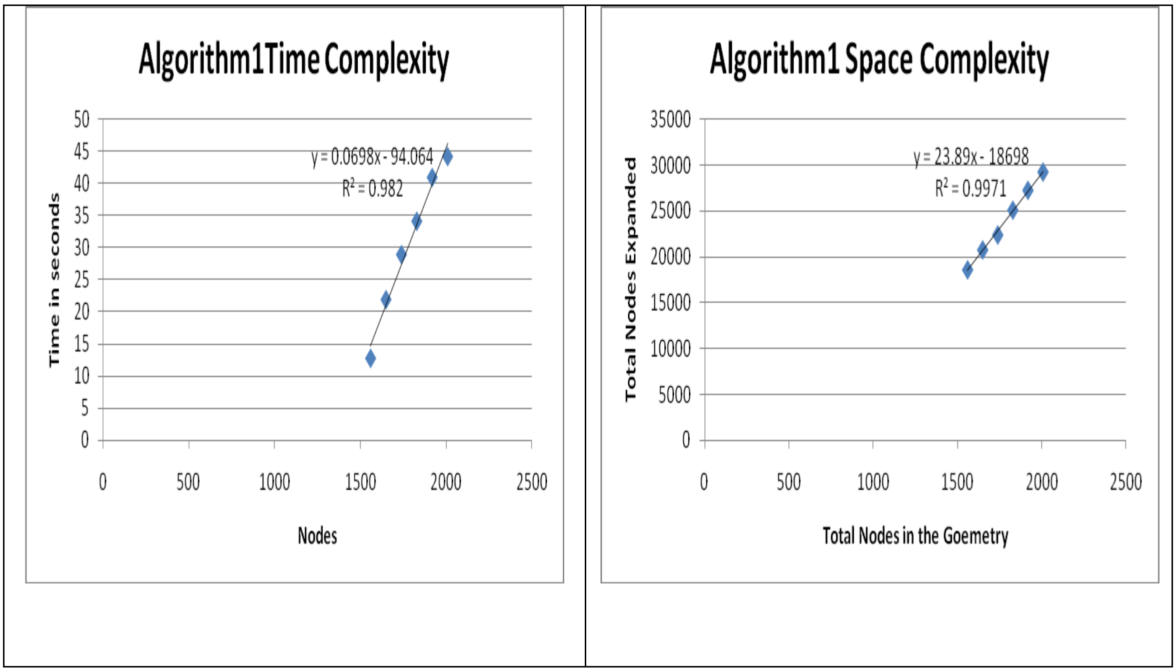
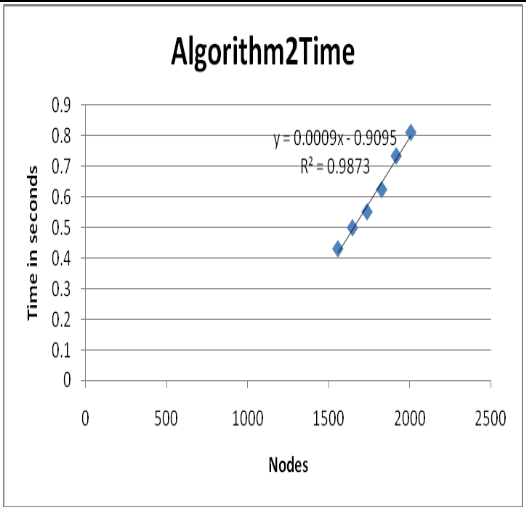


Figure 4-26: Time and Space Complexity of Algorithm 1 with heuristics applied.



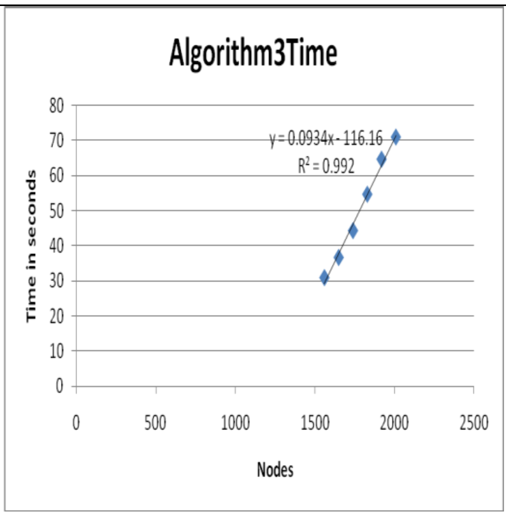


Figure 4-27: Time Complexity of Algorithm 2 and 3

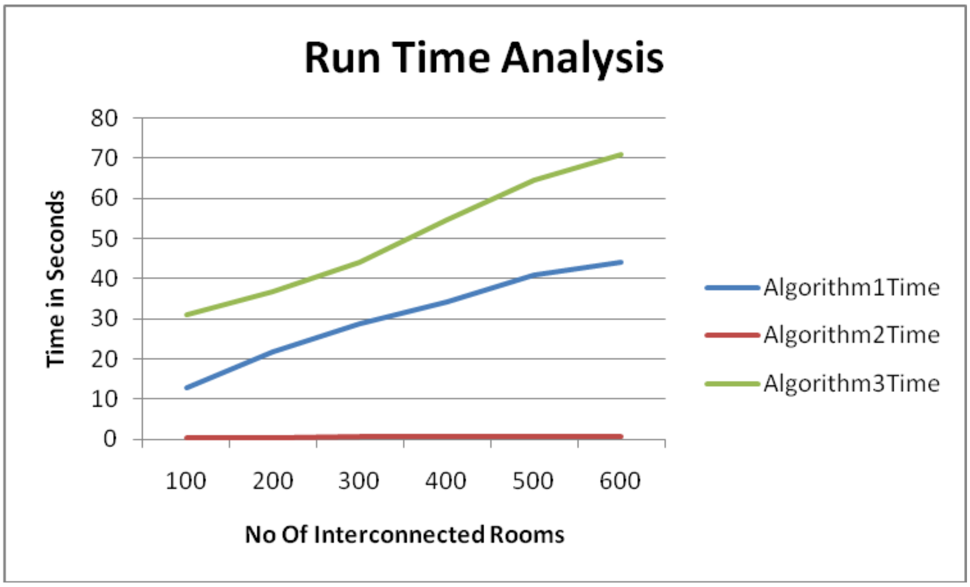


Figure 4-28: Run time analysis of Algorithms 1, 2 and 3.

4.6 Conclusion

This chapter started with details of the spatial representation techniques employed in this thesis. Spatial representation is a very important aspect of wayfinding models and is essential for the implementation of the choice set generation algorithms. Two different graphs were examined: room and route graphs. An intermediate approach was selected and the connectivity graphs were used to implement the path planning algorithms. The connectivity graphs consisted of the key building elements such as internal exits, external exits and room nodes. People exiting a building will move from a room to internal exit to room to internal exit until they reach the final exit or an external exit and hence this connectivity graph forms a logical mathematical representation of space required to model human wayfinding in evacuation/circulation modelling tools for buildings.

The three choice set generating algorithms implemented to provide a choice set of routes for the agents in the wayfinding model were then described. The performance of the three algorithms in terms of the quality of the paths found, time/space complexities were then analysed. Algorithm 1 could determine all possible routes in a building. However, the time and space complexity of Algorithm 1 was polynomial which would not be useful for very large buildings. Therefore heuristics were introduced to reduce the time/space complexities to a linear complexity. However, an attempt was also made to find other more efficient algorithms. Algorithm 2 proved to be the quickest in terms of the run times among the three algorithms. However, this algorithm produces a few good routes alone and missed some routes which are required for the evacuation process. Algorithm 3 takes slightly more time than Algorithm 1 with heuristics. However, Algorithm 3 can be considered to be the best algorithm to determine a choice of set routes as it is capable of finding the K shortest paths whose cost is in a non decreasing order i.e., the shortest path is found first, the second shortest is found next and continues until K shortest paths are determined. The Yen's algorithm which has been modified in Algorithm 3 has performed well in large graphs consisting of 10,000 nodes and 20,000 arcs [Martins and Pascoal, 2003]. Therefore, Algorithm 3 is identified as the best candidate for future research if the wayfinding model needs to be applied for very large buildings giving rise to dense graphs.

This chapter has discussed the algorithms developed in this thesis to generate a choice set of routes for the agents in the wayfinding model. This choice set of routes is not to be confused to be the most likely routes to be used by people in the real world. Rather the aim of the choice set generation algorithms were to provide all the possible routes in a building. However, it is infeasible to generate all possible routes in a building, especially for large geometries as discussed in Section 4.6.1. Therefore, the choice set generation Algorithms 1 and 3 determine at least 10 routes from each room in a building. A provision could be provided to increase or decrease the number of routes in the wayfinding model. Therefore, the routes generated by the Algorithms provide a set of possible routes that agents can choose from. The agents can then use their personal preferences to choose the best route among the route choice set which will be discussed in Chapter 7. However, the next step is to determine the factors that affect the wayfinding behaviour of people. The next chapter provides details of the first wayfinding questionnaire carried out for this purpose.

5 Wayfinding Questionnaire 1

5.1 Introduction

Methodologies to assign a choice set of routes to the agents in the simulation were looked at in Chapter 4. Given a choice set of routes the next step is to model the actual choice or decision making capability of the agents. In order to model the decision making ability it is important to determine the key factors that influence wayfinding. This chapter and the next describe the experiments that were carried out to determine the important factors that influence wayfinding. This chapter tries to answer Question 6 posed in Chapter 1 namely "What factors influence wayfinding in the built environment". More specifically the aim of this chapter is to answer the sub Questions 6.5 – 6.9 branching from Question 6.

In Chapter 2, Section 2.2.4, the factors that influence wayfinding were identified based on past and current wayfinding studies. However, it was also pointed out that most of these studies were designed for the urban environment and it is not clear whether the same results are valid in the built environment. In addition, some of those studies had small sample sizes and therefore produced statistically insignificant results. Each of the past studies tested their own set of wayfinding factors. However, this thesis considers a unique set of wayfinding factors: distance, time, no of turns, longest leg first, shortest leg first, angle of paths, decision points, right-handed paths and left-handed paths (see Chapter 2, Section 2.2.4). These factors will henceforth be referred to in this thesis as the building wayfinding criteria. Since an individual deciding on a path will consider more than one of these factors it is vital to carry out experiments to determine the relative importance of these factors from a building evacuation perspective.

The building wayfinding criteria consist of nine factors and some of these are exact opposite of the other. For example, Longest leg first and shortest leg first, which are paths having the longest leg or the shortest leg as the first leg of the journey, are exactly opposite of each other. Similarly left-handed paths and right-handed paths, which are paths whose first turn is left or right, are again exact opposite of each other. Since it is difficult to combine these factors with the rest of the building wayfinding criteria, it was decided to study these factors in isolation in the first survey. Having determined the most important criterion among these factors the rest of the building wayfinding criteria were decided to be studied in a second survey. This chapter provides the details of the first survey and the next chapter, Chapter 6, will provide the details of the second survey.

The factors studied in the first survey are: longest leg first, shortest leg first, right-handed paths and left-handed paths. Another factor that will also be studied in the first survey is the 'most direct' route (see Chapter 2, Section 2.4).

5.2 Details of the wayfinding questionnaire

Participants were invited to complete an on-line questionnaire. The call for participation to complete the on-line survey was undertaken via several different media e.g. website link, leaflet distribution, online forums, email mailing lists, friends/family/colleagues, a national appeal broadcast on BBC radio, snow balling, etc. The survey is still on line (http://fseg.gre.ac.uk/wayfinding/index.asp).

The first part consisted of five separate wayfinding tasks where the participants were shown five different hypothetical building layouts in turn (see Figure 5-1), each with two paths, labeled A and B, leading to an exit. The participant was provided with written information stating that each path was equal in length and that they were completely familiar with the building layout. On selecting the preferred path, the participant was then asked to rate both paths on a scale of 1 to 6 where 1 is highly undesirable, 2 is very undesirable, 3 is a little undesirable, 4 is a little desirable, 5 is very desirable and 6 is highly desirable. On completing this, the participant was then asked to imagine that they were now in an emergency evacuation situation in the same building and choose their preferred exit path. For the emergency evacuation option, the participant was informed that they now hear the fire alarm and see equal amount of smoke along both paths. Please see Appendix E for a full list of the survey questions as they were presented to the participants.

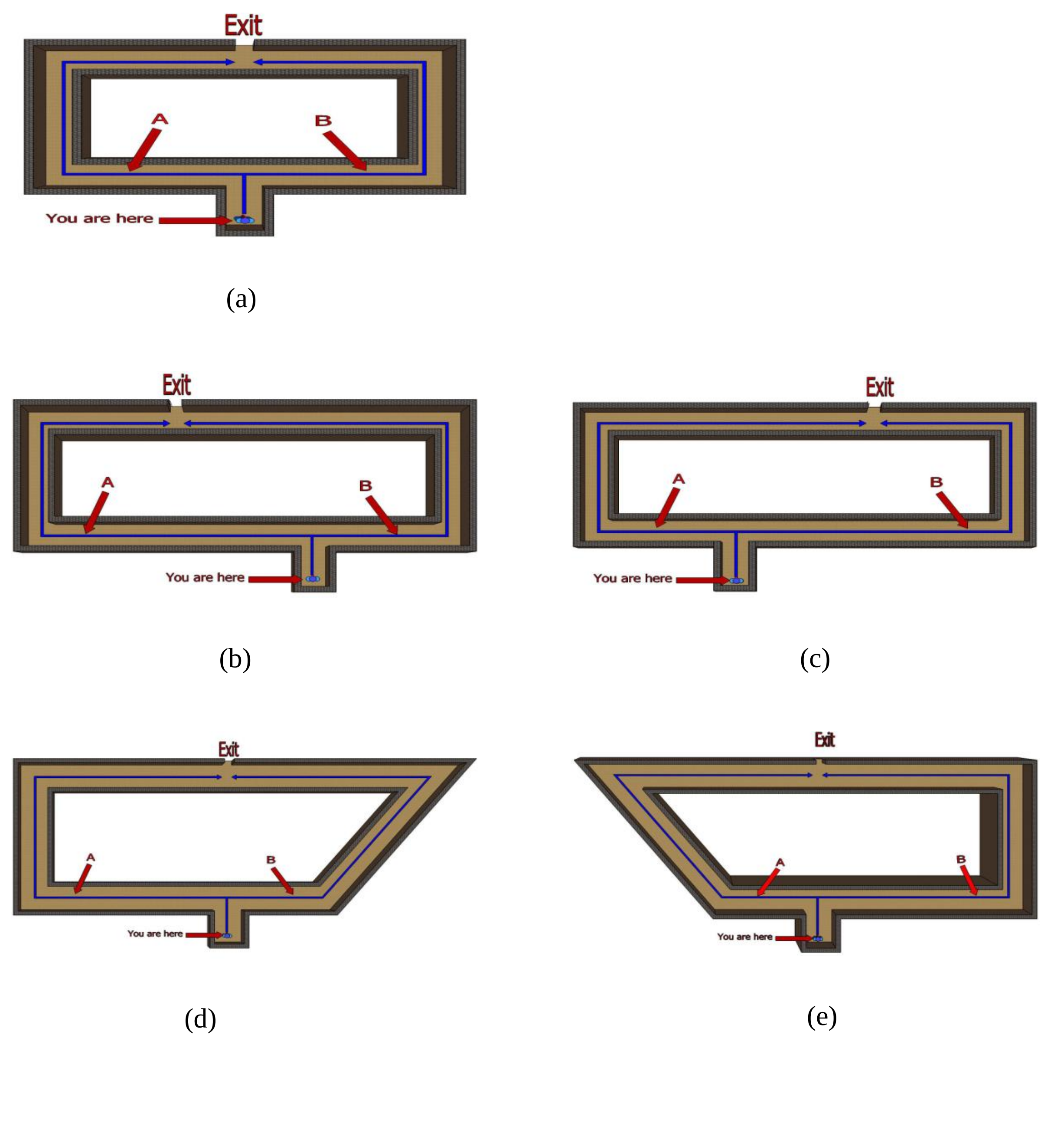


Figure 5-1: Path selection tasks in the questionnaire.

Question 1 is intended to investigate the participant’s preference for selecting the left-hand or right-hand path (see Figure 5-1a). In the second (see Figure 5-1b) and third (see Figure 5-1c) questions, the building geometries either have the LLF path on the left (see Figure 5-1b) or right (see Figure 5-1c). The LLF path is also the most direct path having the least bearing to the exit. In order to remove ‘the most direct path’ factor from consideration, Questions 4 (Figure 5-1d) and 5 (Figure 5-1e) were designed where the start position is in line with the exit, thus both paths have an equal bearing to the exit. Initially the length of the paths in Questions 4 and 5 were kept the same. However, a pilot study indicated that people perceived the angled path, Path B in Question 4 and Path A in Question 5 (Figure 5-1d and Figure 5-1e), to be slightly longer in spite of being reminded that both paths are of the same length. Hence the angled paths were made slightly shorter in order to compensate for this visual illusion.

In the second part of the survey the participants were given a list of factors and were asked to choose those that influenced their wayfinding decisions in the first part of the survey. Participants could select more than one option and were also given the opportunity to list other factors that influenced their decision. The list of factors provided was:

- I prefer to take the path with the longest leg first
- I prefer to take the path with the shortest leg first
- I have a preference for paths on my left
- I have a preference for paths on my right
- I have a preference to take the clockwise paths
- I have a preference to the take the anticlockwise path
- I choose the path which appeared to be the most direct
- I choose randomly

The third part of the survey involved collecting participant demographic information. Two pilot studies were conducted to check the general level of understanding of the questions. A few modifications were made to the questionnaire based on the pilot studies and this data was not included in the overall questionnaire results.

However, when reviewing the findings of the surveys, it must be noted that the study is a map based questionnaire and so relies on the ability of participants to imagine themselves in the described situation. It is not clear if the participants would behave in a similar manner in a real emergency evacuation situation.

5.3 Sample population

A total of 1200 participants from 36 countries took part in the survey of which 1166 were considered eligible to take part in the analysis. The countries with the largest response to the survey are: UK, 649 (56 %); USA, 113 (10 %); Australia, 72 (6 %); India, 62 (5 %); Germany, 46 (4 %) and Netherlands, 25 (2 %). Of this sample, a total of 336 (29 %) of the participants drive on the right-side of the road e.g. USA, Germany, Netherlands, etc, and 830 (71 %) drive on the left-side of the road e.g. UK, Australia, India, etc. Furthermore, 1010 (87

%) of the participants are right-handed while 156 (13 %) are left-handed. Our sample of left-handed people is equivalent to the world average of 10–13 % of the population being left-handed [Raymond, et al., 1996]. Of the sample population who drive on the left-side of the road (830), 728 (88 %) are right-handed (note, the Right-Handed Left-Driving sub-population is referred to as RHLD). Of the left-driving sample, 102 (12 %) are left-handed (note, the Left-Handed Left-Driving sub-population is referred to as LHLD). Of the sample that drive on the right-side of the road (336), 282 (84 %) are right-handed (referred to as RHRD) while 54 (16 %) are left-handed (is referred to as LHRD).

The results of the survey were analysed incrementally for every 100 participants that took the survey. The average results of these samples were then compared (e.g., the results of 100 participants compared with 200, 200 with 300 and so on). These averages remained steady (±1%) after the collection of 700 participants. So the results shown in this chapter for 1166 participants is effectively the same as for the first 700 participants with a ±1% difference. More participants were collected because the number of people in the Left-Handed Right Driving (LHRD) subpopulation had to be increased in order to make statistically significant analysis (see Section 5.4.1.4 for more detail). The participants recruited for this survey consisted of people from different countries, age groups, handedness, professions and hence can be considered to be a good representative of a general population.

The human factors study [Scharine and McBeath, 2002] which makes similar conclusions to the ones presented in this chapter have a smaller sample size. For example, their conclusions are based on participant numbers as low as 3 in the LHLD category and 12 in the LHRD category. All the conclusions made in this chapter are statistically significant using the Chi-Square test with Yates [Yates, 1934] correction.

5.4 The Main Results and Discussion

The findings from Part 1 of the study are first presented, followed by the findings from Part 2. The Part 1 results are first summarized and then the responses to each of the wayfinding questions are examined in turn. It is important to note that the results for the path selection under normal conditions were virtually identical to those under emergency conditions and so only the results under normal conditions are presented.

5.4.1 Discussion of Part 1 Results

In this section the results from the path selection tasks for Questions 1–5 are first summarized. This is then followed by a detailed investigation of the results from each path selection task. The results for each path selection exercise are examined in detail with a focus on: Question 1 – impact of the participants handedness and driving side on the path selection; Questions 2 and 3 – impact of the length of the first leg on path selection (together with participant handedness and driving); Questions 4 and 5 – as for Questions 2 and 3 but with the path directness removed as an influencing factor.

5.4.1.1 Overview of Path Selection Results

A summary of the path choice made by the entire sample population (1166) for each of the five questions is shown in Figure 5-2. In the first four wayfinding tasks (Questions 1–4), the participants clearly have a preference for right-hand paths which is statistically significant at a 0.001 confidence level.

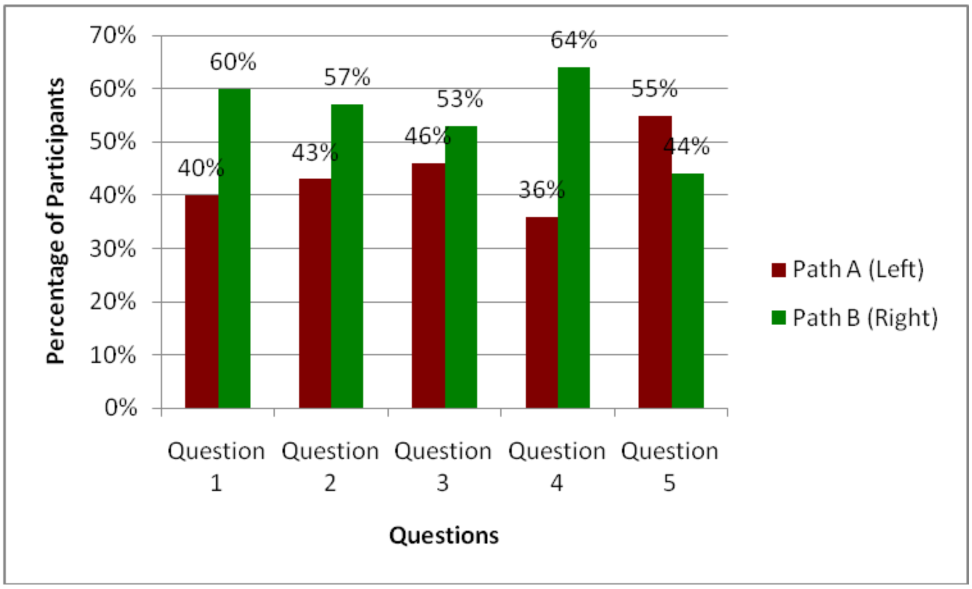


Figure 5-2: Percentage of the sample population selecting Paths A and B in wayfinding tasks.

This preference for right-hand paths is examined in more detail in the following sections. These results suggest that on the whole people generally have a slight preference for right-hand paths. However, in the fifth wayfinding task there is a significant preference for the left-hand path. The reasons for this apparent difference in path selection are examined in the next sections.

5.4.1.2 Question 1: The Influence of Handedness on Path Selection

In the first question, both path options were identical, the only variable that was different was that one path was on the left and the other path was on the right. Taken across the entire sample (1166), 60 % (700) chose the right-hand path and 40 % (466) chose the left-hand path (see Figure 5-3). The chi-square goodness of fit test [Cochran, 1952] (χ^2 = 42.39) suggests that this distribution is valid at a 0.001 level of significance. Thus, people in general are more likely to turn right than left.

Figure 5-3: Percentage of each sub-population choosing right-hand paths.

In the right-handed sub-population (1010), 64 % (646) chose the right-hand path (Figure 5-3). Considering that 87 % of the entire sample is right-handed, it is not surprising that the increase in the preference for right-hand paths is as small as 4 % compared to the entire sample. In the left-handed sub-population (156), 71 % (111) have chosen the left-hand path and 29 % (45) have chosen the right-hand path (see Figure 5-3). This distribution is also valid at a 0.001 level of significance (χ^2 = 23.52) which implies that left-handed people have a strong preference for left-hand paths. Thus, handedness of people is a strong factor which determines people's preference for right/left-hand paths.

A chi-square test of independence was also performed to check if the right/left-hand paths chosen by people are independent of the handedness of the participants. The null hypothesis is that the path choice of people is independent of their handedness. The paths chosen by the right-handed sub-population and the left-handed sub-population have been considered for this analysis. The chi-square result ($\chi^2 = 60.69$) suggests that the null hypothesis can be rejected at a 0.001 significance level. Thus, handedness does have a very strong influence on the right/left-hand path choice.

5.4.1.3 Question 1: The Influence of the Driving Side on Path Selection

In the right-side driving sub-population (336), 71 % (239) have chosen the right-hand path (see Figure 5-3). People driving on the right-side of the road have a strong preference to right-hand paths at a 0.001 level of significance ($\chi^2 = 57.26$). In fact, people driving on the right-side of the road have a stronger preference to right-hand paths than the right-handed sub-population where only 64 % chose the right-hand paths (see Figure 5-3). This is because the majority (84 %) of the right-side driving sub-population is also right-handed. This suggests that in addition to handedness, the driving side also influences the choice of right-hand paths in a complementary (additive) fashion. In the left-side driving population (830) 55 % (457) chose the right-hand path (see Figure 5-3). The right-hand path preference has fallen by 5 % compared to the entire sample which suggests that driving on the left-side influences people to choose left-hand paths. However, 88 % (730) of the left-side driving sub-population is right-handed which explains why right-hand path is still popular. In the case of the left-side driving sub-population, right-handedness and left-side driving are in opposition, reducing the overall number of people who select the right-hand path. This suggests that handedness of people (genetic factor) is a more influential factor than the driving side (cultural factor) when it comes to influencing wayfinding path choices.

A chi-square test of independence was also performed to check if the right/left-hand paths chosen by people are independent of the driving side by considering the right-side driving and left-side driving sub-populations. The chi-square result ($\chi^2 = 24.31$) suggests that the driving side has a strong influence on the right/left-hand paths chosen at 0.001 significance level. It is interesting to note that even though the majority in the right-side drive and left-side drive sub-populations has preferred the right-hand path, the driving side still has a significant influence on the path choice.

5.4.1.4 Question 1: The Influence of the Handedness and Driving Side on Path Selection

According to the previous analysis, the handedness and driving side are factors which each have a significant influence on path selection. In this section the influence of a combination of the two factors is considered. Figure 5-3 shows the percentage of each sub-population choosing right-hand paths in the first question of the questionnaire relating to the geometry in Figure 5-1a. The sub-populations are arranged in descending order of preference for right-hand paths from left to right. Thus, the sub-populations having a higher preference for right-hand paths are on the left and the sub-populations having a lower preference for right-hand paths are on the right. Clearly, right-handed people driving on the right-side have the strongest preference for right-hand paths and the left-handed people driving on the left-side have the lowest preference for right-hand paths (and the highest preference for left-hand paths). The preference for right-hand paths in the first six sub-populations from the left is statistically significant at the 0.001 confidence limit. The preference for left-hand paths for the last two sub-populations is also statistically significant at the 0.001 confidence limit.

The right-handed sub-population has a strong preference for right-handed paths at 64 %. The preference for right-hand paths increases to 75 % in the RHRD sub-population. This suggests that the preference for right-hand paths is amplified if one is right-handed and from a country driving on the right side of the road compared to when one is simply right-handed. The left-handed sub-population has little preference for right-handed paths at 29 %. The preference for right-hand paths further decreases to 23 % for the LHLD sub-population. This suggests that the preference for left-hand paths is amplified if one is left-handed and from a country driving on the left side of the road compared to when one is simply left-handed.

The RHRD sub-population has a 15 % greater preference for right-hand paths than the RHLD sub-population. Thus, if one is right-handed and driving on the left side of the road then the preference for right-hand paths while high is not as high as it is when one is right-handed and driving on the right-side of the road. The LHLD sub-population exhibits a 25 % greater preference for left-hand paths than the LHRD sub-population. This suggests that if one is left-handed and driving on the right-side of the road there is a small preference for left-hand paths, and if one is left-handed and driving on the left side of the road there is a strong preference for left paths. The LHRD sub-population has a 51 % preference for left-handed paths, close to a 50-50 preference for right- and left-hand paths. The small preference for left-handed paths for this sub-population may be attributed to the small number of participants in this category, only 54, with the next smallest category having 102 participants (LHLD). It is expected that if the number of participants in the LHRD category were increased, a stronger preference for left-handed paths would emerge for this sub-population. However, according to Cochran [Cochran, 1952], the expected and observed frequencies in this sub-population are sufficient to make statistically significant conclusions.

Considering that the RHLD sub-population has a strong preference for right-hand paths and the LHRD sub-population has a slight preference for left-hand paths, one can deduce that handedness of people is a stronger factor than the driving side in influencing the right/left-hand path choice. The same deduction can also be made comparing the χ^2 values for the handedness and driving side analyses. The χ^2 value for the influence of handedness, 60.69, is greater than the χ^2 value for the influence of the driving side, 24.31. This supports the conclusion that handedness (a genetic factor) is a more influential factor than the driving side (a cultural factor) in affecting path choice. Furthermore, if the driving side is the same as the handedness, these factors reinforce each other however, if they are opposite, they work in opposition.

5.4.1.5 Questions 2 and 3: Length of the First Leg of the Path

In Questions 2 (Figure 5-1b) and 3 (Figure 5-1c), the length of the first leg is introduced as a path choice factor. In Question 2 the right-hand path is the shortest leg while in Question 3 the right-hand path is the longest leg. Figure 5-4 shows the percentage of each sub-population that selected the right-hand paths in Questions 2 and 3.

It is interesting to note that in Questions 2 and 3, the sub-populations containing a majority of right-handers, which are the first six columns from the left of Figure 5-4, have all shown a significant preference for the right-hand path regardless of whether it is the Shortest Leg First or Longest Leg First path (SLF/LLF) path. A similar trend is found for the sub-populations consisting of left-handed people, which are the last two columns on the right in Figure 5-4, namely a significant preference for the left-hand path regardless of whether it is the SLF/LLF path. The exception to this is the LHRD sub-population who prefers the right-hand path – however, as suggested earlier the sample size may be too small to make meaningful comparisons. The preference for right- or left-hand paths regardless of the length of the first leg suggests that for the majority of the population the handedness of the path is a more influential factor than the length of the first leg in affecting path choice.

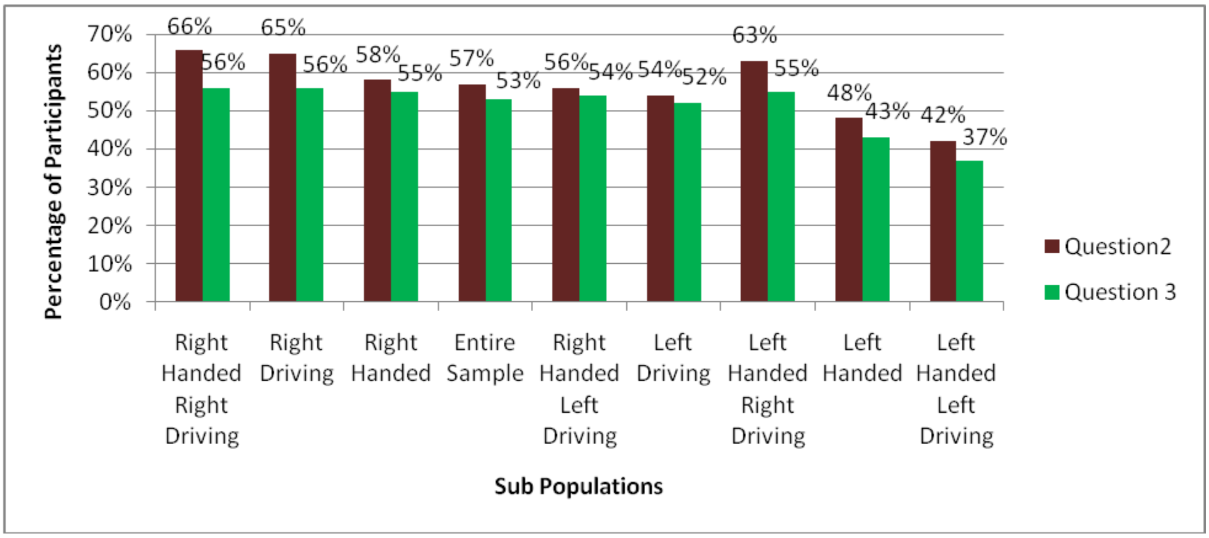


Figure 5-4: The percentage of each sub-population choosing the right-hand path in Questions 2 and 3.

However, for some of the population, selecting the SLF or the LLF will be more important than the handedness of the path. Consider the sub-populations that prefer the right-hand path i.e. the first six columns of the left of Figure 5-4. When the right-hand path preference is compared to that of Question 1 (see Figure 5-3) it is noted that fewer people select the right-hand path when the first leg of the path is short or long. For example, consider the RHRD sub-population for which the preference for selecting the right-hand path is strongest with 75 % of the sub-population preferring the right-hand path in Question 1. For some of this sub-population, selecting the SLF or the LLF will be more important than selecting the right-hand path resulting in the proportion of the sub-population falling below 75 % in Questions 2 and 3.

It is noted from Questions 1 and 2 that 9 % (75–66 %) of the RHRD sub-population that would have been expected to select the right-hand path have selected the LLF path (i.e. the left-hand path) in preference. For this small group, selecting the path with the LLF is more important than the handedness of the path and so they have selected the left-hand path. Similarly, as some of this sub-population will have a stronger preference for the SLF than the right-hand path, the percentage of people selecting the right-hand path in Question 3 will be less than 75 %. It is also noted that 19 % (75–56 %) of the RHRD sub-population have selected the SLF in preference to the right-hand path. For this group, selecting the path with the SLF is more important than the handedness of the path and so they have selected the left path.

Furthermore, 66 % of the RHRD sub-population selected the SLF path when it is the right-hand path (Question 2) while 56 % of the sub-population selected the LLF when it is the right-hand path. This suggests that selecting the SLF is a more dominant secondary factor than selecting the LLF. Within the RHRD sub-population, more people prefer the right-handed path when it is also the SLF path than when it is the LLF path.

Similar trends are found for the sub-populations that prefer the left-hand path; i.e. the last two columns on the right of Figure 5-4. When the left-hand path preference is compared to that of Question 1 (derived by taking 100 % – right-hand preference (%) shown in Figure 5-3) it is noted that fewer people select the left-hand path when the first leg of the path is short or long. For example, consider the LHLD sub-population for which the preference for selecting the left-hand path is strongest with 77 % (100–23 %) of the sub-population preferring the left-hand path in Question 1. For some of this sub-population, selecting the SLF or the LLF will be more important than selecting the left-hand path resulting in the proportion of the sub-population falling below 77 % in Questions 2 and 3.

It is noted that from the 77 % who chose the left-hand path in Question 1 only 63 % (100–37 %) have chosen the left-hand and SLF path in Question 3. Hence 14 % (77–63 %) of the LHLD sub-population that could normally have been expected to select the left-hand path have selected the LLF path (right-hand path) in preference. For this group, selecting the path with the LLF is more important than the handedness of the path and so they have selected the right-hand path. Similarly, as some of this sub-population will have a stronger preference for the SLF than the left-hand path, the percentage of people selecting the left-hand path in Question 3 will be less than 77 %. It is noted that 19 % of the LHLD sub-population have selected the SLF in preference to the left-hand path. For this group, selecting the path with the SLF is more important than the handedness of the path and so they have selected the right-hand path.

Furthermore, 63 % of the LHLD sub-population has selected the SLF path when it is the left-hand path (Question 3) while 58 % of the sub-population has selected the LLF path when it is the left-hand path (Question 2). This suggests that selecting the SLF is a more dominant secondary factor than selecting the LLF. Within the LHLD sub-population, more people prefer the left-handed path when it is also the SLF path than when it is the LLF path. The same trend is also found across the other sub-populations and the entire sample.

From the results of Questions 1–3 we conclude that for the majority of people, the handedness (a genetic factor) is the most important factor in influencing a person's path choice. The handedness however is influenced in turn by the driving side (a cultural factor) – if the driving side is the same as the handedness, these factors reinforce each other while if they are opposite, they work in opposition. The next most important factor influencing path selection is the length of the first leg of the path. The preference for SLF paths is greater than the preference for LLF paths. This result is interesting as it contradicts the conclusions of urban wayfinding research which suggests that the preference for LLF is greater than that for the SLF [Golledge, 1995a, b] [Conroy, 2003]. The urban wayfinding studies contained very small sample size and some of the methodologies followed were questionable (see Chapter 2, Section 2.4). Finally, for a small proportion of the population, selecting the SLF or the LLF will be the most important factor in influencing a person's path choice, with selecting the SLF being more dominant that selecting the LLF.

On completing the Question 2 and 3 path selection tasks, participants were asked to comment on why they selected a particular path (see Figure 5-5). This was an open-ended question with no prompts provided. Each of these comments have been analyzed and generalized into certain common factors. For example the following comment was made by a participant, "… this was my first reaction, I tend to turn to my right …". This was inferred to mean that the participant had a preference for right-handed paths. A comment made by another participant was, "Initial path looks to be shorter". This was inferred to mean that the participant had a preference for the SLF path. From Figure 5-5 it is noted that the SLF criterion is identified as being more important to most people than the LLF path.

It is somewhat surprising that the SLF criterion was mentioned by more people than the right-handed path criterion. However, among the group who claim to have selected paths based on instinct, 64 had selected the right-handed path (and 45 the left-handed path). If these are added to the right-hand path selection, then the right-hand path selection dominates. Furthermore, 18 % and 23 % of the participants who answered Questions 2 and 3 respectively did not provide a reason for their path choice. Here again, at least half of these participants will have selected the right-hand path, but it is not clear if they selected the right-hand path because it was the right-hand path or if it had the SLF. Thus, it is not clear whether right-handed paths or SLF paths exert the most influence on path selection based on the results from this question.

In addition, right-handed paths have been mentioned by more participants than left-handed paths which is consistent with the path selection tasks. The number of participants who claim that they made a random path selection is very small, representing only 2 % of the responses to Questions 2 and 3. Finally, the number of participants who suggested that they made a path selection based on the most direct route was only 7 % of the responses to Questions 2 and 3. While it is not clear what the participants meant by this statement, the results suggest that consciously selecting a path on the basis of its directness appears to exert a low influence on path selection.

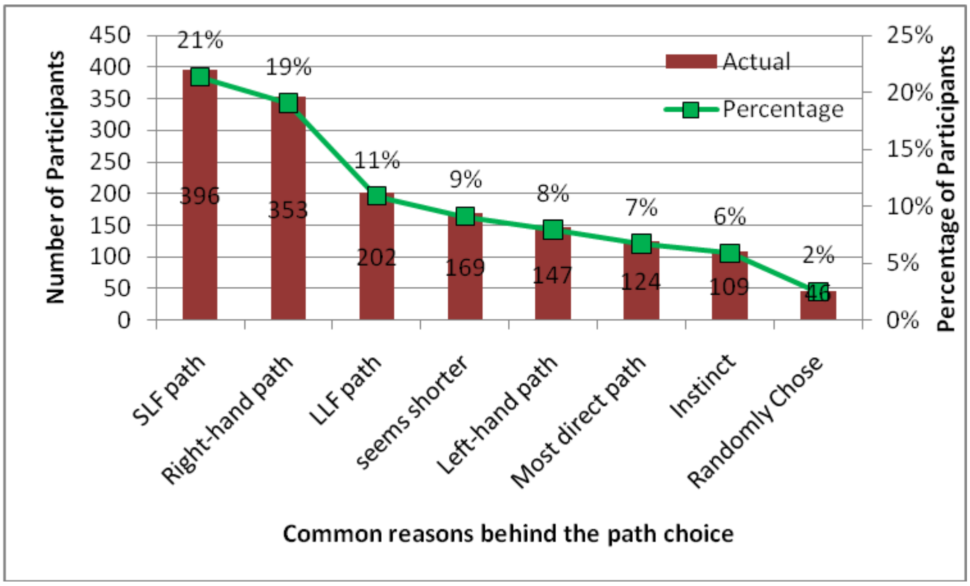


Figure 5-5: Participant path selection comments for Questions 2 and 3.

5.4.1.6 Questions 4 and 5: Removing Directness from Path Selection

Question 4 (Figure 5-1d) and Question 5 (Figure 5-1e) investigate the same factors as Question 2 and 3 with the exception that the LLF path is no longer the most direct path. By positioning the exit directly opposite the starting point, both the LLF and SLF path are considered equally direct as both paths have the same bearing on the exit. Furthermore, the travel distance associated with each path option is still equal as in the other cases. As a result of removing the path directness from consideration while maintaining equal total travel distances, the SLF path has acquired a sharp angle turn. The percentage of each sub-population selecting the right-hand path in Questions 4 and 5 is shown inFigure 5-6. As was found in Questions 2 and 3, the right-handed path which is also the SLF path (Question 4) is preferred by more people than the right-hand path which is also the LLF path (Question 5). Furthermore, the majority of people in Question 4 prefer the right-handed path (which is also the SLF path) however, unlike in Question 2, this trend extends to all of the sub-populations, even those who are expected to have a preference for left-handed paths i.e. the last three sub-populations on the right side of Figure 5-6.

A result which is counter to expectations is that the majority of people in virtually all the sub-populations prefer the left-handed path (which is also the SLF paths) in Question 5. This even includes those sub-populations who are expected to have a preference for right-handed paths. This rejection of the right-hand path by the majority of people in Question 5 may be a result of the strong preference for the SLF path however, if this were simply the case, a similar trend would have been expected in Question 3.

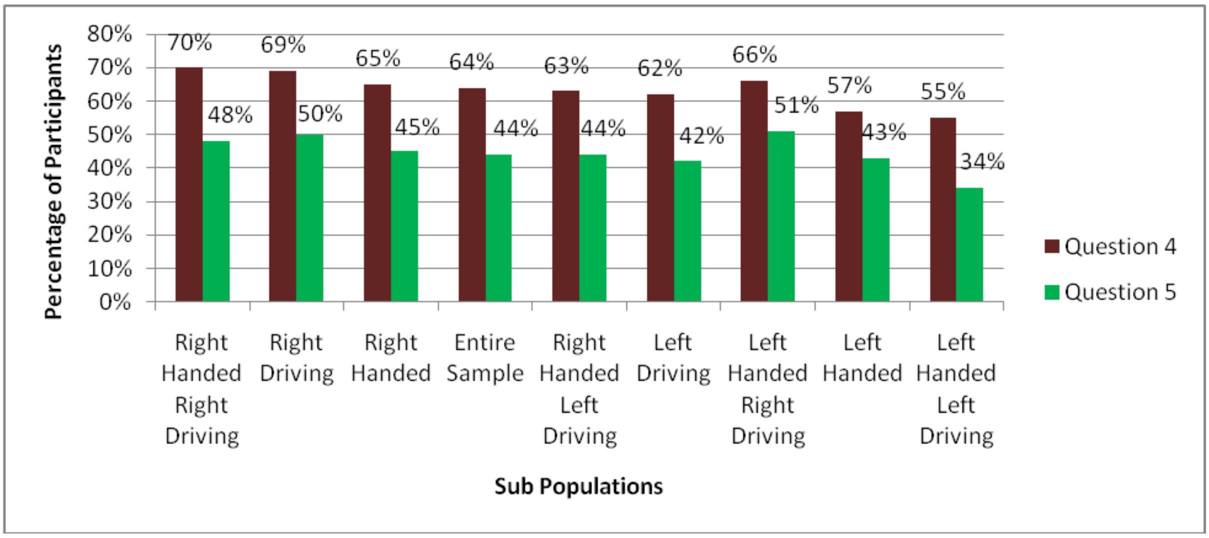


Figure 5-6: The percentage of each sub-population choosing the right-hand path in Question 4 and 5.

As with Questions 2 and 3, it can again be concluded that the majority of people prefer the SLF paths compared to the LLF paths. However, the preference for SLF paths appears to be more significant in Questions 4 and 5 than in Questions 2 and 3, so much so that in Question 5, the majority of people have selected the left-hand path in preference to the right-hand path. There are two possible explanations for the increased trend in the preferences for the SLF path over the LLF path. Either the LLF path has become less attractive or the SLF path has become more attractive.

In an attempt to resolve this question, consider the nature of the paths in Questions 2 and 3 and those in Questions 4 and 5. There are two key differences between the paths in Questions 4 and 5 and those in 2 and 3. The first is that the initial leg of each path in Questions 4 and 5 is such that the bearing of each path to the exit is identical. Thus, each path appears equally direct, whereas in Questions 2 and 3, the LLF path was the more direct path. By removing the path directness aspect from consideration, between 3 % and 13 % more people across all the sub-populations have selected the SLF path in Question 4 compared with Question 2. If this reasoning is correct, this would suggest that for between 3 % and 13 % of the population, selecting the most direct path will be the most important factor in influencing a person's path choice. For this group of people, when the most direct path option is removed, the LLF path (which corresponds to the most direct path) is no longer considered attractive and so the SLF path is selected.

The second difference is that in Questions 4 and 5, the SLF path has a sharp angle turn. Thus, an alternative explanation for the increased popularity of the SLF path is that for between 3 % and 13 % of the population, selecting a path with a sharp angle turn is the most important factor in influencing a person's path choice. While both these explanations are plausible, neither is particularly convincing. By simply considering the path that was selected it is not possible to convincingly resolve the issue as to why the SLF path appears to be more attractive in Questions 4 and 5 compared to Questions 2 and 3. However, the results of the open questions following Questions 4 and 5 provide some insight into the rationale used by participants in selecting their preferred path (see Figure 5-7).

A total of 1671 comments were provided by the participants to Questions 4 (851 comments) and 5 (820 comments). Of these, 19 % (315) provided answers that could not be classified or were in groups that consisted of less than 20 responses or were unclear. Of the comments received, 23 % (386) identified that they selected what they thought was the shorter path, even though they were informed that both paths were the same length. Furthermore, of these people, almost three times as many (296) selected the path with the sharp angle turn, i.e. the path with the SLF. This explains why there was an increase in the number of people who selected the SLF path in Questions 4 and 5 i.e. a large number of people selected the SLF path because they thought this path also had the shorter total length. The reasons suggested previously concerning the most direct path and the sharp angle, while plausible clearly do not correlate with the reasons provided by the participants for their path selection. This demonstrates that interpreting why people have selected a particular path based only on the paths selected can result in incorrect conclusions being drawn. Furthermore, 6 % (103) of the participants have indicated that they selected their particular path because they disliked paths involving sharp angle turns while 5 % (86) selected their path because they liked paths involving sharp angles. In addition, 5 % (87) claimed that they selected their path because it was the most direct, even though both paths had the same heading relative to the exit. Clearly, the term 'most direct' is open to interpretation and may not mean the same thing to different people as defined in Chapter 2, Section 2.4.

The comments also support the observation that the SLF criterion is more influential than the LLF criterion in influencing path choice and that right-handed paths are more influential than left-handed paths. As with Questions 2 and 3, the SLF path appears to be more influential than the right-handed paths. However, of the group that selected their path based on instinct, 43 selected the right-hand path. If these are then added to the group that selected the right-handed path, then the SLF and right-handed paths have approximately the same level of influence on path selection. Furthermore, the number of people who selected the SLF path is inflated due to a substantial number of people selecting this path because they thought the entire path was shorter due to the sharp angled corner.

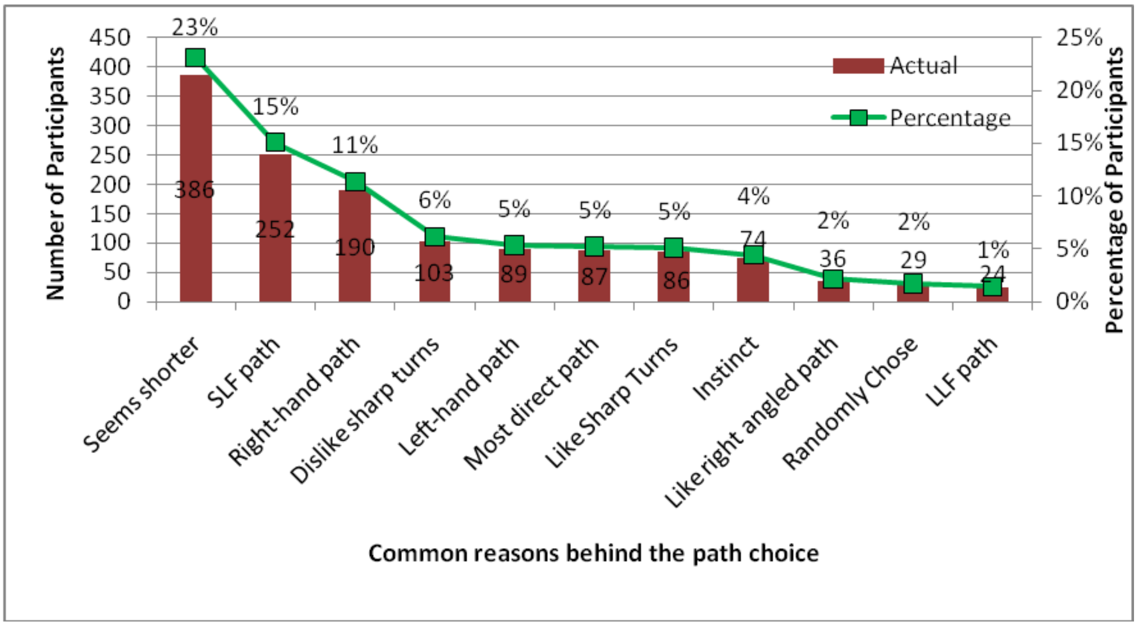


Figure 5-7: Participant path selection comments for Questions 4 and 5.

5.4.2 Discussion of Part 2 Results

On completion of the wayfinding tasks, participants were asked to identify the factors that influenced their wayfinding decisions. Unlike the open questions following each wayfinding task in which participants were asked to provide a reason for their path choice, they were given a list of factors to choose from and more than one factor could be selected. Presented in Figure 5-8 are the results from this question. In total (1150) 99 % of the participants completed this section, making 2309 selections. On average, each participant selected 2.0 criteria. The wayfinding criteria are arranged in descending order with the most popular criteria being on the left and the least important criteria being on the right. It is noted that the criterion 'Most Direct' was selected by 24 % (547) of the participants and so is the criterion which most influenced path selection. This is considered surprising as it did not figure highly in Questions 2 to 5, indeed it was only mentioned by 7 % of the participants in Questions 2 and 3 and 5 % in Questions 4 and 5. Furthermore, as shown in Questions 4 and 5, both paths had the same initial bearing on the exit and so could be considered equally direct. Within the context of this survey, it is suggested that not all the participants had a clear or the same understanding of the term 'most direct'. The term can clearly be interpreted to mean different things to different people. However, the result clearly indicates that participants have a strong preference for paths which appear to them to be the most direct, although it is not clear how they define this term. As the meaning of the term 'most direct' is considered to be ambiguous within the context of this analysis, it is excluded from further consideration.

Excluding the responses identifying the 'most direct' path, the main results support the findings of the path selection tasks, notably right-handed path has been mentioned by more people (12%) than left-handed path, SLF path has been mentioned by more people (12%) than LLF paths. Furthermore, the SLF path criterion is more than two times more influential than the LLF path criterion and the right-handed path criterion is more than two times more influential than the left-handed path criterion. It is noted that the magnitude of the differences between preference for left/right and SLF/LLF paths in this part of the survey is significantly greater than suggested by the findings of the wayfinding tasks. Also, as approximately 5 % of the responses indicated a preference for 'clockwise' or 'anticlockwise' paths, these criteria are not considered to be significant. Also, as only 8 % of the returns indicate a random path selection, this suggests that the majority of the participants had reasons for their path selection.

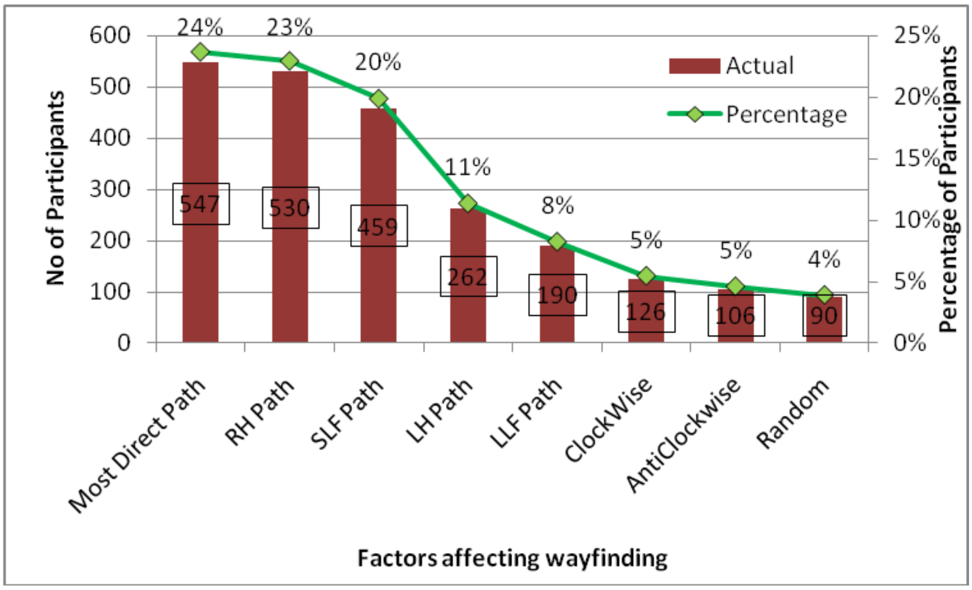


Figure 5-8: Participant identified factors which influenced their path selection decisions.

5.4.3 Relative Importance of The Wayfinding Criteria

The results presented in Figure 5-8 show the relative importance of the main wayfinding criteria as identified by the participants on completing the wayfinding tasks. The most influential criteria, in order of importance are selecting; right-handed paths (23 %), SLF paths (20 %), left-handed paths (11 %) and LLF paths (8 %). These rankings are based on the opinion of the participants and do not necessarily correlate with their actual path selection. To determine the relative importance of the path selection criteria, the results from Questions 2 and 3 are further investigated. The results from Questions 4 and 5 are left out of this analysis due to uncontrolled factors such as perceived total path length and multiple factors such as like/dislike of sharp angle turns impacting the path selection. It is to be noted that these factors are examined in the second survey discussed in Chapter 6. The relative importance of the four path selection criteria is determined as follows: if a participant selected right-hand paths in both Questions 2 and 3 then they clearly prefer right-hand paths over all other criteria (i.e. left-hand paths, SLF, LLF); if a participant selects the left-hand paths in both Questions 2 and 3, then they clearly prefer left-hand paths over all other criteria; if a participant selects the SLF paths in both Questions 2 and 3, then they clearly prefer SLF paths; finally if a participant selects the LLF paths in both Questions 2 and 3, then they clearly prefer the LLF paths. All participants who have answered both Question 2 and 3 must fall into one of these four preference categories. These results for this analysis for various sub-populations are presented in Table 5-1.

Table 5-1: Summary of path preference criteria based on wayfinding tasks in Questions 2 and 3.

Sample population	RH path preference (%)	SLF path preference (%)	LLF path preference (%)	LH path preference (%)
Entire sample	31	29	23	17
RH	30	28	23	20
LH	20	28	23	29
RD	33	32	23	12
LD	30	28	23	20
RHRD	33	33	23	11
LHRD	35	25	23	18
RHLD	32	28	23	18
LHLD	15	29	23	33

If we compare the results for the entire sample in Table 5-1 with those from the Part 2 results (see Figure 5-8) we note that there is broad agreement in the trends namely; right-handed paths are significantly more preferential than left-handed paths and right-handed paths are marginally more preferential than SLF paths. There is also agreement in that SLF paths are more preferential than LLF paths however, the results derived from the wayfinding tasks in Questions 2 and 3 suggest that the difference is marginal whereas the difference derived from the Part 2 results is significant. The results from the two analyses contradict each other in that, based on the results derived from Questions 2 and 3, LLF paths are significantly more preferential than left-handed paths (see Table 5-1) whereas, based on the Part 2 analysis (see Figure 5-8), left-handed paths are marginally more significant than LLF paths. Here we adopt the rankings based on the actual wayfinding tasks as being representative of human behavior within buildings as these were the results of actual wayfinding tasks as opposed to opinions.

The ranking of the path preference criteria based on the entire sample presented in Table 5-1 provide a means for ranking path preference in evacuation models. The results are significantly different from those generated by Golledge's urban wayfinding study [Golledge, 1995a, b] in that the results from this study suggest that SLF paths are more preferential than LLF paths. These differences may be due to Golledge's results being based on an urban environment or due to the small and selective sample used in his study. This result is also different to that of Conroy [Conroy, 2003] for similar reasons. Furthermore, the suggestion by Conroy that path directness is a significant path selection criterion [Conroy, 2003] is not supported by the results of the wayfinding tasks in Questions 2 to 5 and when participants were asked to suggest why they selected their particular path. However, it was highlighted as the most significant criterion when the participants were asked to select path finding criteria from a list. Neither of these studies included the concept of handedness as a determinant of path selection. This study has shown it to be the most important factor. These results are similar to those of [Scharine and McBeath, 2002] however, their study did not include the SLF and LLF factors and their sample was much smaller.

The results for the entire sample are intended to represent an average result which can be applied to the population as a whole. It is acknowledged that not every individual within a given population will exhibit the same type of behaviour as suggested by the preference distribution for the entire sample. People are complex and wayfinding decision making is multi-faceted with a number of different influential factors driving decision making, some of which reinforce each other while others oppose each other. The nature in which these influential factors work may also be dependent on the nature of the individual, in some groups working together while in other groups working in opposition. Not everyone will be influenced in the same way by the influential factors that determine wayfinding behaviour – unfortunately these are not universal truths! However, from a modelling perspective it is desirable to have a global ranking of the wayfinding criteria that can be applied to a population as a whole. Unfortunately, the ranking of path preference criteria presented in Table 5-1 shows that there are significant differences in the nature of the ranking distributions for important sub-populations. For example, a sample population made up of individuals from countries that drive on the left side of the road will display a significantly different wayfinding preference to a sample population made up of people from countries that drive on the right-side of the road. Furthermore, each of these populations can be further broken down into sub-populations of left-handed and right-handed people each of which display significantly different wayfinding preferences. Thus, it is seen that genetic and cultural differences may influence our wayfinding preferences and thus our ability to evacuate efficiently.

It is suggested that in situations where the nature of the population is not clear or there will be a significant mixed population, the path preference ranking for the entire sample is used. If it is known that an application is primarily catering for individuals who drive on the left e.g. a UK application, then the left-side driving path preference is used whereas if the application is primarily catering for individuals who drive on the right e.g. a USA application, then the right-side driving path preference is used. Furthermore, these country specific can be further broken down into left-handed and right-handed sub-populations. While it may not be known which individual within the population is left-handed or right-handed, the international average of 13 % of the population being left-handed can be applied.

5.5 Conclusion

The work in this chapter has identified factors that influence wayfinding decisions in building evacuation and normal circulation conditions. The results are based on an international survey involving 1166 participants from 36 countries. The survey involved participants completing path selection tasks based on five simplified corridor layouts. It was found that there was no significant statistical difference between the path selection criteria used in normal circulation and evacuation. A main result from this study is that the handedness (a genetic factor) and the side of the road that the participants normally drive on (a cultural factor) are important influential factors in path selection. The handedness is considered to be the main influencing factor with the driving side modifying the impact of handedness. Thus, if the driving side is the same as the handedness, these factors reinforce each other however, if they are opposite, they work in opposition. It is therefore important to consider the handedness of an individual and the country from where they come when attempting to predict wayfinding behaviour. These results are considered statistically significant. The length of the first leg of the path also had a considerable influence on an individual’s path choice. The shortest leg first criterion was found to be more influential than the longest leg first criterion. This contradicts earlier urban wayfinding studies and is thought to be due to both the differences in the environments and the small and selective sample used in the urban studies. Furthermore, the path directness does not appear to be a significant path selection criterion based on the results of the wayfinding tasks.

By considering the responses to the wayfinding tasks, the participant's preference for right-handed, left-handed, SLF or LLF paths was determined. The preferences for these paths for the entire sample were found to be: 31 % prefer right-handed paths, 29 % prefer SLF paths, 23 % prefer LLF paths and 17 % prefer left-handed paths. However, it is acknowledged that not every individual within a given population will exhibit the same type of behaviour as suggested by the average preference distribution for the entire sample. Furthermore, there are significant differences in the wayfinding preferences of important sub-populations as genetic e.g. handedness, and cultural e.g. driving side, differences influence wayfinding preferences. Thus, the preference distribution for the factors influencing wayfinding was further refined to reflect handedness and driving side.

Two important building wayfinding criteria were analysed in Questionnaire 1 namely the handedness of paths (left-/right-hand paths) and length of the first leg of paths (shortest leg / longest leg first paths). Handedness of paths has been found to be a more important factor than the length of the first leg of paths. In Section 5.1 of this Chapter, it was mentioned that the factors studied in Questionnaire 1 could not be combined with the rest of the Building Wayfinding Criteria. Therefore the most important factor, handedness of paths, will be compared against the rest of the Building Wayfinding Criteria in Questionnaire 2 which will be described in the next Chapter.

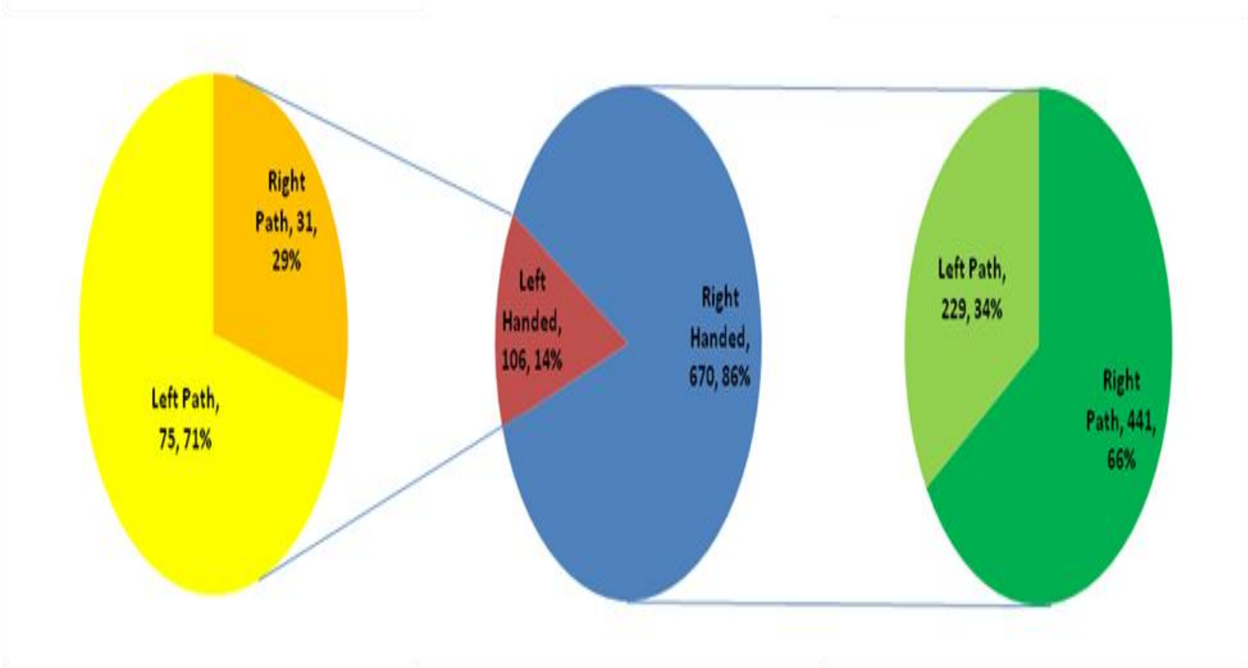
6 Wayfinding Questionnaire 2

6.1 Introduction

In Chapter 5, the first wayfinding questionnaire was described and the key results were presented. The Survey 1 thus examined four of the wayfinding criteria that were specified in Chapter 2, Section 2.2.4 namely right handed path, left handed path, longest leg first and shortest leg first. These factors will hence forth be referred to as the wayfinding criteria in questionnaire 1. The remaining wayfinding criteria (distance, time, turns, angle of turns and decision points) were studied in the second wayfinding survey whose results will be presented in this chapter. These factors will be collectively referred to as the wayfinding criteria in questionnaire 2. The wayfinding criteria of questionnaire 1 and 2 together form a unique set of criteria being tested for the first time and will be referred to as the Building Wayfinding Criteria (BWC).

In Chapter 5, Section 5.1, it was established that the wayfinding criteria such as right/left-hand paths, SLF and LLF paths which were analysed in questionnaire 1 could not be tested in conjunction with the other BWC. Hence for the second questionnaire it was decided that the most important factor from the first questionnaire would be chosen and compared with the wayfinding criteria in questionnaire 2. The handedness factor which has been ignored in the existing urban wayfinding literature was found to be the most important factor affecting people's wayfinding decisions in the first questionnaire (see Chapter 5, Section 5.4.1.4). This fact was determined after analysing the results of 400 participants taking questionnaire 1. Therefore in the second questionnaire right/left-hand paths would be tested against the wayfinding criteria of the second questionnaire.

Prior to administering questionnaire 2, it was necessary to determine the participant's preference for right/left-hand paths. Therefore, questionnaire 1 was first given to the participant in order to determine his/her preference for right/left-hand paths. The preference for right/left-hand paths against the factors in questionnaire 2 would then be tested by showing snapshots of hypothetical buildings similar to questionnaire 1. If a participant has a preference for right-hand paths from questionnaire 1, in questionnaire 2 his/her preference for right-hand paths versus the wayfinding criteria in questionnaire 2 will be tested. Similarly if a participant has a preference for left-hand paths from questionnaire 1, in questionnaire 2 his/her preference for left-hand paths versus the factors in questionnaire 2 will be tested. In the first questionnaire the participant's preference of right/left-hand paths relative to the other criteria in the first questionnaire can be determined. In the second questionnaire this participant's preference of right/left-hand paths relative to the other criteria in the second questionnaire can be determined. Thus, this participant's overall preference for all the wayfinding criteria in both questionnaires can be estimated. This chapter tries to answer Question 6 and more specifically Questions 6.10 – 6.14 that were posed in Chapter 1.



Left Handed Sample Entire Sample Right Handed Sample

Figure 6-1: Classification of the entire sample population based on handedness and their path preference. The centre pie shows the entire sample divided on handedness. The left pie shows the classification of the left handed population by their right/left hand path preference. The right pie shows the classification of the right handed population by their right/left path preference.

6.2 Sample Population

The call for participants was made through radio broadcasts and distribution of flyers to the general public. A total of 776 participants completed the questionnaire from 36 countries. The entire sample population classified based on handedness and right/left-hand path preference is shown in Figure 6-1. The centre pie shows the entire population divided into left and right-handed people. The pie charts on the left and right show a further classification of the left/right-handed people as having a preference for right/left-hand paths.

Similar to the analysis in the first questionnaire, the average results of the participants in the second questionnaire were also incrementally analysed (the results of first 100 participants compared with 200, 200 with 300 and so on). The average results were found to remain steady (±1%) with a sample size of 600. The surveys are still active and the results of 776 participants have been presented in this chapter. The Chi-square results were utilised at an early stage to determine that there was no cultural or genetic differences in the route choices of people and hence this survey unlike survey 1 did not require as many participants. The results were calculated using the path selection tasks and the rating tasks as well which have been analysed in Section's 6.5.3 and 6.5.4.

6.3 Design methodology of questionnaire 2

The design methodology of questionnaire 2 is similar to the design methodology of questionnaire 1. A hypothetical building was shown for comparing each pair of criteria. However, two sets of questions were prepared for questionnaire 2. A set of questions for people having a preference for right-hand paths (Set 1) and another set of questions for people having a preference for left-hand paths (Set 2). If the participant had a preference for right-handed paths from questionnaire 1, then he/she would take Set 1 questions comparing right-hand paths with the remaining questionnaire 2 criteria distance, time, turns, angle of turns and decision points. Since the preference for right-hand paths versus the questionnaire 2 criteria are being tested the right-hand paths are made slightly undesirable by a longer distance path, more time path, more turns path and so on. Participants' preference for the right-hand path in spite of it being the longer path, the least time path and so on is therefore tested. If the participant had a preference for left-hand paths from questionnaire 1, then he/she would take the questions comparing left-hand paths with the remaining criteria in questionnaire 2. In this case since the left-hand paths are preferred, they are made slightly undesirable by a longer distance path, more time path, more turns path, etc.

Prior to designing questionnaire 2, the results of about 400 participants taking questionnaire 1 were analysed and the majority (66%) of the participants were found to have a preference for either left or right-hand paths. Thus, for questionnaire 2 an assumption was made that all people will have a preference for either left or right-hand paths. A number of options were considered for determining the participant's preference for right/left-hand paths. The different options that were considered are:

Option 1: Based on the handedness of the participant

Option 2: Based on the country of residence of the participant

Option 3: Based on the path choice of participants in questionnaire 1

In option 1, one could consider that a right handed participant would have a strong preference for right-hand paths. However, it was observed that some right-handed participants (36%) had a preference for left-hand paths (see Chapter 5, Figure 5.4). In option 2, one could consider that a participant from a country driving on the right would have a strong preference for right-hand paths. However, it was observed that some participants (29%) from right driving countries chose left-hand paths (see Chapter 5, Figure 5.4). A combination of option 1 and 2 could have been used as well. For example a right-handed participant from a right-driving country could be considered to have a strong preference for right-hand paths. However, it was observed that some of the participants (25%) in this category had a preference for left-hand paths (see Chapter 5, Figure 5.4).

In option 3, the path choice of the participant for the first three Questions of questionnaire 1 is analysed to determine their preference for right/left-hand paths. The logic behind these questions was discussed in detail in Chapter 5, Section 5.2. However, a review of the factors tested are given in Table 6-1.

Table 6-1: A review of the criteria being tested in Questions 1-3 of questionnaire 1

Questions from questionnaire1	**Wayfinding Criteria being tested**
Question 1	Left-hand path vs Right-hand path
Question 2	Left-hand, LLF path vs Right-hand, SLF path
Question 3	Left-hand, SLF path vs Right-hand, LLF path

The logic implemented to determine the participant's preference for right/left-hand path is shown in Figure 6-2. If participant chooses all right-hand paths in questions 1, 2 and 3 of questionnaire 1, then he/she is considered to have a strong preference for right-hand paths and is given the Set 1 questions for questionnaire 2. If the participant chooses all left-hand paths in questions 1, 2 and 3 of questionnaire 1, then he/she is considered to have a strong preference for left-hand paths and is given the Set 2 questions for questionnaire 2. If the participant has chosen a mixture of left/right-hand paths in questions 1, 2 and 3 of questionnaire 1, then the path chosen in question 1 is considered to determine their preference for the left/right-hand path choice. If the participant chooses the right-hand path in question 1 then they have a preference for right-hand paths, else they have a preference for left-hand paths.

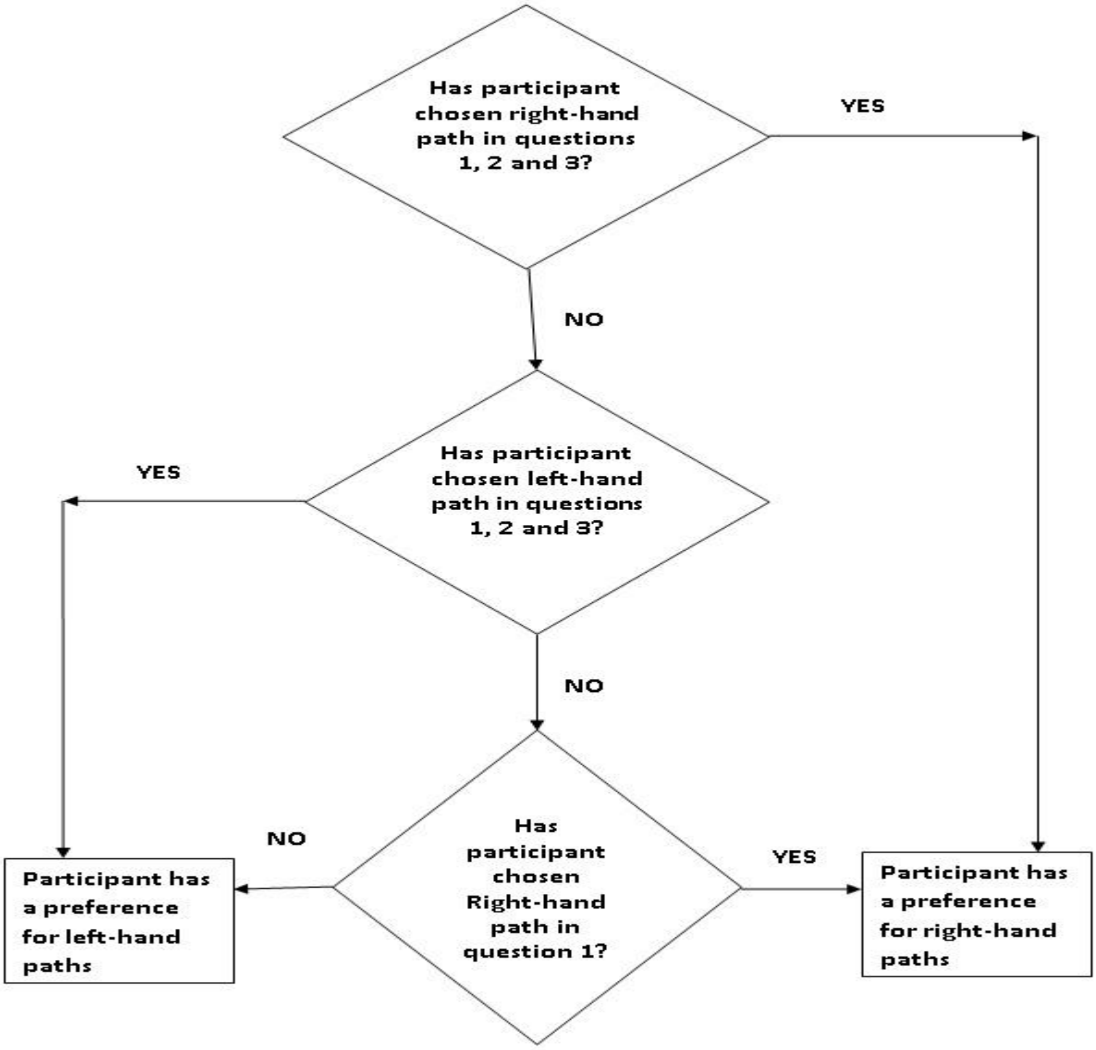


Figure 6-2: Determination of right/left-path preference of participant.

The questionnaires carried out in this thesis were placed online and the Option 3 was implemented using JavaScript. The participants would automatically be directed to the correct set of questions to be taken in questionnaire 2 based on their answers to the first three questions in questionnaire 1. This process takes place in the background and the participant is unaware of it.

6.4 Details Of Wayfinding questionnaire 2

Similar to questionnaire one, questionnaire two has three parts as well. The first part of the questionnaire 2 consists of five questions testing the wayfinding criteria shortest distance, least time, least turns, least angle and least decision points. In the second part of questionnaire 2, the participants are asked to choose the factors that affected their wayfinding decision in the first part of the questionnaire 2. The participants are given all nine wayfinding criteria from both questionnaires and are asked to rate these criteria on a scale of 1 to 9 under routine and emergency conditions. The third part consisted of the same demographic questions that were used in questionnaire 2. However, since questionnaire 1 and 2 have been merged, participants only answer the demographic questions once. Please see Appendix E for a full list of the survey questions as they were presented to the participants.

6.4.1 Wayfinding questionnaire 2 – Part 1

The first part of questionnaire 2 has five questions. In each question the top view of a 3-D model of a building created using GoogleSketchUp [Roskes, 2011] was shown to the participants (see Figure 6-3 - Figure 6-7). For each building the participants were given two types of tasks: path selection tasks and path scoring tasks. In the path selection tasks the participants were asked to choose one of the two paths to the exit first under normal circumstances and later under emergency evacuation circumstances. They were also asked to specify the reason for choosing the paths. In the path scoring tasks the participants were asked to rate their preference for both paths (Path A and Path B) under normal circumstances on a Likert scale. The Set 1 Questions of questionnaire 2 for people having a preference for right-hand paths are discussed in this section (Figure 6-3a - Figure 6-7a). The Set 2 questions (Figure 6-3b - Figure 6-7b) for people having a preference for left-hand paths are similar using flipped versions of the snapshots in Set 1.

6.4.1.1 Question 1

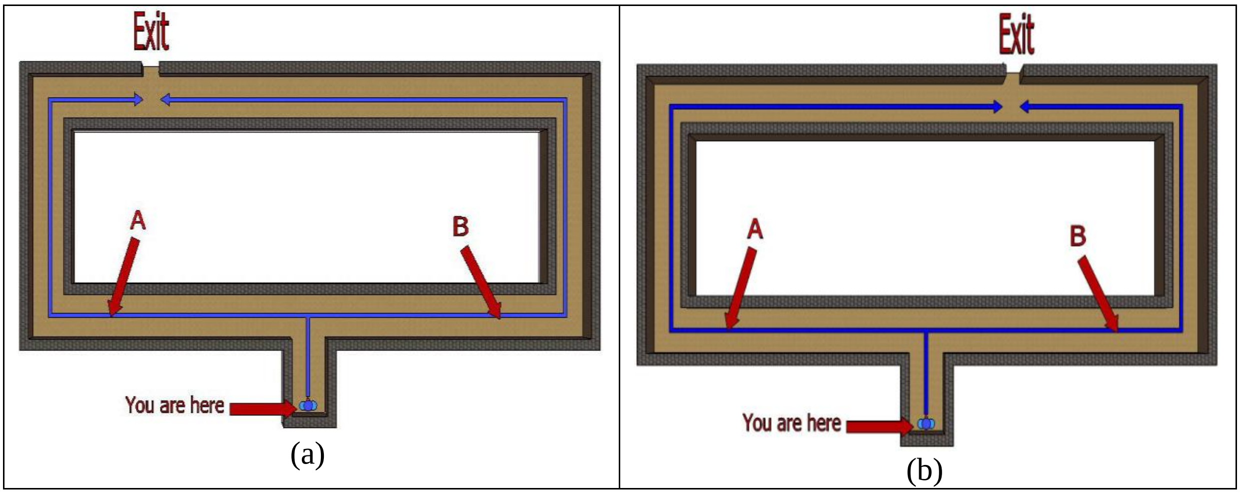


Figure 6-3: Path Selection task1 of questionnaire 2. (a) Task1 in Set 1 (b) Task1 in Set 2.

The building shown for the participants in Question 1 of questionnaire 2 will be either Figure 6-3 (a) or Figure 6-3 (b) depending on the right/left-hand path preference determined in questionnaire 1. The participants having a preference for right-hand paths will be shown Figure 6-3 (a) from the Set 1 questions. In this case clear instructions are given to the participants that path B is longer than path A. This question checks people's preference for right-hand paths versus the shortest distance paths. Path A the left-hand path is made shorter. If Path B is chosen, a clear preference for right-hand paths over shorter distance paths is indicated. If Path A is chosen a clear preference for shorter distance paths over right-hand paths is indicated. The participants having a preference for left-hand paths will be shown Figure 6-3 (b) which is a mirror image of Figure 6-3(a) where the left-hand path is made slightly longer than the right-hand path. Participants taking this question are clearly instructed that Path A is longer than Path B.

6.4.1.2 Question 2

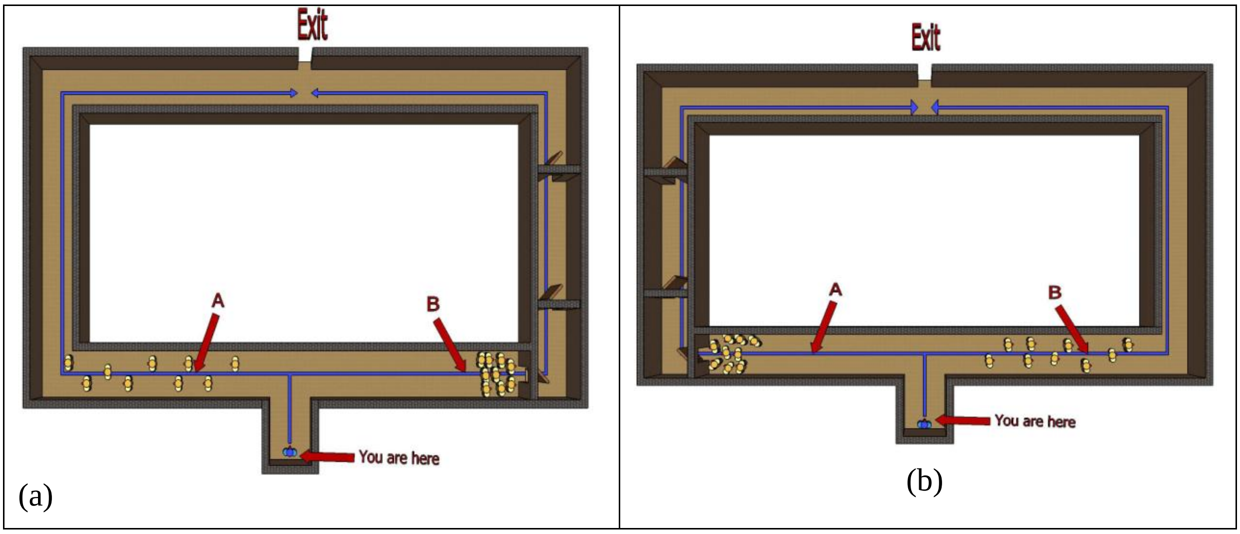


Figure 6-4: Path Selection task2 of questionnaire 2. (a) Task2 in Set 1 (b) Task2 in Set 2.

The participants having a preference for right-hand paths will be shown Figure 6-4 (a) from Set 1 Questions of questionnaire 2. The participants were informed that both paths are of equal length; there are equal numbers of people represented by the yellow agents along each path; and that path B has 3 internal doors. Since both paths contain the same amount of people, it is obvious that path B having more doors will take a longer time to traverse than path A. If Path B is chosen a clear preference for right-hand paths is indicated. If Path A is chosen a clear preference for least time paths is indicated. The participants having a preference for left-hand paths will be shown Figure 6-4 (b) from Set 2 questions of questionnaire 2.

6.4.1.3 Question 3

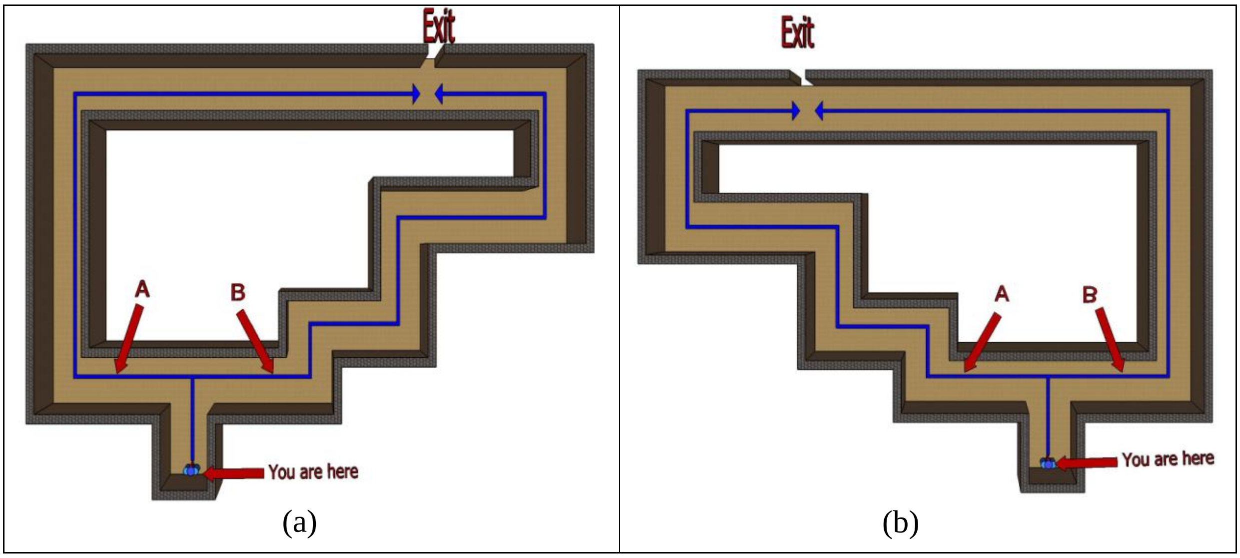


Figure 6-5: Path Selection task3 of questionnaire 2. (a) Task3 in Set 1 (b) Task3 in Set 2.

The participants having a preference for right-hand paths will be shown Figure 6-5 (a) from Set 1 Questions of questionnaire 2. The participants are clearly informed that both paths are of equal length. They are also informed that Path A has 2 bends and Path B has 6 bends. If Path B is chosen a clear preference for right-hand paths is indicated. If Path A is chosen a clear preference for least turns path is indicated. The participants having a preference for left-hand paths will be shown Figure 6-5 (b) from Set 2 Questions of questionnaire 2.

6.4.1.4 Question 4

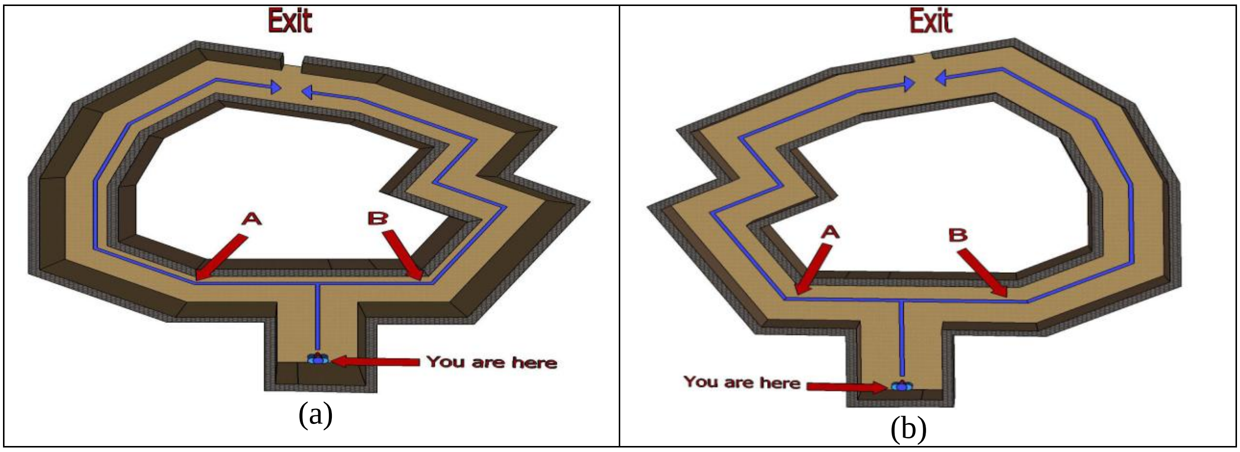


Figure 6-6: Path Selection task4 of questionnaire 2. (a) Task4 in Set 1 (b) Task4 in Set 2.

The participants having a preference for right-hand paths are shown the building in Figure 6-6 (a) from Set 1 Questions of questionnaire 2. The participants are informed that: both paths are of equal length; both paths have the same number of bends; path B has sharper bends. If Path B is selected a clear preference for right-hand path is indicated. If path A is selected a clear preference for paths with less sharp bends is indicated. The participants having a preference for left-hand paths are shown the building in Figure 6-6 (b) from Set 2 Questions of questionnaire 2.

6.4.1.5 Question 5

Participants with a preference for right-hand paths are shown Figure 6-7 (a) from Set 1 Questions of questionnaire 2. The participants are informed that both paths are of equal length; both paths have the same number of bends; and path B has 2 decision points. Decision points increase the complexity of a path [Best, 1970] and people have a preference to minimise complexity when it comes to wayfinding. If Path B is chosen a clear preference for right-hand paths is indicated. If Path A is chosen a clear preference for left-hand paths is indicated. The participants having a preference for left-hand paths are shown Figure 6-7 (b) from Set 2 Questions of questionnaire 2.

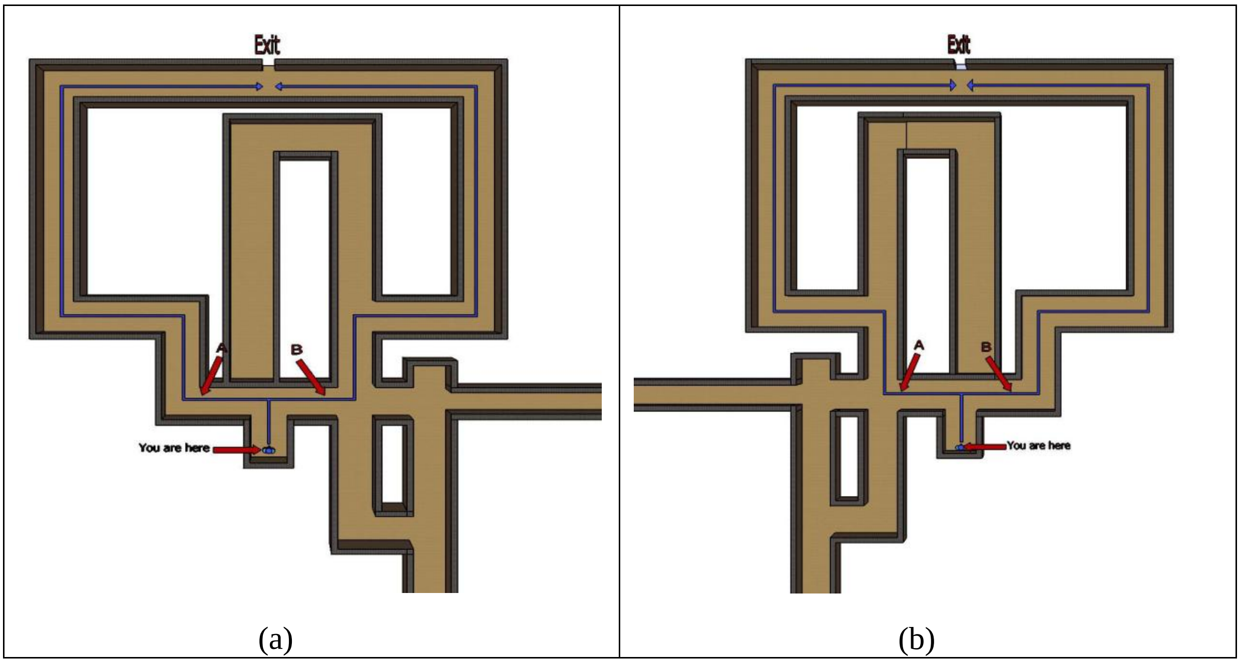
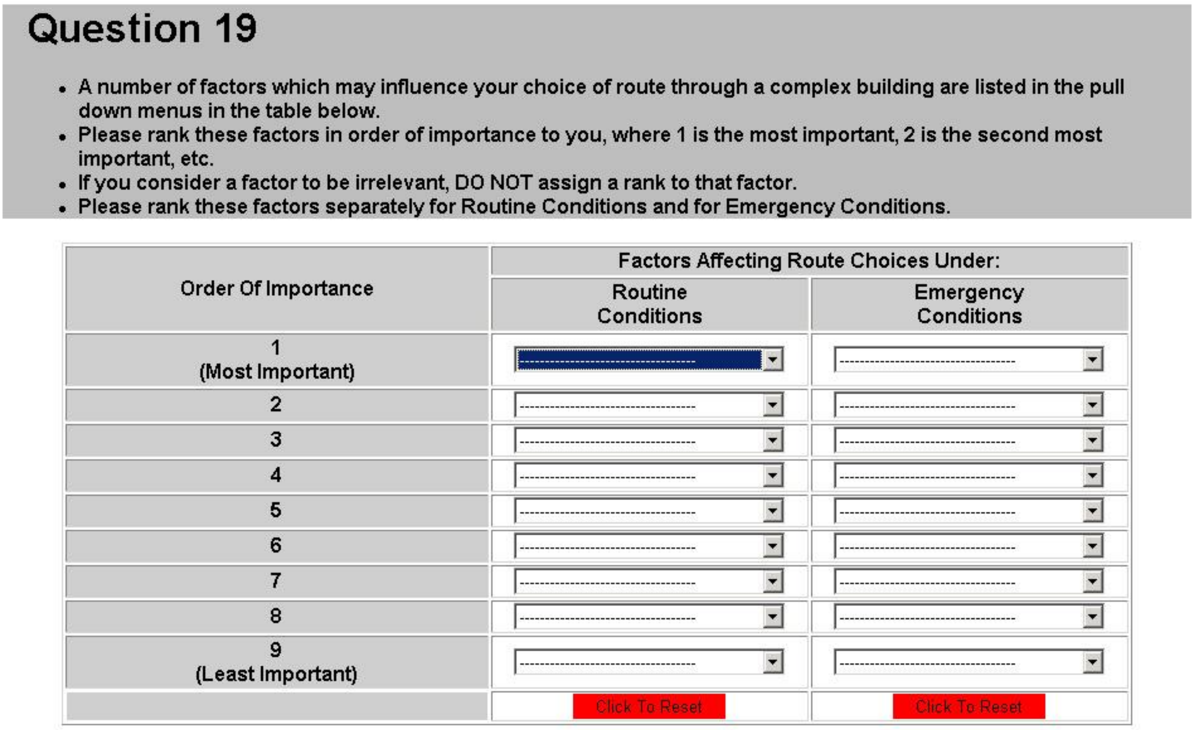


Figure 6-7: Path Selection task5 of questionnaire 2. (a) Task5 in Set 1 (b) Task5 in Set 2.

6.4.2 Wayfinding questionnaire 2 – Part 2

In the second part of questionnaire 2 a list of factors that might influence people's choice of route through a complex building are listed in a pull down menu. The participants are requested to rate those factors in the order of importance on a scale of 1 to 9 where 1 is the most important, 2 is the second most important and so on. The participants are asked to rank these factors separately for routine and emergency conditions. A snapshot of this task is shown in Figure 6-8. The factors that are given to the participants are: least number of sharp turns; least number of turns; shortest travel time; shortest travel distance; least number of decision points; longest leg first; shortest leg first; going right; going left. The participants are also given an opportunity to state any other factors which influence their path selection.



Question 19

- A number of factors which may influence your choice of route through a complex building are listed in the pull down menus in the table below.
- Please rank these factors in order of importance to you, where 1 is the most important, 2 is the second most important, etc.
- If you consider a factor to be irrelevant, DO NOT assign a rank to that factor.
- Please rank these factors separately for Routine Conditions and for Emergency Conditions.

Order Of Importance	Factors Affecting Route Choices Under:	
	Routine Conditions	Emergency Conditions
1 (Most Important)		
2		
3		
4		
5		
6		
7		
8		
9 (Least Important)		
	Click To Reset	Click To Reset

Figure 6-8: A snapshot of the question in part 2 of questionnaire 2.

The pull-down menu in Figure 6-8 consists of the items shown in Figure 6-9. The most important wayfinding criteria shortest travel time and shortest travel distance are deliberately placed lower down in the list. If these criteria were placed at the top of the list, it could be argued that the participants gave importance to these criteria since they are at the top of the list. An item selected from a pull-down menu will be removed from the subsequent pull-down menus. For example if "Shortest Travel Time" was selected as the most important factor (1) then this item will be removed from the list presented in all the other pull-down menus in this category (Routine/Emergency conditions). This prevents participants from wrongly choosing the same factor more than once and also makes the selection process easier by removing used items. A reset menu was also provided for each category routine/emergency conditions to reset all chosen factors in that category.

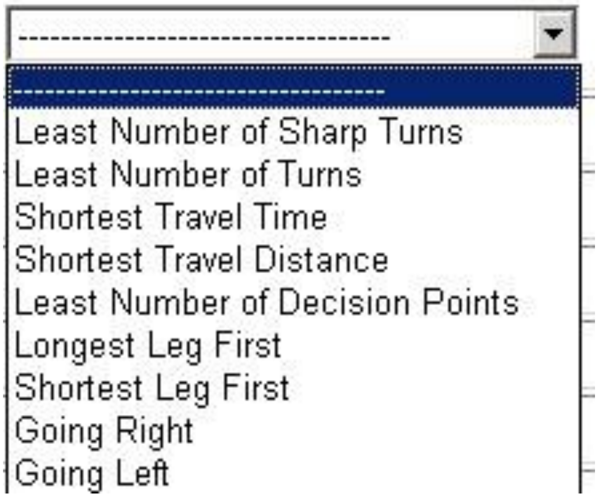


Figure 6-9: The items in the pull-down menu's for the second part of questionnaire 2.

A number of designs were tested out for the second part. The initial design of this task listed the factors affecting wayfinding and asked the participants to rank the factors on a scale of 1 to 9. However, pilot tests indicated that majority of the participants were confused with this design. Some participants correctly assigned scores for the factors with 1 being more important. However, some participants assigned scores for the factors assuming the larger the score (1-9) the more important a factor is even with clear instructions to the contrary. The final design shown in Figure 6-8 proved to be the most intuitive design.

6.5 Results of questionnaire 2

A total of 776 participants from 36 different countries have completed questionnaire 2. This sample was then divided into sub-populations based on handedness and driving side into the following categories:

- Right-handed sub-population
- Left-handed sub-population
- Right driving sub-population
- Left driving sub-population,
- Right-handed Left Driving (RHLD) sub-population,
- Right-handed Right Driving (RHRD) sub-population,
- Left-handed Right Driving (LHRD) sub-population and
- Left-handed Left Driving (LHLD) sub-population.

Figure 6-1 shows the classification of the entire sample based on handedness and their right/left-hand path preference. Majority of the right-handed participants (66%) have a preference for the right-path while only 36% have a preference for the left-hand path. This agrees with the results of questionnaire 1 where 64% of the right-handed population chose the right-path over the left path (see Chapter 5, Figure 5.4). Majority of the left-handed participants (71%) have a preference for the left-hand path which again agrees with the results of questionnaire 1 (see Chapter 5, Figure 5.4). Each sub-population is further divided into those who have a preference for right and left-paths. The results of each sub-population are compiled after analysing the results of the people with right/left-hand path preference separately as these participants take different sets of questions.

6.5.1 Influence of Handedness and Driving Side on Path Choice

Table 6-2: Criteria chosen by the participants in the path selection tasks (under normal circumstances)

	Sub-populations								
	Right Hand (670)	**Left Hand (106)**	**Right Drive (205)**	**Left Drive (571)**	**Right Hand Right Drive (176)**	**Right Hand Left Drive (494)**	**Left Hand Right Drive (29)**	**Left Hand Left Drive (77)**	**Entire Sample (776)**
Distance (Question 1)	612	97	193	516	166	446	27	70	709
Time (Question 2)	619	101	188	532	161	458	27	74	720
Turns (Question 3)	387	64	116	335	98	289	18	46	451
Angle (Question 4)	435	66	138	363	118	317	20	46	501
DP (Question 5)	346	51	112	285	97	249	15	36	397
Right/Left	951	151	278	824	240	711	38	113	1102

In the first questionnaire, it was observed that handedness and driving side had a significant impact on path choice. Their influence on path choices in this questionnaire is examined in this section. Table 6-2 shows the results of the path selection tasks in the first part of questionnaire 2 under normal conditions. The number of people in each sub-population is shown in brackets. The number of people choosing the shortest distance, least time paths and so on in Questions 1-5 is shown in the matching cell. For example in the right-handed sub-population containing a total of 670 participants, 612 participants chose the shortest distance path in the path selection task of the first Question (see Figure 6-3). The remaining 58 participants in this sub-population chose the right/left-hand paths. The least time path has been chosen by 619 participants in this sub-population and hence one can conclude that time was a slightly more important factor for this sub-population than distance. The right-handed sub-population have chosen the right/left-hand path 951 times out of 3350 (670 times 5) chances they had to choose the right/left-hand paths over the other paths. There were 5 questions in the first part of questionnaire 2 and in each question the participants had a choice of right/left-hand path over the other criteria distance, time and so on. As a result each participant has five opportunities to choose the right/left-hand paths whereas only one opportunity to choose each of the other criteria in questionnaire 2. Hence in Table 6-2 though the right/left-hand paths have been chosen more number of times than the other criteria in each sub-population, one needs to bear in mind that each participant had five chances to choose the right/left-hand path while they had just one chance to choose the other criteria distance, time and so on.

Table 6-3: Chi-square test of independence results to check for the influence of handedness and driving side on path choice in questionnaire 2.

	Sub-populations							
	Right Hand	**Left Hand**	**Right Drive**	**Left Drive**	**Right Hand Right Drive**	**Right Hand Left Drive**	**Left Hand Right Drive**	**Left Hand Left Drive**
Degrees of Freedom	5	5	5	5	5	5	5	5
χ^2	0.038	0.393	1.261	0.331	1.203	0.165	0.408	0.749
p	< 0.99	< 0.99	< 0.93	< 0.99	< 0.94	< 0.99	< 0.99	< 0.98

The chi-square test of independence [Wayne, 1999] is used to determine if the handedness and driving side have an influence on the path choice of participants in the second questionnaire. The path choice of the different sub-populations is tested against the path choice of the entire sample. The chi-square test results are shown in Table 6-3. In order for there to be a significant influence the χ^2 value needs to exceed 11.07. However, all the χ^2 values in Figure 6-4 are much less than 11.07 which imply that there is no significant difference in the path choice of the entire sample from the different sub-populations. The lower the χ^2 value the lesser the influence of handedness and driving side has on the path choice. Hence, handedness and driving side which proved to be influential factors in the right/left-hand path choice in the questionnaire 1 have turned out to be insignificant in the path choices in questionnaire 2. This is as a result of going right/left being far less in importance than the other wayfinding criteria in questionnaire 2. However, this suggests that if paths are the same in terms of the other criteria (i.e., distance and time) people might choose paths based on the handedness of paths. This is deduced from Table 6-2 as majority of the participants in each sub-population choose the shortest distance and time paths against right/left-hand paths. However, the importance of the right/left-hand paths increases when compared against turns, angles and decision points.

6.5.2 The Influence of Emergency Conditions on path choice

Table 6-4: Criteria chosen by the participants in the path selection tasks (under emergency circumstances)

	Sub-populations								
	Right Hand (670)	**Left Hand (106)**	**Right Drive (205)**	**Left Drive (571)**	**Right Hand Right Drive (176)**	**Right Hand Left Drive (494)**	**Left Hand Right Drive (29)**	**Left Hand Left Drive (77)**	**Entire Sample (776)**
Distance (Question 1)	615	101	195	526	167	453	28	73	721
Time (Question 2)	604	95	182	504	159	432	23	72	686
Turns (Question 3)	422	76	133	402	114	345	19	57	535
Angle (Question 4)	459	78	148	415	129	356	19	59	563
DP (Question 5)	384	70	156	381	134	333	22	48	537
Right/Left	866	110	211	627	177	551	34	76	838

The results of the path selection tasks in the first part of questionnaire 2 under emergency conditions are shown in Table 6-4. In the entire sample results for the first question 12 more people have chosen the shortest distance path in emergency conditions than under normal conditions. In normal circumstances these participants did not mind travelling the extra distance. However, under emergency conditions they preferred to choose the shortest distance paths to make a quick exit from the building. 34 participants have preferred the path which takes more time under emergency circumstances than under normal circumstances in question 2. This is surprising as one would expect more participants to choose the least time path under emergency circumstances than under normal circumstances. The comments by the participant's choosing the longer time path under emergency conditions revealed that they perceived this path to be safer under emergency conditions as it had doors and the less time path did not have any doors. The participants perceived that doors could block the spread of fire making a path with doors safer than one without. Probably if both paths were made to have no doors and one path were to have more people than the other then perhaps more participants may have correctly chosen the least time path in emergency conditions. The decrease in importance of the least time factor in emergency circumstances in questionnaire 2 is due to the design of question 2 and is not to be mistaken to mean that people prefer paths that take a longer time in emergency. Though only a minority, 4.3%, of the entire sample have perceived the longer path to be safer in emergency, this could be an important finding as people in emergency may prefer a path with more doors than one with less doors.

Table 6-5: Chi-square test of independence for the wayfinding criteria under normal and emergency conditions.

	Distance	Time	Turns	Angle	Decision Points	Right/Left Paths
Degrees of Freedom	1	1	1	1	1	1
χ^2	0.08	0.77	6.98	3.61	20.68	35.65
p	< 0.75	< 0.36	< 0.05	< 0.05	< 0.001	< 0.001

Considering the path choice of the entire sample in normal and emergency circumstances, the χ^2 value of 68.6 indicates that there is a significantly different pattern in the choice of paths in the two conditions at $p < 0.001$. An individual chi-square analysis of the different wayfinding criteria in normal and emergency conditions is shown in Table 6-5. Even though the number of people preferring the shortest distance path is slightly more under emergency conditions this difference is not statistically significant as $\chi^2 < 3.84$. Surprisingly, fewer people have chosen the least time paths in emergency than under normal circumstances. However, this is as a result of the participants assuming that the longer time path was safer. The number of people choosing the least turns path has increased significantly under emergency conditions χ^2=6.98, $p < 0.05$. Under normal circumstances some participants found the path with more turns to be more interesting. However, under emergency conditions more participants find the least turns path to be easier to navigate to the exit. Under emergency conditions more people have chosen a smoother path with less sharp bends as a preferred path to the exit than under normal circumstances with χ^2=3.61. The maximum increase in preference among all criteria has been least decision points as under emergency conditions people prefer to keep things simple and tend to avoid a path with decision points. The maximum decrease in preference among all criteria has been the right/left paths as under emergency conditions people prefer to take paths with the other criteria like paths with less distance, less turns, less angle and less decision points.

Table 6-6 shows the mean rating of the wayfinding criteria by the entire sample in the second part of the questionnaire. Similar to the results of the path selection task participants have ranked the wayfinding criteria differently under normal and emergency conditions. Shorter distance path criterion has increased slightly in importance under emergency conditions. Least time criterion has also increased slightly in importance under emergency conditions. This contradicts the results of the path selection tasks where its importance decreased under emergency conditions. However, this result is what one expects in reality as in the path selection tasks the participant's favoured the least time path under emergency conditions as they assumed that it was the safer path. Least turns, less sharp turns criteria have increased in importance similar to the results of the rating tasks. Less decision points criteria has increased in importance more than any other criteria under emergency conditions which is again similar to the path selection results. Going right/left has decreased in importance under emergency conditions.

Table 6-6: Mean rating of the criteria under normal and emergency circumstances in the second part of the questionnaire.

Wayfinding Criteria	**Mean Rating of Criteria Under Normal Circumstances**	**Mean Rating of Criteria Under Emergency Circumstances**
Shortest Distance	6.0	6.1
Least Time	6.5	6.7
Least Turns	3.5	3.8
Less sharp Turns	3.8	4.3
Less Decision Points	3.4	4.8
Going Right	2.9	1.9
Going Left	1.9	1.3
SLF	2.7	2.5
LLF	1.9	2.0

6.5.3 Relative Importance of the Wayfinding Criteria based on Path Selection Tasks

The relative importance of the wayfinding criteria in questionnaire 1 were established in Chapter 5, Section 5.4.3. In this section the weights of the wayfinding criteria in questionnaire 2 are determined based on the path selection tasks. The weights of the questionnaire 1 and 2 set of criteria will then be calculated. In section 6.5.1, it was seen that the handedness and the driving side only had an influence on the right/left-hand path chosen and did not have an influence on the other wayfinding criteria. Therefore the entire sample results are considered for the determination of the weights for the questionnaire 2 set of criteria in this section. Table 6-2 and Table 6-4 showed the total number of times each of questionnaire 2 wayfinding criteria were chosen by the different sub-populations. Table 6-7 shows the number of times each wayfinding criterion was chosen normalised by the percent of total number of times that wayfinding criterion was encountered by the participants in the first part of the questionnaire 2. All the wayfinding criteria except going right/left are encountered by each participant only once. Going right/left path criteria is encountered by each participant 5 times. Therefore for all criteria except going right/left the number of times each criterion was chosen by the entire sample is divided by the total number of participants which is 776. For going right/left the number of times this criterion was chosen by the entire sample is divided by 5 times 776. The values thus obtained (multiplied by 100) under normal and emergency conditions for the entire sample is shown in Table 6-7.

Table 6-7: Normalised values of the wayfinding criteria in questionnaire 2 from the path selection tasks

Wayfinding Criteria (Questionnaire 2)	Normal Circumstances	Emergency Circumstances
Shortest Distance	91	93
Least Time	93	88
Least Turns	58	69
Less sharp Turns	65	73
Less Decision Points	51	69
Going Right/Left	28	22

Table 6-8: Normalised values for the wayfinding criteria in questionnaire 1.

Wayfinding Criteria (Questionnaire 1)	No of People Having a Clear Preference	Normalised by Percent of Total Population
Going Right/Left	550	48
SLF	333	29
LLF	261	23

The relative importance of the wayfinding criteria in questionnaire 1 was described in Chapter 5, Section 5.4.3. These values for the entire sample are shown in the second column in Table 6-8. The last column in Table 6-8 shows the number of people having a clear preference for the questionnaire 1 set of criteria normalised by the percentage of the total population.

Table 6-9: Weights for all wayfinding criteria under normal and emergency circumstances using the path selection tasks in part 1 of questionnaire 2.

Wayfinding Criteria (Questionnaire 2)	Normal Circumstances (%)	Emergency Circumstances(%)
Shortest Distance	22	21
Least Time	22	20
Least Turns	14	16
Less sharp Turns	15	17
Less Decision Points	12	16
Going Right/Left	7	5
SLF	4	3
LLF	3	2

Going right/left criterion is common to both questionnaire 1 and 2. Going right/left in the second questionnaire is considered to be the real estimate of the importance of this criterion as the second questionnaire considers more number of criteria and more important set of criteria. Hence the weights for SLF and LLF from questionnaire 1 are scaled down to the value of going right/left in questionnaire 2. The weights thus obtained for all the wayfinding criteria in questionnaire 1 and 2 are shown in Table 6-9. These final weights obtained from questionnaire 1 and 2 results can be said to be the most realistic from a building evacuation modelling perspective.

6.5.4 Relative Importance of the Wayfinding Criteria based on the Rating task

The weights for the wayfinding criteria can also be determined from the rating task in the second part of questionnaire 2. The determination of the relative importance of the wayfinding criteria based on rating tasks could be considered to be more reliable than that based on the path selection tasks. This is because in the rating tasks the participants were given all nine criteria to choose from and hence no merging of results was necessary as in the path selection tasks discussed in the previous section. However, there are a few disadvantages of the rating task as well. When asked to choose the nine most important factors it is possible that the participant might choose the first few correctly and may not pay much attention to the later ones. Also when considering all the nine factors a weight has to be attached to each factor. The most important factor has a weight of nine while the least important factor has a weight of one. However it is dubious whether the most important factor is actually nine times more important than the least important factor. The relative importance of the Building

Wayfinding Criteria when considering the most important criterion alone, the top three most important criteria and all nine criteria is shown in Table 6-10.

Table 6-10: Relative importance of the wayfinding criteria using rating tasks under normal circumstances.

Wayfinding Criteria (Questionnaire 2)	One Criterion	Three Criteria	Nine Criteria
Least Time	49.7	35.5	20.0
Shortest Distance	26.0	28.5	18.5
Least Turns	7.7	7.7	11.7
Less sharp Turns	5.2	7.2	10.8
Less Decision Points	3.4	5.9	10.3
Going Right	3.2	4.5	9.0
Going Left	2.9	4.3	8.1
SLF	1.3	4.3	5.8
LLF	0.6	2.1	5.8

In Table 6-10, the first column shows the results that are based on the most important factor alone. A vast majority of the participants have chosen ‘shortest distance’ path to be the most important criterion. The second column shows the results based on the first, second and third most important factors chosen by the participants. Distance is still more important than time but its popularity has decreased. When all the nine criteria are considered distance is still the most important factor but its popularity has decreased significantly than when only the most important criteria was considered. The three criteria analysis shown in the third column of Table 6-10 could be considered to be the most reliable as it is highly likely that participants might not pay much attention to their choice of the other factors.

6.6 Conclusion

The results of the questionnaires carried out in this thesis suggest that handedness and driving side only influence the right/left-hand path choice of people and does not affect the other wayfinding criteria (see Section 6.5.1). An important research finding of the questionnaire 2 is that people choose different routes under normal and emergency evacuation circumstances. This has been found in the path selection tasks in part 1 and the rating tasks in part 2 as well (see Section 6.5.2). However, when reviewing these findings it must be noted that the methodology employed here is a map based questionnaire and so relies on the ability of participants to imagine themselves in a described situation. It is not clear if the participants would behave in a similar manner in a real emergency situation. However, from the comments by the participants it is clear that some of them have used a lot of imagination while taking the questionnaire. For example one of the participants said "*I wouldn't choose path B (path with many turns) as if there is smoke I am more likely to become disorientated and maybe reverse my route*". It is clear that this participant has used vivid imagination to perceive that in the presence of smoke he would find the path with many turns very confusing.

The weights for the wayfinding criteria are determined in Section 6.5.4 from the path selection tasks (see Table 6-9) and from the rating tasks (see Table 6-10). In both tasks shortest distance and least time have emerged as the most important criteria. Least turns, least sharp turns and least decision points are the next most important set of criteria with similar weights. Going right/left, SLF and LLF have emerged as the not so important set of criteria having the lowest weights among the other wayfinding criteria.

The relative importance (weights) of the wayfinding criteria determined in this Chapter will be used to model the decision making ability of the agents in the wayfinding model. This is expected to provide more realistic results than assuming the weights as in [Veeraswamy, et al., 2009]. The wayfinding model developed and integrated with the buildingEXODUS model will be described in the next Chapter.

7 The Building Wayfinding Model

7.1 Introduction

The building wayfinding model developed in this thesis is described in this chapter. The building wayfinding model was developed using C++ and was integrated into the buildingEXODUS model. Question 1 posed in Chapter 1 "How to represent human wayfinding in computer models" is answered in this chapter. The four main steps involved in representing wayfinding (namely spatial representation, path planning, cognitive mapping and path execution/refinement) within evacuation/circulation models are first described in Section 7.2. The integration of the building wayfinding model within buildingEXODUS is described in Section 7.3. In Chapter 6, the relative importance of the building wayfinding criteria was established based on path selection and rating tasks. Based on these results the different weight distributions of the building wayfinding criteria considered in this chapter is described in Section 7.4.

The buildingEXODUS evacuation/circulation modelling tool is then used to perform simulations on four test cases to demonstrate the application of the building wayfinding model. The paths taken by the agents in the simulation in the different models and under different wayfinding modes are discussed in Section 7.5.

7.2 The Wayfinding model

The wayfinding model implemented within the buildingEXODUS software involves a four stage process. The first step is to encode the spatial information of the enclosure in terms of a graph. The second step is to apply graph search algorithms to the graph to find possible paths to the destination. The third step is to model the decision making ability of people which involves the selection of a path from the available paths. The fourth step is the route execution and refinement. In this step, following the concept of [Downs and Stea, 1973], the agent moves along the chosen route, reassesses the route at regular intervals and may decide to take an alternative path if an alternate route seems more favourable e.g. initial path is highly congested or is blocked due to fire.

7.2.1 Spatial Representation

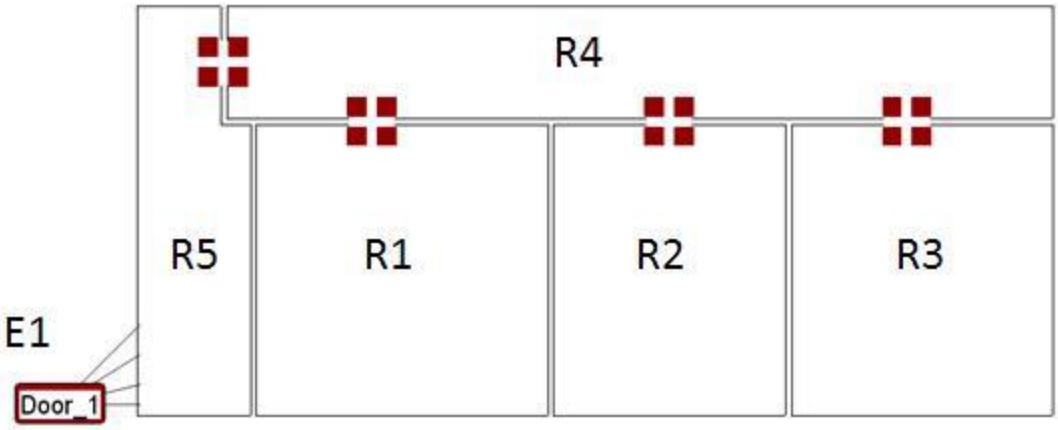


Figure 7-1: Building1 consisting of 3 rooms (R1 to R3), 2 corridors (R4 and R5) and an external exit E1.

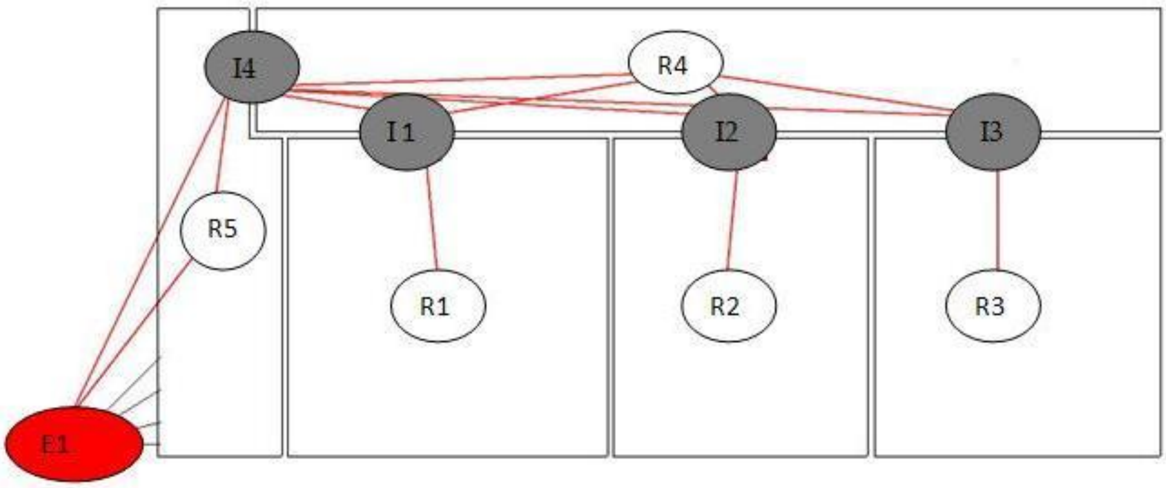


Figure 7-2: The connectivity graph of Building 1 overlaid on the Building 1 geometry.

Spatial representation of the enclosure is achieved by creating a mathematical graph the connectivity of which is representative of the enclosure. The key elements of the enclosure are the rooms (and corridors), the internal exits and the external exits. Each of these elements is considered a node in the graph. These nodes are linked by arcs which represent the connectivity graph of the building. A sample building is shown in Figure 7-1. The connectivity graph for the building is shown superimposed on the original building inFigure 7-2. The buildingEXODUS model has the capability to generate such a connectivity graph of any given enclosure.

7.2.2 Path Planning

A very important aspect of any wayfinding model is the modelling of the path planning strategies employed by the agents. According to [Schneider, 1975] there are two kinds of strategies employed by people when searching for a target which he calls – ‘space exhausting’ and ‘route finding’. In the space exhausting strategy, people do not bother looking for a map of their environment; instead they sequentially search each location (or node in the connectivity graph) till they reach their destination. Lovas [Lovas, 1997] has employed such a strategy in the EVACSIM model (see Chapter 2, Section 2.7). In the route finding strategy, people obtain a map of the space and plan the entire route before the start of the journey. These two different strategies are bound to provide very different set of results [Garbrecht, 1971]. Schneider, in his study of urban environments assumed that people would follow one of the two strategies – ‘space exhaustion’ or ‘route finding’ to reach their target.

People who are unfamiliar with a building are very likely to utilise the ‘space exhaustion’ strategy to exit from a building. They may make use of environmental cues, ask for guidance, follow signs or use some heuristics [Murakoshi and Kawai, 2000] to find an exit. However, people who are familiar with a building already possess a mental map of the building. They would have a configuration level knowledge [Seigel and White, 1975] of the building where they would be capable of mentally visualising paths that they have not traversed before. Therefore, people who are familiar with a building are highly likely to follow the ‘route finding’ strategy.

The path planning strategy employed in this thesis is similar in concept to the ‘route finding’ strategy. A combination of both strategies where agents consider available paths sequentially at each node has also been implemented. A number of alternative strategies have also been implemented more details of which is provided in Section 7.2.4. The wayfinding model implemented in this thesis differs from any other wayfinding model by assigning a choice set of routes to the agents. The route choice set generation algorithms described in Chapter 4, Section 4.4 have been employed to generate a choice set of routes for the agents.

The choice set of routes represents all the routes that the agent in the wayfinding model considers between the source and destination locations. This is usually a sub set of all the available routes between the source and destination locations. Ideally the entire set of routes should be provided to the agent; so that the agent can choose the route that he likes the best.

In a large complex building this could lead to the agent using Multi Criteria Decision Analysis (see Section 7.2.3.2) for a large number of routes (say 100) sequentially at each room. This will not only increase the computational load but *do people in life consider all the routes possible to get to a target location?* This is highly unlikely. It is more likely that people consider a few paths and choose to use one of them. Even if a person is very familiar with a large complex building and knows about 100 routes to get to the exit from different locations, he may still only consider a few paths. This leads to the question: *how many paths do people consider to reach a target location?* In psychology the number seven is considered to be a "magic number". The short term memory of people is good for remembering up to "seven items, plus or minus two" [Miller, 1956]. Therefore, in this thesis it is assumed that assigning ten routes (seven plus three) from the agents' location to an exit should be sufficient.

However, another question still exists: *which ten routes from the set of all possible routes between source and destination do people choose?* Distance and time are the most important wayfinding criteria as determined from the surveys 1 and 2 (see Chapter 6, Section 6.5.4). However, distance is proportional to time and hence in this thesis the first ten shortest paths from an individual's initial location to the target location are provided as the choice set of routes he/she considers. The inclusion of the time factor could be considered in future.

7.2.3 Decision Making

Decision making here refers to the selection of a route from the routes known to the agent. Each route has a set of attributes such as distance and time. Each agent will have a set of attributes which reflect his preference to the route. The route attributes will be called the Route Preference Criteria (RPC) in this thesis. The preference values attached to each RPC will be called the weight of that RPC. The various RPC considered have been discussed in Chapters 5 and 6. However, the manner in which they are implemented within the Building Wayfinding model will be described next.

7.2.3.1 Route Preference Criteria (RPC)

Chapter 2, Section 2.3 provided a list of factors that were identified to include in the wayfinding model implemented in this thesis. The surveys described in Chapters 5 and 6 investigated the influence of these criteria and determined their relative importance. In this section these factors are defined from the perspective of how they have been implemented in the wayfinding model.

7.2.3.1.1 Distance – RPC_1

Distance of the path is the sum of the lengths of all the links in a path. In Golledge's urban wayfinding experiments shortest distance was the most important factor [Golledge, 1995a] [Golledge, 1995b].

7.2.3.1.2 Time – RPC_2

The time taken to traverse the path is the sum of the time taken to traverse the distance of the path and the time spent in congestion at each door along the path. Equation 1 is used to estimate the time to reach an external exit. The distance is the sum of the length of all arcs in a path from the agent's present location to the destination. The agent walk speed is 1.35 metre/second which is the walk speed of agents in buildingEXODUS [Galea, et al., 2006]. The size of the queue at each internal exit is assumed to be 20. This default value can be changed by the user if required. The unit flow rate of the doors is1.33 occupants/m/s which is the HMSO flow rate [Galea, et al., 2006] by default, which again can be modified by the user.

$$Time = D/S + (N*Q) / (UFR*W) \qquad \text{(Equation 1)}$$

D = Distance of the path in meters
S = Agent walk speed = 1.35 m/s
N = Number of doors along the path
Q = Size of the queue at each door = 20
UFR = Unit flow rate of the doors = 1.33 occ/m/s
W = Width of the door in meters

7.2.3.1.3 Average angle – RPC_3

The average angle of the path is defined as the sum of the angles made at each intersection in the path. This angle is always the non reflex angle at the intersection, is between 0^0 and 180^0, with turning back taken as 0^0 and going straight forward taken as 180^0 [Conroy, 2003]. The higher the angle the more straight the path is and hence the more preferable.

7.2.3.1.4 Turns – RPC_4

At each intersection of the path, the angle of intersection is calculated and the number of turns is increased by one for each intersection making an angle less than 175^o. An intersection with an angle between 175^0 and 180^0 is almost straight and hence is not considered a turn. Paths with more turns are estimated to be longer than paths with less turns as shown by [Sadalla and Magel, 1980]. Hence the more turns in a path the less preferable the path is.

7.2.3.1.5 Longest Leg First – RPC_5

The longest leg first criterion refers to the path whose first leg is the longest. In Chapter 5, it was seen that some people do have a preference for taking the longest leg first. The longer the first leg of the path, the more preferable the path is for the people who have a preference for this criterion.

7.2.3.1.6 Shortest Leg First – RPC_6

The shortest leg first criterion refers to the path whose first leg is the shortest. In Chapter 5, it was seen that some people do have a preference for taking the shortest leg first. The shorter the first leg of the path, the more preferable the path is for the people who have a preference for this criterion.

7.2.3.1.7 Decision Points – RPC_7

In wayfinding a decision point generally refers to a location where there is more than one route option and the person needs to decide which one to take. A room node is considered to be a decision point if there is more than one exit in the room. Consider the connectivity graph of building 2 shown in Figure 7-3. Room R4 is only connected to one internal exit and hence is not considered to be a decision point. Room R3 on the other hand has two exits I3 and I4 connected to it. An agent in room R4 can choose a path through I3 or I4 and hence room R3 will be considered to be a decision point.

Consider the internal exit I4 which has only internal exit I3 connected to it. Internal exit I4 is thus not a decision point. Internal exit I3 has two internal exits (I2 and I4) connected to it. However, when an agent reaches internal exit I3, they would have traversed either I2 or I4. Hence, internal exit I3 is not considered to be a decision point as well. An internal exit will only be considered to be a decision point if it has at least more than two internal exits connected to it. The greater the number of decision points along the path the less preferable the path.

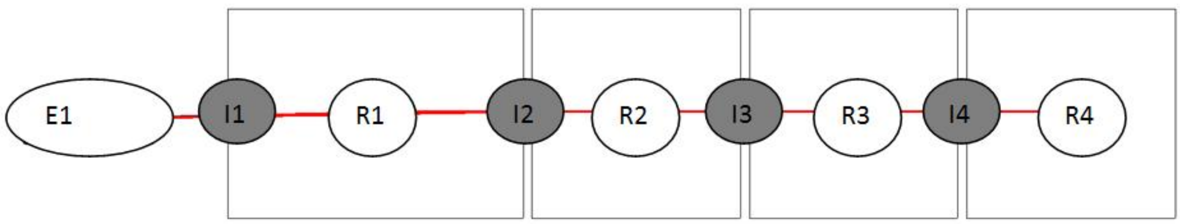


Figure 7-3: Building 2 and its connectivity graph.

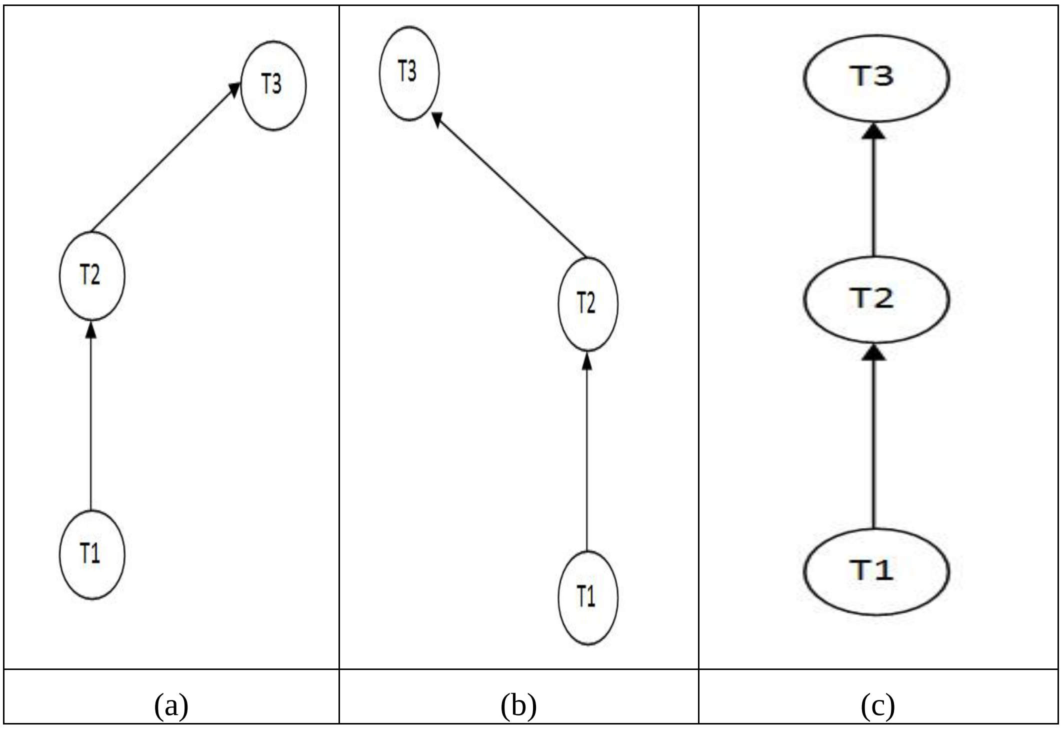


Figure 7-4: Handedness of paths; (a) Right-handed path, (b) Left-handed path and (c) Straight path

7.2.3.1.8 Right-Handed path – RPC$_8$

This criterion was studied in Questionnaire 1 described in Chapter 5. In the questionnaire the right handed path was the path going to the right of the occupant in a building. However, this involves determining the actual orientation of the person in a building. In the wayfinding model this criterion is implemented by considering the next three target nodes of the agent. The nodes in a path are assigned as target nodes for the agent. Consider an agent traversing a path and his present target node is T1, the next target node T2 and the one after that is T3. The agent would be considered to make a right turn if node T3 is to the right of T1 (see Figure 7-4a).

7.2.3.1.9 Left-Handed path – RPC$_9$

If the target node T3 is to the left of the present target node T1, then that path is considered to be a left handed path (see Figure 7-4b).

7.2.3.1.10 Straight path – RPC_{10}

If the target node T3 is in a straight line with the present target node T1, then that path is considered to be a straight path (see Figure 7-4c). Going straight is assumed to have the same preference as going right.

There is a tolerance of ±5 degrees applied to determine the handedness of the paths which is applied to the right-handed (RPC_8), left-handed (RPC_9) and straight path (RPC_{10}) calculation. This is consistent to the logic applied in the calculation of the turns (RPC4) criteria (see Section 7.2.3.1.4.

7.2.3.2 Determination of path cost

RPC_1 – RPC_7 are then normalised by identifying the largest value of $RPC_{k,}$ for route preference criteria k, for all the identified paths i.e. MAX RPC_k and dividing all the other RPC_k values by MAX RPC_k. This process is repeated for all the RPC_1 – RPC_7 with the exception of RPC_3 (Average angle) and RPC_5 (Longest Leg First). Unlike the other criteria which are inversely related to the preference value, RPC_3 and RPC_5 are directly related to the preference value of a path. That is, the higher the angle of a path or the longer the length of the first leg the more preferable the path is. These RPC are normalised by identifying the largest value of RPC_k for all identified paths, subtracting MAX RPC_k from all RPC_k and dividing the difference by MAX RPC_k. For RPC_3, MAX RPC_3 is taken as 180^0 since that is the largest possible angle. A different methodology is employed for normalising RPC_8 (Right-Handed path), RPC_9 (Left-Handed path) and RPC_{10} (Straight path). These RPC's can only take two values zero or one, i.e., if a path is right-handed then the RPC_8 value of this path will be one or zero. Hence these RPC's are already normalised. However, since the final path score needs to be less for a path to be liked the values of these RPC's have to be reversed. For example if a path is right-handed then its RPC_8 value will be 0 and RPC_9 and RPC_{10}values will be 1.

The Weighted Sum Model [Triantaphyllou, E., 2002] is then used to determine the path costs. Having determined the normalised values for the route preference criteria i.e. $\overline{RPC_k}$ the cost associated with path "i" for agent "j" with path preference weightings $W_{k,j}$ for route preference criteria "k" is given by:

$Cost_{i,j} = W_{1,j} * \overline{RPC_{1,j}} + W_{2,j} * \overline{RPC_{2,j}} + W_{3,j} * \overline{RPC_{3,j}} + \ldots + W_{10,j} * \overline{RPC_{10,j}}$ (Equation 2)

Where $W_{k,j}$ stands for the personal weightings associated with $RPC_{k,j}$ for agent "j". The sum of all the weights adds to 100. The weights were determined from Survey 1 and 2 discussed in Chapters 5 and 6. Eleven different weight distributions have been considered as described in Section 7.4.

In this way a path cost, for each route, is determined based on the personal wayfinding preferences of each agent. The path with the lowest cost provides the best match with the agent's personal wayfinding preferences. However, a drawback of the methodology used to calculate the path cost is that the exact values of the RPC are used. Some of the RPC such as distance and time cannot be estimated with 100 % accuracy by people in real life. In order to introduce some fuzziness in an individual's estimation capability it is assumed that people cannot differentiate between paths that are within 10 % of the least cost path. The value 10 is an assumption and further research may be required to determine the most appropriate value. The end user could also be allowed to change this value if desired. Hence in the wayfinding model, instead of choosing the least score path, the agents are randomly assigned one of the paths within 10 % of the least cost path.

7.2.4 Path Execution and Refinement

The third step in the process involves the agent moving along the selected path. Here there are two approaches, Non Sequential Wayfinding (NSW) and Sequential Wayfinding (SW). There are two steps involved in the movement of the agents. The wayfinding model assigns a path or target node to the agents (depending on NSW or SW) and the buildingEXODUS model is responsible for moving the agents physically from one target node to the next. The two models of wayfinding non-sequential and Sequential Wayfinding are described next.

7.2.4.1 Non Sequential Wayfinding (NSW)

In Non Sequential Wayfinding (NSW), all agents make a path decision from their initial position and maintain their chosen path throughout the simulation. Using this approach there is no refinement of the exit path. This is a very simplistic model. However, it is quite possible that some people stick to their original decision regardless of the situation especially in circulation conditions where there is no urgency.

7.2.4.2 Sequential Wayfinding (SW)

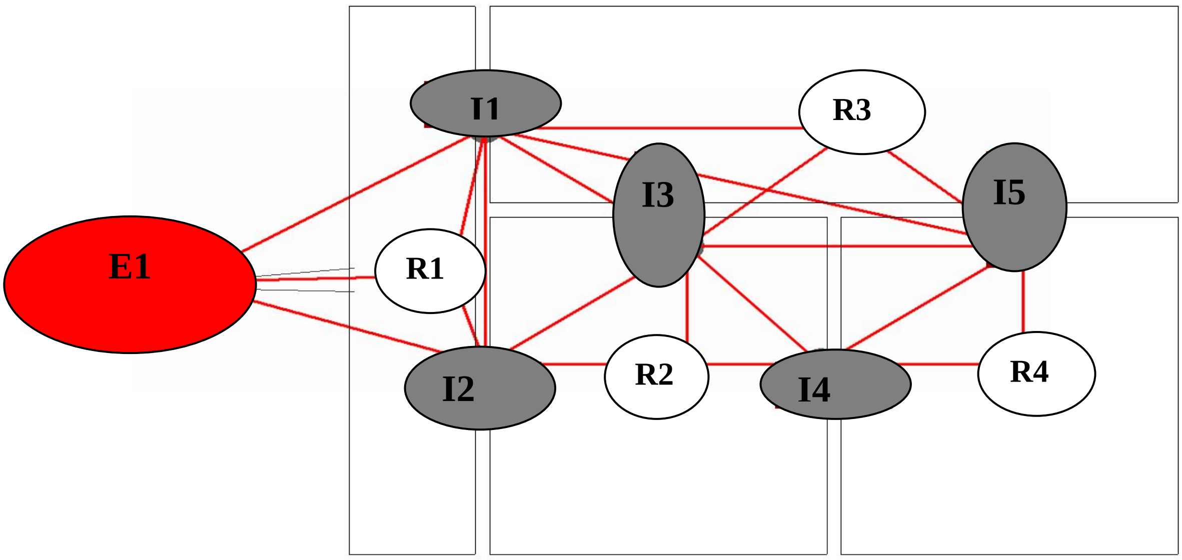


Figure 7-5: Connectivity graph of Building 3 overlaid on the Building 2 geometry. The internal exits are replaced by the grey nodes, the rooms are represented by the white nodes at the centre of each room and the external exit is represented by the red node.

Sequential Wayfinding (SW) is similar to Non Sequential Wayfinding (NSW) except that the agents are allowed to re-evaluate their path choice at each room. Hence, the agents sequentially make a path choice at each room. SW is more dynamic as it allows the agent to choose an alternate path if the initial path is undesirably congested or hazardous. Consider building 3 and its connectivity graph shown in Figure 7-5. Let us assume an agent starts from room R4 and heads towards the exit E1. The paths between R4 and E1 determined by Algorithm 3 (see Chapter 4, Section 4.4.3) are:

P_1 = R4 – I4– I2 – E1

P_2 = R4 – I5– I1 – E1

P_3 = R4 – I5 –I3 –I2 – E1

P_4 = R4 – I4 –I3 –I1 – E1

Let us assume that the agent applies the path determination methodology described in Section 7.2.3.2 and chooses path P_1. In SW the agent would follow this path to the exit regardless of the conditions along the path. In NSW, on reaching the first target node I4, the agent enters room R2. On entering the room R2, the agent is then provided with the paths available from that room which are:

P_1 = R2 – I2 – E1

P_2 = R2 – I3 – I1 – E1

P3 = I4 – I5 – I1 – E1

The agent again applies the path determination methodology described in Section 7.2.3.2 for the paths available from this room. Here if the agent chooses path P1: R2 – I2 – E1, then he would be choosing the same path as his initial path decision from room R4 which was R4 – I4 – I2 – E1. However, assuming that there is severe congestion at the internal exit I2, the agent may find it preferable to use the alternate path P2: R2 – I3 – I1 – E1. Therefore, in SW, the agent is able to modify their path based on congestion or fire conditions they encounter on their way to an exit. SW provides a more dynamic wayfinding model where agents reassess their route options at each room. However, this is similar to a person rolling a dice at each room and randomly choosing one of the paths within 10% of the least cost path. This is not how people choose routes. People will be able to remember the routes that they have taken and there has to be some preference for the originally chosen path and some penalty for retracing paths. Thus, at each room, the agents present path score is decreased by 10 % to make it more preferable. For example in Room R2 the cost of the path P1: R2 – I2 – E1 is reduced by 10% as this is the agents originally chosen path from room R4.

Retracing of paths is also penalised by increasing the path score of any path that involves revisiting the last visited node of the agent by 10 %. For example, consider the agent taking the path P1: R4 – I4 – I2 – E1 from room R4. For this agent the cost of path P3: I4 – I5 – I1-E1from room R2 will be increased by 10% since it involves revisiting the node I4. This has the effect of discouraging agents from retracing their path but still allowing them to retrace if all the forward paths are more disadvantageous.

In the Sequential Wayfinding mode the path costs are modified due to congestion. Congestion impacts the route preference criteria RPC_2 i.e. the estimated time required to travel along the chosen path. There are two approaches which can be used to take this into account.

7.2.4.2.1 Local-Prescribed (LP)

In the Local-Prescribed (LP) time estimation method default values specified in Equation 1 are used to estimate the time penalty at each door along the path with the exception of the door (local door) in the room the agent is currently in. The agent is assumed to have access to all the queuing information in their current room and so knows the queue size, door width and the flow rate of the local doors. For the other doors (remote doors) along the paths, default values are used to estimate the time. This information is used to re-evaluate the path options from the current location (using Equation 1).

7.2.4.2.2 Local-Local (LL)

The Local-Local (LL) time estimation is similar to the Local-Prescribed (LP) time estimation. However, rather than using the default values to estimate the time required to pass through the remote doors along a path, the agent assumes that all the doors along a path will have similar conditions to the local door in their current room.

7.3 Integration of the wayfinding model into EXODUS

In this thesis the code for the wayfinding model was developed separately and then integrated into the buildingEXODUS code by means of a DLL plugin. When buildingEXODUS starts, the wayfinding code runs as a separate piece of code in the background. The DLL plugin transfers the messages between the wayfinding code and buildingEXODUS.

There are two main interactions between buildingEXODUS and the wayfinding model. One is before the start of the simulation shown in Figure 7-6a and the other is during the simulation shown in Figure 7-6b. The interaction before the start of the simulation occurs only once for each simulation but the interactions during the simulation can take place more than once. At the start of the simulation buildingEXODUS passes the spatial and population information to the wayfinding model. The wayfinding model in turn assigns the next target node to all agents in the population. The second type of interaction takes place sequentially at certain conditions during the simulation. The conditions which trigger the second type of interaction with the wayfinding model is when the agent:

- reaches his target node (in Sequential Wayfinding mode).

- finds himself in congestion and wants to redirect.
- finds hazardous conditions along his original path and wants to redirect.

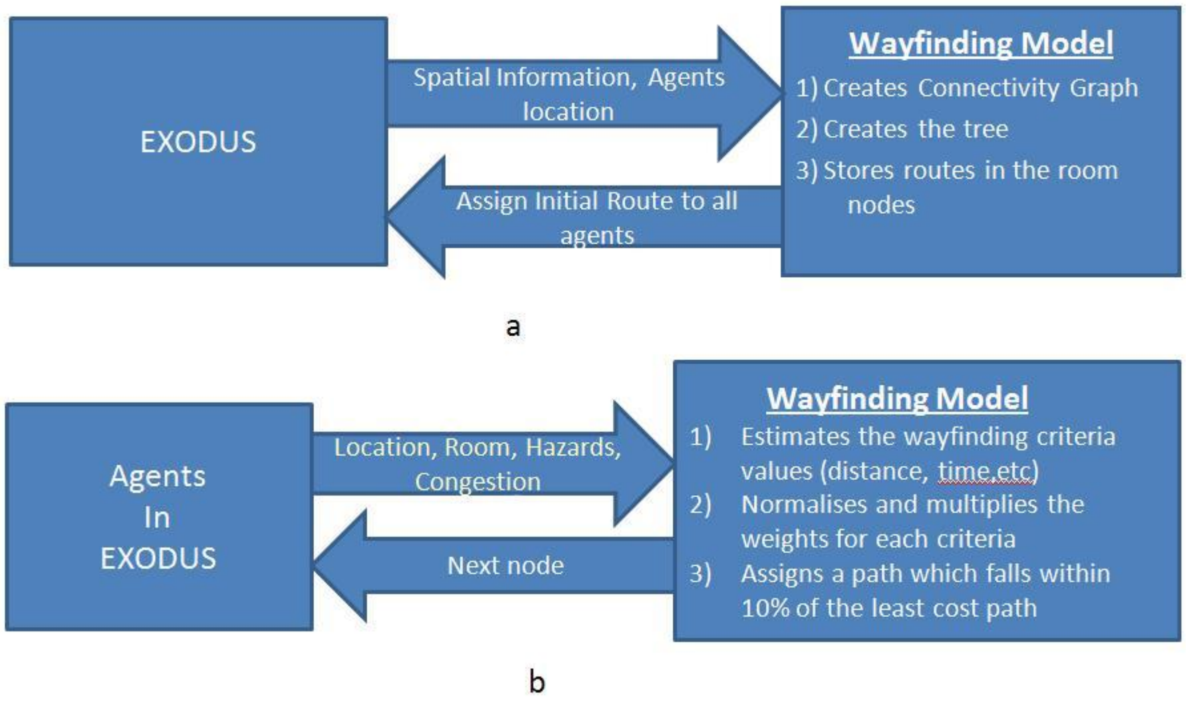


Figure 7-6: The communication between EXODUS and the wayfinding model (a) Before the start of the simulation and (b) During the simulation.

In the second type of interaction, buildingEXODUS passes information like the location of the agent, the local conditions around the agents which the wayfinding model makes use of to determine the next node for the agent to go to.

7.4 The models

Eleven models are investigated and the weight distribution in each model are given in Table 7-1. The weight distrbution of the route preference criteria in each model can be designed to add up to any number. In these models for simplicity the weights add up to 100. The weights of the RPC_{10} 'going straight' is not shown here as this has been added as an additional factor having the same weight as 'going left'. The weight distribution for the eleven models is as follows:

- In Model 1, agents follow the shortest distance path. This is the technique followed by most of the existing evacaution models.

- In Model 2 distance is the only criterion which influences the path score carrying a weight of 100% and the weights for all other criteria being 0.

- In Model 3, time is the only criterion which influences the path score carrying a weight of 100% and the weights for all other criteria being 0.

- In Model 4, distance and time are the only two criteria which influence wayfinding with a weight of 55.4% for time and 44.6% for distance. These weights for distance and time are based on the 'three criteria' analysis of the rating tasks in Questionnaire 2 (see Chapter 6, Section 6.5.4)

- In Model 5, Distance, Time, 'going right' and 'going left' are the only criteria which influence wayfinding, with a weight of 46.7% for time, 37.5% for distance, 10.2% for 'going right' and 5.9% for 'going left'. These weights are also based on the 'three criteria' analysis as in Model 4.

- The weights in Model 6 are based on the 'one criterion' analysis (see Chapter 6, Section 6.5.4).

- The weights in Model 7 are based on the 'three criteria' analysis (see Chapter 6, Section 6.5.4) and is assumed to be the best indicator of the relative weights of the wayfinding criteria.

- The weights in Model 8 are based on the 'nine criteria' analysis (see Chapter 6, Section 6.5.4).

- The weights in Model 9 are based on the actual wayfinding tasks (see Chapter 6, Section 6.5.3) carried unlike the rest of the Models which are based on rating tasks.

- In Model 10, the distribution corresponded with Golledge's distribution of the mean rating of criteria by the participants in his tasks [Golledge, 1995a,b].

- In Model 11, the distribution corresponded with Golledge's distribution of the mean ranking of criteria usually chosen by people in real life [Golledge, 1995a,b].

Table 7-1: Models (M) and the weights (in percentage) of the criteria used in the models.

Criteria	M1	M2	M 3	M4	M5	M6	M7	M8	M9	M10	M11
Time	**No Wayfinding**	0	100	55.4	46.7	49.7	35.5	20.0	22.2	25.8	16.0
Distance		100	0	44.6	37.5	26.0	28.5	18.5	21.9	26.4	27.2
Right		0	0	0	10.2	7.7	7.7	9.0	4.0	0.0	0.0
Left		0	0	0	5.9	5.2	4.3	5.8	2.8	0.0	0.0
DP		0	0	0	0.0	3.4	5.9	10.3	12.3	0.0	0.0
Angle		0	0	0	0.0	3.2	7.2	11.7	15.5	0.0	0.0
SLF		0	0	0	0.0	2.9	4.3	8.1	4.1	10.7	21.0
LLF		0	0	0	0.0	1.3	2.1	5.8	3.2	14.5	14.2
Turns		0	0	0	0.0	0.6	4.5	10.8	13.9	22.6	21.6

The wayfinding model was run for the different weight distributions in models M2 – M11 for the first three test cases in order to analyse the sensitivity of varying these weights. The sensitivity is examined by analysing the difference in the paths selected for the different models. The wayfinding model also takes into account the possible errors in the calculation of these weights by randomly assigning agents to one of the paths within 10% of the least cost path (see Section 7.2.3.2).

7.5 Simulation Results

The building wayfinding model has been applied on a number of different buildings. The results of four test cases utilising the eleven models described in the previous section will be discussed next.

7.5.1 Test Case 1

In this section a simple building is considered and the steps involved in creating a tree or a cognitive map of the building are outlined. The test case geometry is a simple enclosure with three rooms R23, R24 and R25 connected via internal doors and two corridors R21 and R22. Each of the rooms is also connected to corridor R22. The room R23 and corridor R22 are connected to corridor R21. The corridor R21 is connected to the only external exit (see Figure 7-7). Though there are two possible paths P1 (solid line) and P2 (dotted line) to exit from this enclosure, most evacuation models assign only the shortest distance path to the agents. Imagine that the rooms R23 and R24 are highly congested and the room R22 is empty, the evacuees in room R25 in real life would certainly choose the path P1 to exit in an emergency situation. However, most evacuation models simplify this situation by having all occupants choose the shortest distance path P2. In some evacuation models including buildingEXODUS the user can manually specify paths to the agents in the simulation. Manual path assignment may be feasible for simple test cases such as test case 1 shown in Figure 7-7. However, the wayfinding model developed in this thesis automates this process by first determining the available paths, assigning initial paths to the evacuees based on their attributes and enabling dynamic path selection based on local and global congestion. The test case 1 is a simple test case demonstrating the difference between the evacuation results with and without wayfinding.

The connectivity graph for the enclosure is shown in Figure 7-8. Note that the logical paths are determined by the sequence; room to internal exit to room to internal exit …. to room to external exit. However, within the wayfinding model, the agent's paths are simply internal exit to internal exit to internal exit …. to internal exit to external exit. In this example, all the agents are initially located in room R25 for simplicity.

Each agent searches a subset of the main tree connected to the known exit based on the agents exit familiarity. Consider room node R25 (see connectivity graph in Figure 7-8), there are seven paths (acyclic paths which does not involve visiting the same room more than once) from the room node R25 to the exit node E0. These paths are:

P1: R25 I11 R22 I1 R21 E0

P2: R25 I18 R24 I13 R23 I4 R21 E0

P3: R25 I11 R22 I7 R23 I4 R21 E0

P4: R25 I18 R24 I10 R22 I1 R21 E0

P5: R25 I11 R22 I10 R24 I13 R23 I4 R21 E0

P6: R25 I18 R24 I10 R22 I7 R23 I4 R21 E0

P7: R25 I18 R24 I13 R23 I7 R22 I1 R21 E0

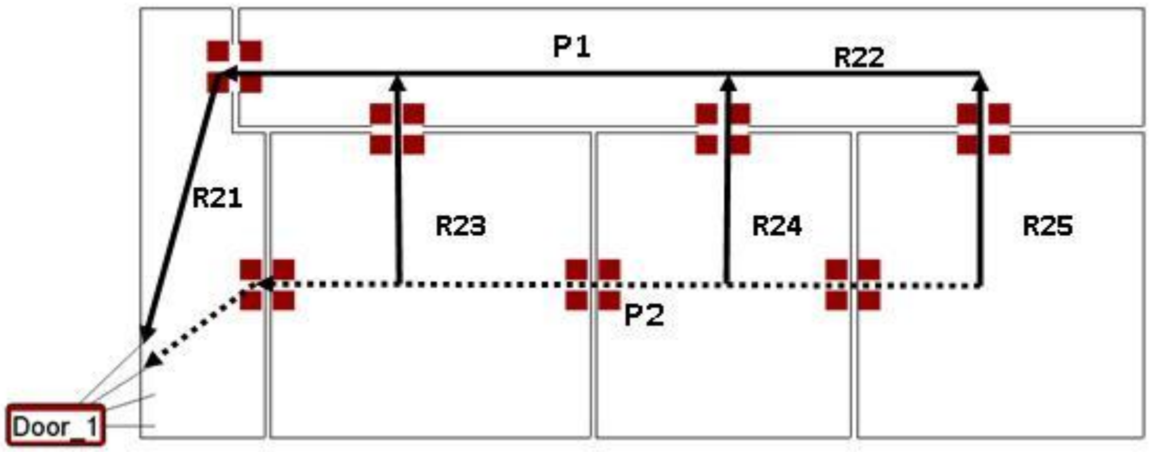


Figure 7-7: Building 1 containing three rooms (R23, R24 and R25) and two corridors (R21 and R22) having an area of 108.50m^2.

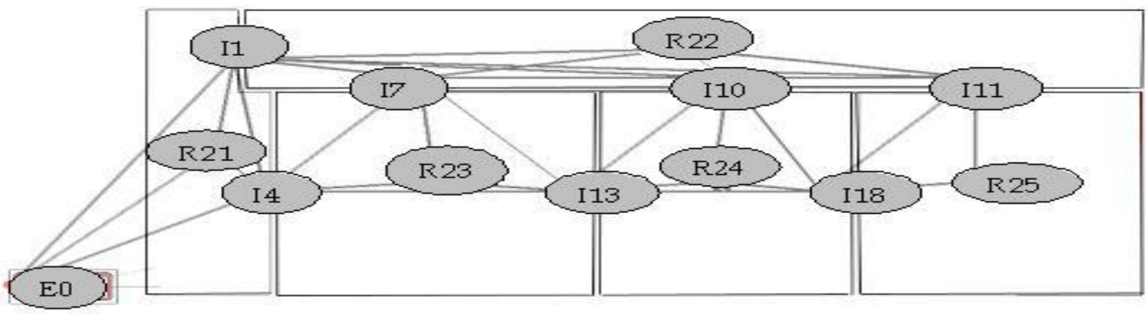


Figure 7-8: Connectivity graph of Building 1 overlaid on the Building 1 geometry.

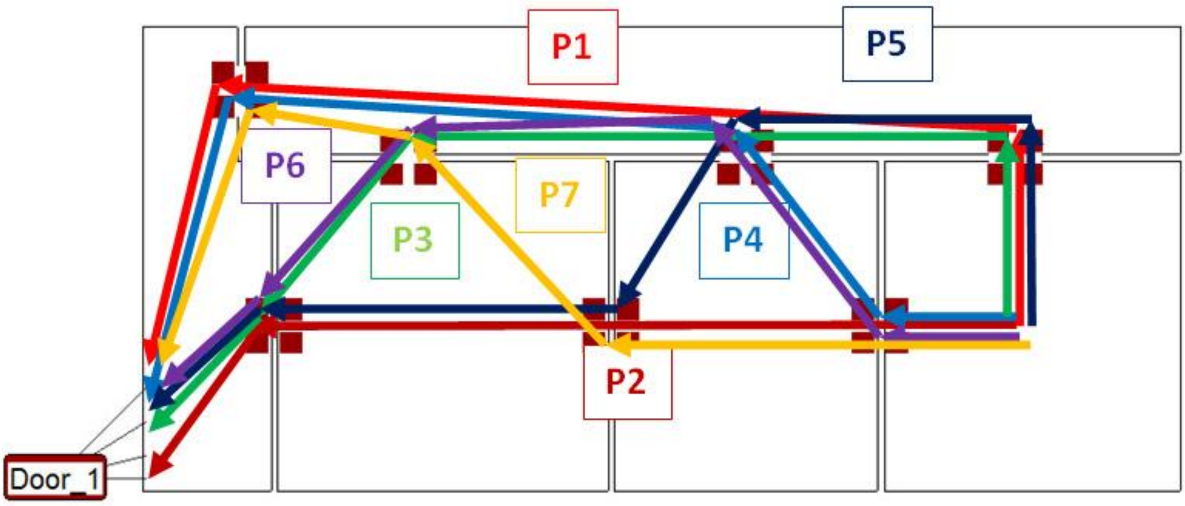


Figure 7-9: Paths determined by algorithm 3 from Room R25.

A similar collection of paths is constructed from each room to the external exit and stored in each of the room nodes. As agents enter each room they are given this path knowledge. This approach is more efficient than requiring each agent to search the tree for paths.

The values for the various RPC for the seven paths originating from R25 are presented in **Table 7-2**. The highest values for each criterion among the seven paths are highlighted grey for RPC_1 (Distance) to RPC_7 (Decision Points). For example, path P1 is the longest distance path. The distance values of the remaining paths are normalised with respect to the distance value of P1. Similarly the values of the RPC_1 to RPC_7 are normalised. A different technique is used to normalise RPC_8 (Right-Handed path) to RPC_{10} (Straight Path) as they can have only two values (1 or 0) which need to be inverted for normalisation (see Section 7.2.3.2 for more details). The normalised values of the RPC for the seven paths from room R25 are shown in Table 7-3.

Table 7-2: Values of the RPC for each path from room R25. The highest values of RPC1 to RPC7 are highlighted in grey.

Paths	Distance (m)	Time (s)	Average angle (degrees)	Turns	Longest Leg First (m)	Shortest Leg First (m)	Decision Points	Right-handed Path	Left-handed Path	Straight Path
P1	20.24	37.5	88.89	2	3.62	3.62	3	0	1	0
P2	11.07	38.7	168.76	1	0.99	0.99	4	0	0	1
P3	18.36	43.6	118.88	3	3.62	3.62	4	0	1	0
P4	17.24	42.8	115.83	3	0.99	0.99	4	1	0	0
P5	18.36	51.1	117.31	4	3.62	3.62	5	0	1	0
P6	15.36	48.9	131.58	4	0.99	0.99	5	1	0	0
P7	16.94	50.1	138.49	3	0.99	0.99	5	0	0	1

Table 7-3: Normalised values of the RPC for each path from room R25

Paths	Distance	Time	Average Angle	Turns	Longest Leg First	Shortest Leg First	Decision Points	Right-handed Path	Left-handed Path	Straight Path
P1	1.00	0.733	0.506	0.5	0.00	1.00	0.600	1	0	1
P2	0.578	0.757	0.062	0.25	0.723	0.276	0.800	1	1	0
P3	0.907	0.853	0.340	0.75	0.000	1.000	0.800	1	0	1
P4	0.852	0.837	0.357	0.75	0.724	0.276	0.800	0	1	1
P5	0.907	1.000	0.348	1.000	0.000	1.000	1.000	1	0	1
P6	0.759	0.956	0.269	1.000	0.724	0.276	1.000	0	1	1
P7	0.837	0.979	0.231	0.75	0.724	0.276	1.000	1	1	0

Table 7-4: Weighted values of the RPC wayfinding criteria applied to Path 1 to Path7. The path P2 with the least score has been highlighted grey.

Paths	RPC1 (28.5)	RPC2 (35.5)	RPC3 (7.2)	RPC4 (4.5)	RPC5 (2.1)	RPC6 (4.3)	RPC7 (5.9)	RPC8 (7.7)	RPC9 (4.3)	RPC10 (7.7)	Total Score	% Difference
P1	28.50	26.03	3.64	2.25	0.00	4.30	3.54	7.70	0.00	7.70	83.67	23.09
P2	16.48	26.87	0.45	1.13	1.52	1.19	4.72	7.70	4.30	0.00	64.35	0.00
P3	25.86	30.29	2.44	3.38	0.00	4.30	4.72	7.70	0.00	7.70	86.38	25.50
P4	24.28	29.71	2.57	3.38	1.52	1.18	4.72	0.00	4.30	7.70	79.35	18.91
P5	25.86	35.50	2.51	4.50	0.00	4.30	5.90	7.70	0.00	7.70	93.96	31.51
P6	33.96	21.63	1.94	4.50	1.52	1.19	5.90	0.00	4.30	7.70	82.63	22.12
P7	34.77	23.86	1.66	3.38	1.52	1.19	5.90	7.70	4.30	0.00	84.28	23.65

Each agent then multiplies the normalised values with their personal weights that they have for each criterion. While it is possible that each agent has their own unique weight distribution, for simplicity all agents have the same weight distribution in each model. Presented in Table 7-4 are the weighted normalised RPC and the total score for each path. The weights for each RPC are shown in brackets in Table 7-4.

The least cost path from Room R25 from Table 7-4 is

P2: R25 I18 R24 I13 R23 I4 R21 E0

The weight distribution in Table 7-4 implies time to be a more important factor than distance. However, the path that takes the least time P1 has not been considered to be a feasible path. This is because the distance value of P1 is almost double that of P2 whereas the difference in times between these paths is just one second. The worst path is P5 which requires the agent to visit R25, R22, R24, R23 and R21 prior to exiting and so the agent must pass through many internal doors incurring high time penalties.

P5: R25 I11 R22 I10 R24 I13 R23 I4 R21 E0

7.5.1.1 The Path Scores

The path scores and the percentage difference of each path's score from the best path score for test case 1 for one agent chosen randomly are shown in Table 7-5. The path with the least score is the best path and is shaded grey. This path is the best taking into consideration the route preference criteria RPC1 to RPC10 and the weight distribution of the RPC's in each model. The percentage difference of each path score from the best path score is shown in the 'Percentage Difference' column and is shaded light grey if it falls within 10% of the best path.

It is interesting to note that the shortest distance path P2 has been the only path considered as viable in all models except Model 3. In Model 3, the least time path P1 has been considered to be best path but path score of P2 is within 10% of P1. The agent under consideration now has equal probability of choosing either P1 or P2 and zero probability of choosing any of the other paths.

Table 7-5: Path scores and the percentage difference of each path from the best path score for models 2 to 11 applied to test case 1 using Non Sequential Wayfinding. The viable paths in each model are highlighted grey.

	Model 2		**Model 3**		**Model 4**		**Model 5**	
	Path Score	**Percentage Difference**	**Path Score**	**Percentage Difference**	**Path Score**	**Percentage Difference**	**Path Score**	**Percentage Difference**
P1	100.00	42.17	73.35	0.00	85.23	20.55	92.15	20.64
P2	57.83	0.00	75.68	3.09	67.72	0.00	73.13	0.00
P3	90.72	36.25	85.31	14.03	87.72	22.80	94.26	22.41
P4	75.89	23.80	83.69	12.36	84.36	19.72	87.13	16.06
P5	90.72	36.25	100.00	26.65	95.86	29.35	101.12	27.67
P6	85.18	32.10	95.66	23.33	86.84	22.02	89.23	18.05
P7	83.73	30.93	97.95	25.12	91.61	26.08	93.24	21.57
	Model 6		**Model 7**		**Model 8**		**Model 9**	
	Path Score	**Percentage Difference**	**Path Score**	**Percentage Difference**	**Path Score**	**Percentage Difference**	**Path Score**	**Percentage Difference**
P1	92.15	20.64	83.67	23.09	76.77	23.49	72.46	25.47
P2	73.13	0.00	64.35	0.00	58.74	0.00	53.99	0.00
P3	94.26	22.42	86.38	22.50	80.25	26.81	76.43	29.35
P4	87.13	16.06	79.35	18.90	74.24	20.88	73.27	26.31
P5	101.12	27.68	93.96	31.51	88.05	33.29	85.76	37.04
P6	89.24	18.05	82.63	22.12	78.65	25.32	78.48	31.19
P7	93.24	21.57	84.28	23.64	77.41	24.12	76.63	29.54
	Model 10		**Model 11**					
	Path Score	**Percentage Difference**	**Path Score**	**Percentage Difference**				
P1	67.32	19.95	70.74	30.28				
P2	53.89	0.00	49.32	0.00				
P3	73.61	26.78	75.53	34.70				
P4	74.48	27.64	68.84	28.36				
P5	83.05	35.11	83.28	40.78				
P6	80.77	33.27	73.63	33.02				
P7	77.78	30.71	70.73	30.27				

7.5.1.2 Non Sequential Wayfinding (NSW) Results

To examine the implication of weight distribution in Models 1 – 11 on the paths chosen by the agents, test case 1 was populated with 50 agents in room R25. The simulation was run 20 times and the average results for all models using Non Sequential Wayfinding are presented in Table 7-6. In Model 1 no wayfinding is used and all agents take the shortest path to the exit. In Model 2 wayfinding is employed but distance is the only criterion influencing wayfinding choice and hence it is seen that the results are similar to Model 1. However, there is a small difference in the results of models 1 and 2 as two agents in Model 2 have taken paths that are not the shortest. This is because the distance of paths for the agents depends on their location and the location of these two agents have been such that Paths P3 and P5 have been shorter or within 10% of the shortest path. In Model 3, 66 % have chosen the least time path, P1 while 34% have chosen the shortest distance path, P2. With time being the only criterion influencing wayfinding, majority of the population has chosen the least time path but Path P2 takes only slightly more time than Path P1 and hence some of the agents (34 %) have chosen it. In Models 4 – 11, majority of the population has always taken the shortest distance path, P2 and the second most popular path has been the least time path, P1.

Table 7-6: Average evacuation simulation statistics for 20 repeat simulations of each model for Test case 1 using Non Sequential Wayfinding.

	Paths					
	P1	**P2**	**P3**	**P4**	**P5**	**P6**
Model 1	0	50	0	0	0	0
Model 2	0	48	1	0	1	0
Model 3	33	17	0	0	0	0
Model 4	7	40	3	0	0	0
Model 5	4	42	2	3	0	0
Model 6	5	41	2	2	0	0
Model 7	7	41	1	1	0	0
Model 8	9	38	1	2	0	0
Model 9	6	44	0	0	0	0
Model 10	12	38	0	0	0	0
Model 11	6	40	4	0	0	0

7.5.1.3 Sequential Wayfinding with LP Time Estimation (SWLP) – Results

Table 7-7: Average evacuation simulation statistics for 20 repeat simulations of each model for Test case 1 using sequential (LP) wayfinding.

	Paths					
	P1	**P2**	**P3**	**P4**	**P5**	**P6**
Model 1	0	50	0	0	0	0
Model 2	0	48	1	0	1	0
Model 3	35	15	0	0	0	0
Model 4	8	39	3	0	0	0
Model 5	8	38	1	2	0	1
Model 6	5	39	3	2	0	2
Model 7	10	36	2	1	0	1
Model 8	11	35	1	3	0	0
Model 9	6	43	1	0	0	0
Model 10	15	35	0	0	0	0
Model 11	8	39	3	0	0	0

The simulation results using the Sequential Wayfinding with LP time estimation (SWLP) method has produced the results shown in Table 7-7. With Sequential Wayfinding agents are given the option to choose an alternative route based on the local congestion. Though there is no significant differences between the results in Table 7-6 and Table 7-7, it is seen that slightly more number of people have chosen the least time path P1 in Models 3 – 11. In the Sequential Wayfinding mode, agents make dynamic decisions choosing paths that are less congested. Therefore paths that are less used have slightly more probability of being chosen in the Sequential Wayfinding mode.

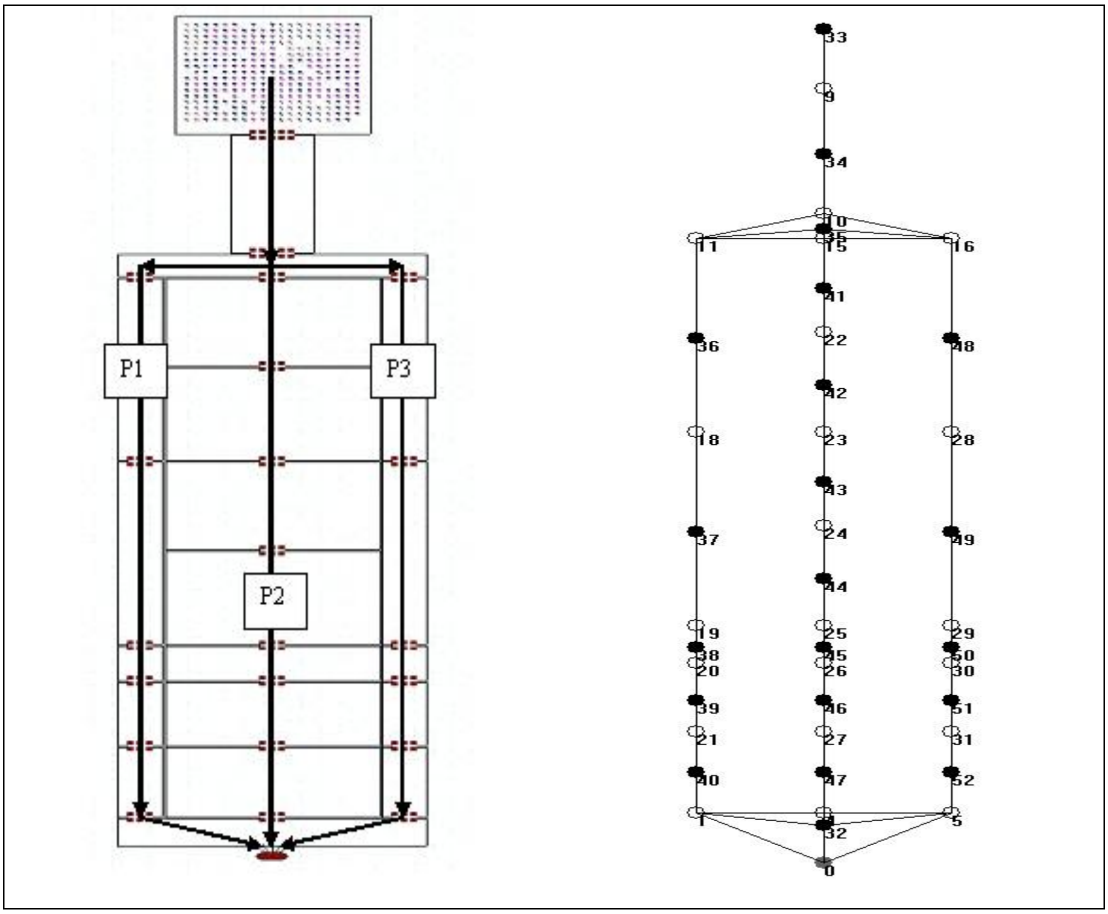
7.5.1.4 Sequential Wayfinding with LL Time Estimation (SWLL) – Results

The simulation results of the sequential wayfinding using SWLL are shown in Table 7-8. The number of people using path P1, the least time path has increased in Models 3 – 11 compared to the SWLP method (see Table 7-8 and Table 7-7). There are two reasons for this: with Local-Local time estimation, least time paths are even more favourable and the local queuing is assumed along the entire route, thus making a less used route even more preferable. Therefore, path P1 is being used by more agents in the SWLL method than in the SWLP method.

Table 7-8: Average evacuation simulation statistics for 20 repeat simulations of each model for Test case 1 using sequential (LL) wayfinding.

	Paths					
	P1	**P2**	**P3**	**P4**	**P5**	**P6**
Model 1	0	50	0	0	0	0
Model 2	0	48	2	0	0	0
Model 3	48	0	2	0	1	0
Model 4	11	28	11	0	0	0
Model 5	11	32	5	1	1	0
Model 6	12	29	6	2	1	0
Model 7	15	30	4	1	0	0
Model 8	13	36	0	1	0	0
Model 9	9	40	0	0	0	0
Model 10	20	30	0	0	0	0
Model 11	10	38	2	0	0	0

7.5.2 Test Case 2



(a) (b)

Figure 7-10: Geometry of Test case 2 showing (a) three exit paths (P1, P2, P3) from assembly room and (b) connectivity graph for case 2 (filled black circles are room nodes, open circles are internal exits and the grey filled circle is the external exit).

The test case 2 geometry is shown in Figure 7-10(a) and its connectivity graph is shown in Figure 7-10(b). This building consists of an assembly room (top room) with a population of 300 agents, connected via a wide corridor to a horizontal corridor leading to three connections to the other part of the structure; a long vertical corridor on the left, a central collection of seven rooms lined vertically from top to bottom and another long vertical corridor on the right. Each room within the central section is connected to the next room via a set of doors. The two long vertical corridors flank the vertical collection of the rooms, one to the left and one to the right. Each corridor is separated into five compartments with six internal doors. The final exit to the geometry is at the bottom. There are three different paths to the exit; P1, P2 and P3 (Figure 7-10(a)). The most direct path to the exit is P2 which is the path from the assembly room to the exit via the central section. The two alternate exit paths are; P1 which is the path via the left corridor and P3 which is the path via the right corridor. The shortest path is P2 which requires the agents to pass through 10 internal doors prior to exiting. The path P2 has two more doors than encountered on paths P1 and P3. Within this test case, agents have knowledge of all three Paths P1, P2 and P3. Note while other paths are possible, they require the agent to revisit at least one compartment on the exit path and hence are not considered (only acyclic paths are considered).

The existing evacuation modelling tools (see Chapter 2, Section 2.7) would simulate the evacuation in test case 2 by assigning the shortest path P2 (see Figure 7-10) to all evacuees regardless of the congestion encountered along the way. This default behaviour can only be overridden by assigning tasks along the other paths or by assigning paths P1, P3 to some of the agents in the simulation which is not realistic. However, with the introduction of the wayfinding model developed in this thesis, this process is automated. The wayfinding model assigns paths to people dynamically based on local and global conditions which simulate the evacuation process more realistically. The main objective of test case 2 is to show the difference between the evacuation statistics without wayfinding and with the introduction of wayfinding. The effect of the different combinations of weights for the RPC is analysed. The Sequential Wayfinding mode is utilised and the difference between the evacuation results with Local-Local time estimation and Local-Prescribed times estimation methods are compared and analysed.

7.5.2.1 Path Scores

Table 7-9: Path scores and the percentage difference of each path from the best path score for models 2 to 11 applied to test case 2 using Non Sequential Wayfinding. The viable paths in each model are highlighted grey.

	Model 2		**Model 3**		**Model 4**		**Model 5**	
	Path Score	**Percentage Difference**	**Path Score**	**Percentage Difference**	**Path Score**	**Percentage Difference**	**Path Score**	**Percentage Difference**
P1	100	14.29	94.51	0	96.95	3.44	97.73	2.86
P2	85.71	0.00	100	5.49	93.63	0.00	94.94	0.00
P3	100	14.29	94.51	0	96.95	3.44	97.73	2.86
	Model 6		**Model 7**		**Model 8**		**Model 9**	
	Path Score	**Percentage Difference**	**Path Score**	**Percentage Difference**	**Path Score**	**Percentage Difference**	**Path Score**	**Percentage Difference**
P1	93.26	2.04	89.86	7.28	83.20	13.63	82.36	17.70
P2	91.36	0.00	83.32	0.00	71.86	0.00	67.78	0.00
P3	93.26	2.04	89.86	7.28	83.20	13.63	82.36	17.70
	Model 10		**Model 11**					
	Path Score	**Percentage Difference**	**Path Score**	**Percentage Difference**				
P1	84.08	22.96	84.92	22.62				
P2	0.00	0.00	65.71	0.00				
P3	84.08	22.96	84.92	22.62				

The path score calculation for one of the agents in the simulations involving test case 2 using the Non Sequential Wayfinding mode is shown in Table 7-9. In Model 2, distance is the only criterion influencing wayfinding and it is seen that only the shortest path, P2 has been considered as a viable path. In Model 3, time is the only criterion influencing wayfinding; however it is seen that all three paths are viable in this model. This suggests that the difference in distance is more than the difference in time between the paths. In Models 4 – 7, as well it is seen that all three paths are considered viable. It is interesting to observe that the percentage difference of the paths from the best score path in Models 4, 5 and 6 decreases from 3.44 to 2.86 to 2.04 as the weights for the time criterion decreases from 55.4 to 46.7 to 35.5. This implies that the time is the driving factor affecting the path scores in these models. However, in Model 7, the path difference is much higher than models 4 – 6. This is because in this Model 7, the angle and turns criteria have higher weights 7.2 and 4.5. Paths P1 and P3 which have the same score possess more turns and less angle than the best Path P2. This has increased the difference in the path scores between P1, P3 and P2. In Models 8 – 11, the weight for the turns and angle criteria are very high making P2 the only viable path. The implication of the selected paths on the evacuation simulations results was then examined using NSW, SWLP and SWLL methods which will be examined next.

7.5.2.2 Non Sequential Wayfinding (NSW) Results

Table 7-10: Average evacuation simulation statistics for 20 repeat simulations of each model for Test case 2 using Non Sequential Wayfinding.

NSW	**Average CWT (seconds)**	**Average Distance Travelled (m)**	**Average PET (seconds)**	**Number of people Using Path1**	**Number of people Using Path2**	**Number of people Using Path3**	**Total Evacuation Time (seconds)**
Model 1	85.35	76.89	185.02	0	300	0	280.25
Model 2	85.35	76.89	185.02	0	300	0	280.25
Model 3	49.09	81.19	151.00	99	105	96	218.26
Model 4	49.00	81.19	150.89	96	100	104	218.28
Model 5	49.15	81.34	151.12	104	96	100	219.28
Model 6	48.76	81.11	150.59	103	102	95	219.58
Model 7	48.56	81.14	150.38	99	101	100	216.78
Model 8	85.35	76.89	185.02	0	300	0	280.25
Model 9	85.35	76.89	185.02	0	300	0	280.25
Model 10	85.35	76.89	185.02	0	300	0	280.25
Model 11	85.35	76.89	185.02	0	300	0	280.25

Table 7-10 shows the average of 20 evacuation simulation results of test case 2 using Non Sequential Wayfinding (NSW). The following evacuation statistics have been analysed in this section:

In Model 1, no wayfinding is used and hence all agents take the shortest distance path P2. Model 2 produces the same results as Model 1 as in this model though wayfinding is used, distance is the only factor being considered carrying a weight of 100 %. In both cases, the shortest path P2 will thus be the path with the least score. The other paths P1 and P3 will have been considered if the percentage difference between their scores were within 10% of P2. However, for the test case 2 using Model 2 none of the agents have chosen any path other than P2.

In Model 3, time is the only criterion being considered. Therefore the path scores of paths P1 and P3 are the lowest. However, the score of path P2 falls within 10% of the least path score and hence all the paths have been used. The usage of all three paths in Model 3 has produced significantly different evacuation statistics compared to Model 1 and 2 where only the shortest path was used by the agents. The average Cumulative Wait Time (CWT) has decreased by 42% which implies that the agents are spending lesser times in queues. The average distance travelled has increased by 6% which implies that the agents are choosing longer paths. Traversing longer paths should increase the time spent by the agents. However, the average Personal Elapsed Time (PET) has decreased by 18% which implies that people are now spending lesser times in queues. The total evacuation time has thus decreased by 22%.

Though the weight distribution in Models 3 – 7 are different they produce similar results with a good utilisation of all the available paths in the building. In Models 8 – 11, only the shortest distance path P2 has been used as this path was also good in terms of the turns and angle criteria which have a higher weight in these models.

7.5.2.3 Sequential Wayfinding with LP Time Estimation (SWLP) – Results

The average evacuation simulation results using Sequential Wayfinding with LP time estimation (SWLP) method is shown in Table 7-11. Even though in the Sequential Wayfinding mode agents are allowed to choose an alternative path at each target node, this has not produced a difference in the results of Model 2. This is because in Model 2, distance is the only criterion which influences wayfinding. This demonstrates that time is the only criterion which is capable of changing the agent's path choice in the Sequential Wayfinding mode. In Model 3, Paths 1 and 3 which take the least time are being used by majority of the population (96 %). This is to be expected as in model 3 only time affects wayfinding and hence majority of the population have chosen the least time path. In model 4, time is slightly more important than distance and hence one would expect more people to take the least time paths P1 and P3. However, the difference in distance is greater than the difference between times between paths P1, P3 and P2. Paths P1 and P3 are 16.67 % longer than path P2 but take just 4 % less time to traverse. Therefore in Model 4, 64 % of the population chose the shortest distance path.

Table 7-11: Average evacuation simulation statistics for 20 repeat simulations of each model for Test case 2 using Sequential Wayfinding and local prescribed time estimation.

SWLP	**Average CWT (seconds)**	**Average Distance (m)**	**Average PET (seconds)**	**Number of people Using Path1**	**Number of people Using Path2**	**Number of people Using Path3**	**Total Evacuation Time (seconds)**
Model 1	85.35	76.89	185.02	0	300	0	280.25
Model 2	85.35	76.89	185.02	0	300	0	280.25
Model 3	51.91	85.89	157.28	140	12	148	223.00
Model 4	52.33	78.63	152.64	50	191	59	216.32
Model 5	55.93	79.10	156.87	87	204	10	224.90
Model 6	53.97	79.12	154.78	89	194	17	218.29
Model 7	64.18	78.08	164.59	53	236	11	243.54
Model 8	85.35	76.89	185.02	0	300	0	280.25
Model 9	85.35	76.89	185.02	0	300	0	280.25
Model 10	85.35	76.89	185.02	0	300	0	280.25
Model 11	85.35	76.89	185.02	0	300	0	280.25

In Models 3 and 4 paths P1 and P3 are being used by almost the same number of people. However, in Model 5, it is noticed that path P3 is being used by fewer people than path P1. Considering the direction in which the occupants are evacuating, path P1 is the right handed path and path P3 is the left handed path (see Figure 7-10). In Model 5, 'going right' criterion has more weight than the 'going left' criterion which is the reason for the right handed path P1 being used by more number of people than path P2. This explains why there are less people using path P3 in Models 5 – 7. Though 'going right' and 'going left' criteria have very little significance compared to the most important criteria distance and time they still have produced significant difference in the paths chosen by the agents and thus the evacuation simulation statistics. In Models 8 – 11, the distribution of the weights has been such that all agents take the shortest distance path only.

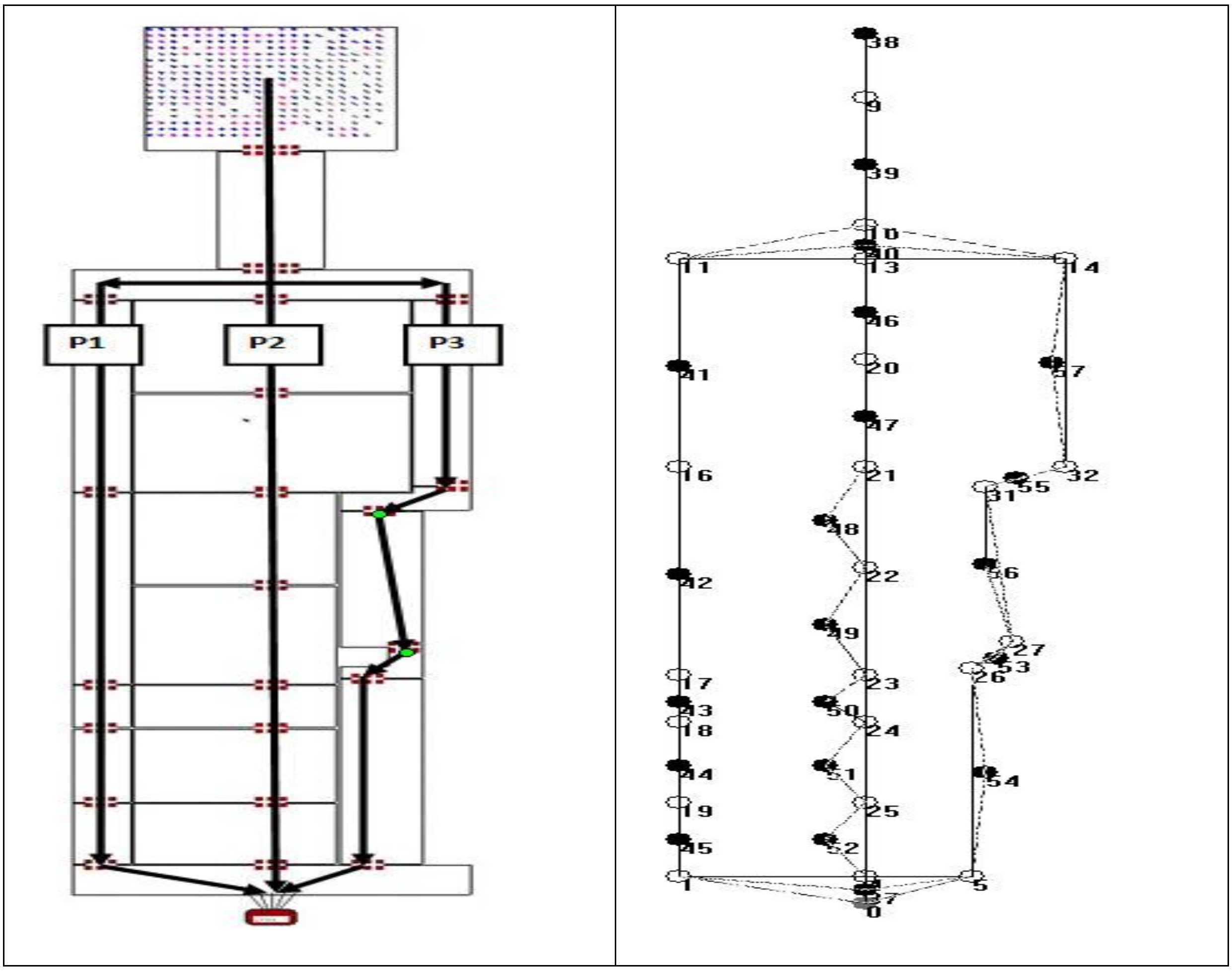
Table 7-12: Average evacuation simulation statistics for 20 repeat simulations of each model for Test case 2 using Sequential Wayfinding and Local-Local time estimation.

SWLL	**Average CWT (seconds)**	**Average Distance (m)**	**Average PET (seconds)**	**Number of people Using Path1**	**Number of people Using Path2**	**Number of people Using Path3**	**Total Evacuation Time (seconds)**
Model 1	85.35	76.89	185.02	0	300	0	280.25
Model 2	85.35	76.89	185.02	0	300	0	280.25
Model 3	53.25	86.25	159.32	129	23	148	231.22
Model 4	49.19	81.65	151.46	100	95	105	218.80
Model 5	48.57	81.11	150.48	114	107	79	219.69
Model 6	48.9	81.33	150.93	111	100	89	217.36
Model 7	50.08	79.81	150.95	86	162	52	214.88
Model 8	67.46	78.00	167.75	57	243	0	245.54
Model 9	63.03	78.20	163.34	50	228	22	236.03
Model 10	56.24	78.89	157.09	48	206	46	224.32
Model 11	85.35	76.89	185.02	0	300	0	280.25

7.5.2.4 Sequential Wayfinding with LL Time Estimation (SWLL) – Results

The average evacuation simulation results using SWLL method is shown in Table 7-12. In Models 3 and 4 it is interesting to observe that all three paths are being used almost equally. This is different from the corresponding results using local prescribed time estimation in Table 7-11. In the Local-Local time estimation method more people are encouraged to use paths that are less used and hence there is an even distribution of people along the available paths. In Models 5 – 7, the right-handed path attribute plays an important role making more people to choose path P1 than path P2. In the other two strategies, NSW and SWLP, Models 8 – 10 showed all agents taking the shortest distance path. With the introduction of the Local-Local time estimation some agents have taken the other paths (P1, P2) however having more preference for the right handed path P1 than the left handed path P2. In Model 11, however the distribution of weights has been such that all agents take the shortest distance path.

7.5.3 Test Case 3



(a) (b)

Figure 7-11: Geometry of Test case 3 showing (a) three exit paths (P1, P2, P3) from assembly room and (b) connectivity graph for case 3 (filled black circles are room nodes, open circles are internal exits and the grey filled circle is the external exit

Test case 3 geometry and its connectivity graph are shown in Figure 7-11. The geometry is similar to test case 2 but with 2 additional turns being introduced along Path 3. Path 3 is of the same length as Path 1 but is now slightly undesirable than Path 1 because of the two additional turns.

7.5.3.1 Path Scores

The scores of the three paths P1, P2 and P3 for Test case 3 are shown in Table 7-13. In Models 2 – 5, the scores of paths P1 and P3 are only slightly different from each other. The small difference in the path scores are due to path P3 being slightly longer than path P1 by about 0.1 metre. An attempt was made to make the lengths of both paths equal; however a 0.1 metre difference could not be avoided. There is a more dominant difference between the scores of paths P1 and P3 in Models 6 – 11 which is due to the addition of the turns along path P3. Path 3 is also unfavourable due to sharp turns. The weight for the angles and turns increases from Model 6 – 11 (Table 7-1) and hence the score of path P3 increases as well.

Table 7-13: Path scores and the percentage difference of each path from the best path score for models 2 to 11 applied to test case 3 using Non Sequential Wayfinding. The viable paths in each model are highlighted grey.

	Model 2		Model 3		Model 4		Model 5	
	Path Score	Percentage Difference	Path Score	Percentage Difference	Path Score	Percentage Difference	Path Score	Percentage Difference
P1	99.91	13.65	94.39	0.00	97.72	3.93	101.95	2.44
P2	86.26	0.00	100.0	5.61	93.87	0.00	99.45	0.00
P3	100.00	13.74	94.43	0.04	97.77	3.99	102.00	2.50

	Model 6		Model 7		Model 8		Model 9	
	Path Score	Percentage Difference	Path Score	Percentage Difference	Path Score	Percentage Difference	Path Score	Percentage Difference
P1	95.43	1.55	91.05	5.15	81.14	8.93	76.81	12.14
P2	93.96	0.00	86.36	0.00	73.89	0.00	67.48	0.00
P3	96.07	2.19	94.00	8.12	87.64	15.68	85.20	20.80

	Model 10		Model 11	
	Path Score	Percentage Difference	Path Score	Percentage Difference
P1	72.73	14.62	74.08	14.73
P2	62.09	0.00	63.16	0.00
P3	84.06	26.13	84.91	25.61

7.5.3.2 Non Sequential Wayfinding (NSW) Results

The average results of the Non Sequential Wayfinding (NSW) applied to Test case 3 is shown in Table 7-14. In Models 3 – 7 there is a good distribution of people along the paths available. In Model 8, the path with many turns, P3, has been ignored by all the agents. The only difference between paths P1 and P3 is the introduction of turns along P3. The turns have thus made the path P3 unfavourable. In Models 9 – 11, the weight distribution is such that all agents only take the shortest distance path.

Table 7-14: Average number of people taking paths P1 – P3 for 20 repeat simulations of each model for Test case 3 using Non Sequential Wayfinding.

NSW	Average CWT (seconds)	Average Distance (m)	Average PET (seconds)	Number of people Using Path1	Number of people Using Path2	Number of people Using Path3	Total Evacuation Time (seconds)
Model 1	80.71	76.92	178.91	0	300	0	275.32
Model 2	80.71	76.92	178.91	0	300	0	275.32
Model 3	44.90	80.82	144.88	102	100	98	211.54
Model 4	44.76	80.74	144.63	100	101	99	214.22
Model 5	45.00	81.02	145.12	105	98	99	214.71
Model 6	45.10	80.69	144.95	95	105	100	212.41
Model 7	45.12	80.62	144.92	89	105	105	211.85
Model 8	47.76	80.38	147.84	140	160	0	215.47
Model 9	80.71	76.92	178.91	0	300	0	275.32
Model 10	80.71	76.92	178.91	0	300	0	275.32
Model 11	80.71	76.92	178.91	0	300	0	275.32

7.5.3.3 Sequential Wayfinding with LP Time Estimation (SWLP) – Results

Table 7-15: Average number of people taking paths P1 – P3 for 20 repeat simulations of each model for Test case 3 using Sequential Wayfinding and local prescribed time estimation.

SWLP	Average CWT (seconds)	Average Distance (m)	Average PET (seconds)	Number of people Using Path1	Number of people Using Path2	Number of people Using Path3	Total Evacuation Time (seconds)
Model 1	80.71	76.92	178.91	0	300	0	275.32
Model 2	80.71	76.92	178.91	0	300	0	275.32
Model 3	48.99	85.94	152.63	154	9	137	219.08
Model 4	47.50	78.54	146.11	67	186	47	209.66
Model 5	49.69	78.88	148.69	89	198	13	214.45
Model 6	48.79	79.24	148.06	99	189	12	212.09
Model 7	56.69	78.26	155.45	64	223	13	228.77
Model 8	67.82	77.34	166.24	37	263	0	253.67
Model 9	80.71	76.92	178.91	0	300	0	275.32
Model 10	80.71	76.92	178.91	0	300	0	275.32
Model 11	80.71	76.92	178.91	0	300	0	275.32

The average results of the Sequential Wayfinding with LP time estimation (SWLP) method is shown in Table 7-15. In model 1 there is no wayfinding and hence all agents take the shortest distance path P2. In model 2 the introduction of wayfinding has not made a difference because the shortest distance path P2 is much shorter than paths P1 and P3. In model 3, since time is the only criterion influencing wayfinding majority (97%) of the agents take the least time paths P1 and P3. In models 4 – 7, the introduction of distance as one of the wayfinding criteria has made the least distance path P2 more favourable than P1 and P3. Another reason for path P2 being used more in the sequential wayfinding mode than in the non-sequential model (see Table 7-14) is that the agents are now able to consider the local congestion in room 40 (see Figure 7-11). In model 5, more agents have chosen path P2 (30%) than path P3 (4%) because '*going right'* criterion has more weight (10.2) than the '*going left'* (5.9) criterion. Though '*going right'* and '*going left'* criteria have lower weight (16.1%) than time (46.7%) and distance (37.5%) they still have a major influence in the route choices of the agents. The shortest distance path P2 is still the favourite, however the right and left paths are being chosen as there are less agents using it. In models 6 – 7, path P2 is being increasing used as this path is not only more favourable in terms of turns and angle but is also the shortest leg first path in room 40 (see Figure 7-11). Though distance and time are the major factors influencing wayfinding, the other criteria also influence the path choices of the agents. In models 8 to 11, turns, angles and shortest leg first criteria have a higher weight thus making the shortest distance path P2 the only viable path.

7.5.3.4 Sequential Wayfinding with LL Time Estimation (SWLL) – Results

The average results of the Sequential Wayfinding with LL time estimation (SWLL) is shown in Table 7-16. The Local-Local (LL) time estimation results in a more dynamic model making the least used paths more favourable. In model 3, more people (5%) have used path P2 than with Local-Prescribed (LP) time estimation. Similarly, in models 4 – 7, the least used path P3 (see Table 7-15) is used by significantly more people with LL time estimation. In Models 5 to 7, the right-handed Path P1 is being used by more people than the left handed Path P2 since these models have higher weights for the *going right* criterion than for the *going left* criterion. In Models 8 to 11, only Paths P1 and P2 are being used because the additional turns on Path P3 make it highly unfavourable. These models have a very higher weight for angles and turns than the other models.

Table 7-16: Average number of people taking paths P1 – P3 for 20 repeat simulations of each model for Test case 3 using Sequential Wayfinding and Local-Local time estimation.

SWLL	**Average CWT (seconds)**	**Average Distance (m)**	**Average PET (seconds)**	**Number of people Using Path1**	**Number of people Using Path2**	**Number of people Using Path3**	**Total Evacuation Time (seconds)**
Model 1	80.71	76.92	178.91	0	300	0	275.32
Model 2	80.71	76.92	178.91	0	300	0	275.32
Model 3	50.43	86.45	154.97	138	25	137	224.74
Model 4	45.28	81.21	145.50	106	97	97	214.14
Model 5	45.01	81.02	145.12	115	104	81	214.71
Model 6	45.32	81.06	145.54	111	103	86	212.74
Model 7	45.98	79.54	145.29	103	161	36	211.03
Model 8	51.08	79.42	150.58	101	199	0	215.37
Model 9	52.64	79.27	152.17	93	207	0	218.02
Model 10	50.06	79.60	149.72	105	195	0	214.89
Model 11	70.07	77.33	168.35	33	267	0	254.77

7.5.4 Test case 4

The evacuation of the Station nightclub under different conditions were analysed in Chapter 3. This geometry (Figure 7-12) is now revisited and the simulation results with and without the wayfinding model integrated in buildingEXODUS is analysed. The focus here is not to model the actual evacuation of the Station nightclub during the fire but to analyse the influence of wayfinding in the evacuation simulation results.

The main purpose of simulating this test case is to demonstrate the capability of the wayfinding model to work with signage. Therefore, additional buildingEXODUS features have been turned on for the test case 4. All agents start with knowledge of the main exit alone. However, when they fall within the Visibility Catchment Area (VCA) of any of the six exit signs they gain knowledge of that exit. In buildingEXODUS without the wayfinding model, agents only gain knowledge of that exit and the shortest route to that exit. With the introduction of the wayfinding model, the difference is that the agents' cognitive map is updated to include knowledge of the sub optimal routes to that exit as well. The agents then recalculate the path costs of all the paths in their knowledge and choose an alternate path if it is more favourable than continuing along the present path.

Another new buildingEXODUS feature that was not used in the previous test cases will be used in this case – agents redirection due to congestion. When agents experience congestion and their patience value increases beyond a certain threshold, they are allowed to recalculate their path costs and choose a different path. These features are not new to evacuation models and buildingEXODUS, however there is a difference in the way they have been implemented in the wayfinding model. Evacuation models as they exist now use formulas and allow agents to redirect to a different exit on falling within VCA's or on experiencing congestion. However, in the wayfinding model the agents recalculate the path costs (see Section 7.2.3.2) and choose an alternate path. Therefore, a major difference introduced by the wayfinding model is that agents now select routes rather than exits.

Two scenarios are being investigated in this section – Scenario 1 and Scenario 2. Scenario 1 does not use wayfinding whereas Scenario 2 uses Model 7 (see Table 7-1) for the weight distribution and the Sequential Wayfinding Local-Local time estimation (SWLL) wayfinding mode. Model 7 has been chosen from Models 2 to 11, as the weight distribution in this model is based on the 'three criteria' analysis of the rating tasks which is considered to be the most realistic distribution of weights (see Chapter 6, Section 6.5.4). Both scenarios make use of signage, redirection due to signage, redirection due to congestion, the same geometry, population and population characteristics. Though both the scenarios have a mechanism to implement redirection due to signage and redirection due to congestion, the methodology used for redirection is different. These features were discussed in Chapter 3, Section 3.6.1.4. The difference in the implementation of these features with the introduction of the wayfinding model will be described next.

In the buildingEXODUS model, when signage is used, there are two circumstances under which the agents could redirect:

1. On falling within the Visibility Catchment Area (VCA)
2. On encountering congestion around the exit

In the first instance agents redirect to the nearest exit when they fall within the VCA of a sign pointing to a new exit they were unaware of. In the second instance, when they encounter congestion, agents would choose the exit that takes the least time. With the introduction of the wayfinding model (see Chapter 7), the major difference introduced is that the agents will have knowledge of a set of routes to the exits they are aware of and choose the route that is optimal in terms of the set of wayfinding criteria (see Section 7.2.3) and not just distance and time. The key differences in the buildingEXODUS model due to the introduction of the wayfinding model has been summarised in Table 7-17.

Figure 7-12: The Station nightclub modelling using buildingEXODUS.

Table 7-17: Difference between the working of buildingEXODUS without wayfinding and with the introduction of wayfinding.

	buildingEXODUS without wayfinding (Scenario 1)	**buildingEXODUS with wayfinding (Scenario 2)**
Route knowledge	They are aware of the shortest route to exits.	They are aware of the K shortest routes to the exits. Where K is a positive integer.
Route choice on falling within VCA	Shortest route to nearest exit	Optimal routes based on wayfinding criteria
Route choice on encountering congestion	Shortest route to the exit taking the least time	Optimal route based on the wayfinding criteria

The experimental set up of The Station nightclub in this section is similar to the OS3 scenario with the important settings described in Table 7-18. The occupant distribution is as specified in Chapter 3, Section 3.6.1.1. All agents have instant or zero response times. Agents start with knowledge of the main door alone and gain knowledge of other doors when they fall within the Visibility Catchement Area (VCA) of the signs. The occupant redirection due to congestion has been turned on which enables agents experiencing congestion around their target exit to choose another exit if it is more optimal. The fire data has not been coupled for these scenarios.

Table 7-18: Simulation settings scenarios 1 and 2 for test case 4.

Exit Selection	Redirection due to congestion	Exit open/close times	Response Times	Hazards	Population
Signage	Yes	All exits open throughout the simulation	Zero or instantaneous	No	Maximum population density as defined by building Codes See Chapter 3, Section 3.6.1.1

Table 7-19: Average evacuation statistics of 20 simulation runs of The Station nightclub with and without wayfinding.

Models	Kitchen Door	Bar Door	Main Door	Platform Door	Total Evacuation time	Cumulative Wait time	Average Distance Travelled
Scenario 1 (Without Wayfinding)	34	17	312	77	163.02	36.35	37.99
Scenario 2 (With Wayfinding)	48	27	234	131	132.03	26.64	33.24

Table 7-19 shows the average results of 20 simulations of the Station nightclub with and without wayfinding. The total evacuation time has decreased by 19 % with the introduction of the wayfinding model. The main door usage has decreased by 17 % with wayfinding which is the major factor contributing to the decrease in the total evacuation time. It is interesting to observe that the main door is being used by less people in Scenario 2 than in Scenario 1. In order to understand the difference in the exit usage, let us consider the differences in the two scenarios. Conceptually, the major difference is that agents choose exits in scenario 1 whereas with wayfinding agents choose routes rather than exits. The Station nightclub geometry is very simple with only one route to the exits and hence this could not have been the cause for the difference. The other major difference is that in scenario 1, agents choose the nearest exit on falling within the VCA whereas in scenario 2 agents choose the route based on the wayfinding criteria specified in Section 7.2.3.1. Amongst these factors time is a very important one which has influenced more agents to choose less used exits/routes. Therefore, the less used exits in scenario 1 – the kitchen exit, bar exit and platform exit have been used by more agents in scenario 2. The platform exit has been used almost two times more in scenario 2 which is the main reason for the reduction in the total evacuation time.

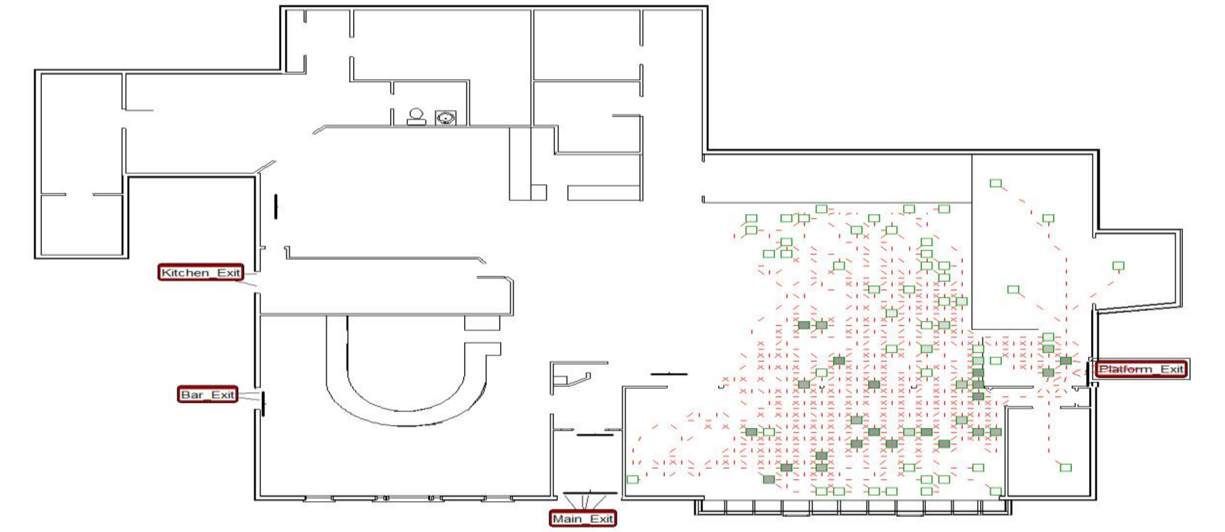
Another reason for fewer agents choosing the main exit and more agents choosing the platform exit in scenario 2 is: initially all agents start with the main exit knowledge and hence move towards the main exit. By the time they fall within the VCA of the platform exit majority of the agents would thus have moved towards (closer to) the main exit. In scenario 1, agents choose the nearest exit in their exit knowledge and hence majority would have chosen to use the main exit. In scenario 2, agents choose the exit based on time and other factors with time being the major factor. Since the platform exit is being used by much fewer agents, more agents have preferred to use it in scenario 2 than in scenario 1. The wayfinding techniques used in Scenario 2 thus has a better distribution of people using the main and platform door which has decreased the total evacuation times.

Table 7-20 shows the times of the first and last usage of the exits in test case 4 for scenarios 1 and 2. In both scenarios the main exit is the last to finish. The other exits have been open for longer times in scenarios 2 especially the platform door. The sequential wayfinding with local-local time estimation used in scenario 2 is very dynamic encouraging agents to make more use of less used exits which is a reason for all exits to be more active in scenario 2 than in scenario 1.

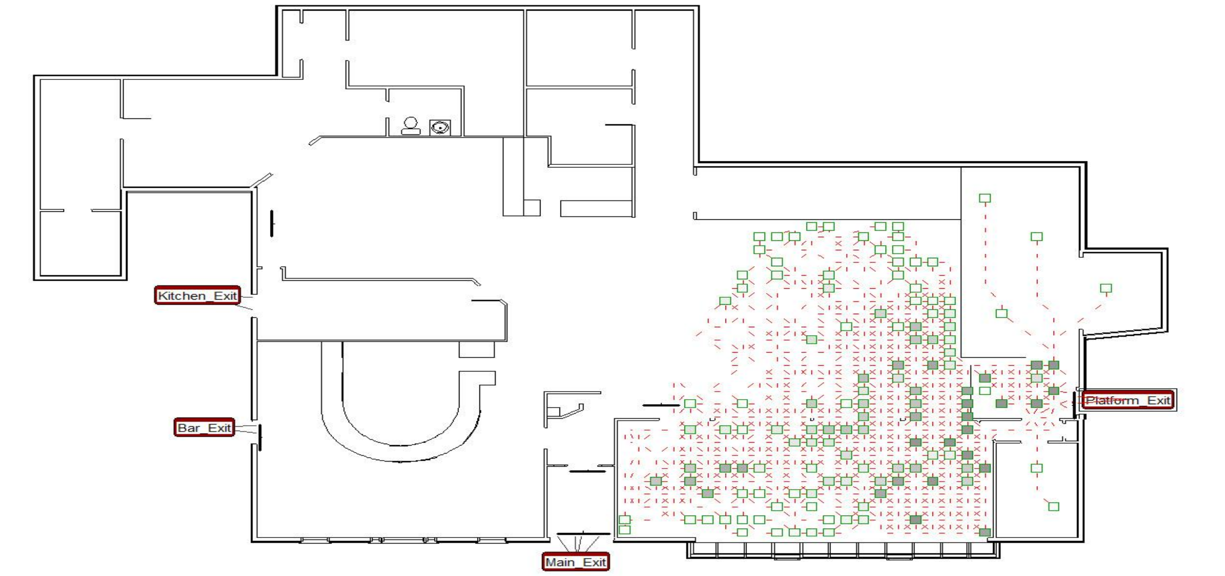
Table 7-20: First and last used times of the exits in Scenarios 1 and 2 for test case 4.

Scenarios	Kitchen Door		Bar Door		Main Door		Platform Door	
	First Used (seconds)	Last Used (seconds)	First Used (seconds)	Last Used (seconds)	First Used (seconds)	Last Used (seconds)	First Used (seconds)	Last Used (seconds)
Scenario 1	8.6	41.9	4.7	144.1	6.7	162.8	4.2	85.5
Scenario 2	6.2	54.4	5.0	112.0	7.0	130.7	4.8	124.0

Figure 7-13 shows the initial locations of the agents choosing the platform exit in scenarios 1 and 2. Though the area of the initial location of the agents is similar more agents have chosen the platform exit in scenario 2 than in scenario 1. The main reason for the difference is that in scenario 1 distance was the only criterion influencing the exit choice whereas in scenario 2 distance and time are the major influential factors which has made the least used exits (the platform, bar and kitchen exit) more popular. Whereas in scenario 1, majority of the agents using the platform exit are closer to it; in scenario 2, agents slightly away from the platform exit have also used it.



(a) Scenario 1



(b) Scenario2

Figure 7-13: Initial locations of the agents using the platform exit (a) scenario 1 without wayfinding and (b) scenario 2 with wayfinding.

7.6 Conclusions

The development of the building wayfinding model was described in this Chapter. The four stages in the wayfinding model: spatial representation in terms of a graph, path planning by applying choice set generation algorithms, decision making (path selection) by the agents and path execution/refinement has been described in Section 7.2. The wayfinding criteria analysed in Surveys 1 and 2 (see Chapter 5 and 6) were implemented as Route Preference Criteria (RPC) within the wayfinding model (see Section 7.2.3.1). The agents select a path from the set of paths assigned to them by considering the normalised values of the different wayfinding criteria and applying the Weighted Sum Model (see Section 7.2.3.2).

Two different modes of wayfinding were introduced – Non Sequential Wayfinding (NSW) and Sequential Wayfinding (SW) (see Section 7.2.4). In the NSW mode, agents are assigned a path from their initial position which they follow without changing the path en route. The SW mode is more dynamic allowing the agent to re-evaluate their path choice sequentially at each room. Time (RPC_2) is the criterion which changes dynamically as the simulation progresses. Two different time estimation methods were introduced in the SW mode – Local-Prescribed (LP) and Local-Local (LL) time estimation to allow agents to dynamically alter their route selection based on the local congestion. However, in SW the current path score is decreased by 10% to make it more preferable representing a person's preference to adhere to the original route choice. Revisiting same locations is penalised by increasing the score of the paths involving the previously visited node (location) by 10%. The SW model is thus a sophicsticated model representing human decision making ability using Multi Criteria Decision Analysis (MCDA) [Triantaphyllou, 2000] techniques such as WSM , their ability to dynamically re-evaluate routes and their ability to remember the previously visited locations/paths.

The integration of the coarse node wayfinding model with the fine node buildingEXODUS model has been described in Section 7.3. The wayfinding model is responsible for assigning paths consisting of a set of target nodes to the agents. The buildingEXODUS model is responsible for navigating the agents from target node to target node using the distance map [Galea, et al., 2006]. The buildingEXODUS model also triggers events when an agent reaches his target node or on encountering congestion or on gaining knowledge of a new exit by means of signs. The wayfinding model listens and assigns a new route to the agent if it is more favourable than the current route considering the local congestion.

Eleven models were introduced in Section 7.4. Model 1 is representative of how the buildingEXODUS model works (default settings with all exits having equal potentials) without wayfinding. Models 2 – 9 follow possible weight distributions based on the data collected from Questionnaires 1and 2. Models 10 – 11 are based on past wayfinding studies by Golledge [Golledge, 1995a, b]. The weight distribution in Model 7 can be considered to be the best as it is based on the 'three criteria' analysis of the rating tasks in Questionnaire 2 (see Chapter 6, Section 6.5.4).

Four test cases were considered for demonstrating the working of the wayfinding model. The evacuation simulation results of the test cases were shown in Section 7.5. These simulations were run under three regimes – Non Sequential Wayfinding (NSW), Sequential Wayfinding with LP time estimation (SWLP) and Sequential Wayfinding with LL time estimation (SWLL). The eleven models with different weight distributions for the wayfinding criteria were applied under each regime and the results were analysed.

If agents within evacuation simulations are simply permitted to select the shortest exit path, unrealistic evacuation dynamics may result leading to over use of particular paths with associated predicted evacuation times being unreliable. The introduction of wayfinding into evacuation simulation potentially overcomes this problem by generating more sophisticated exiting behaviours resulting in improved dynamics in the occupant flow dynamics. The wayfinding approach adopted here, based on actual data collected in this thesis, demonstrates the impact that wayfinding can have on evacuation simulation. Even the introduction of somewhat simplistic Non Sequential Wayfinding produces significantly more balanced exiting behaviour and route selection when compared to situations in which agents simply follow a shortest exit route. The more sophisticated Sequential Wayfinding algorithm, in which agents are capable of reassessing their exit routes and effectively "change their minds" as to which path they adopt offers far greater realism. The redirection decisions are based on congestion, with time estimations for congestion at remote internal exits along the exit path being based on either fixed default values (Local-Prescribed) or on local experienced conditions (Local-Local). The later approach producing more dynamic and arguably more realistic results with agents having a higher preference for less congested paths. The Sequential Wayfinding algorithm also takes into consideration people's preference for the originally chosen path and penalties for retracing paths. The introduction of wayfinding has in general produced reduced evacuation times and congestion with all available paths being better utilised by the agents in the simulation.

8 Conclusions

This chapter provides a summary of the conclusions of this thesis. In Section 8.1 the questions posed in Chapter 1 are revisited focussing on how they have been addressed in this thesis. The major results and findings of the thesis are then presented in Section 8.2.

8.1 Summary

Existing evacuation/circulation models have simplified wayfinding by modelling agents choosing the shortest paths to the exits. Distance and time are the only wayfinding factors considered. The wayfinding model developed in this thesis consists of ten wayfinding factors (see Chapter 7, Section 7.2.3.1) which were identified by a review of urban wayfinding studies. These factors were then analysed by conducting two questionnaires to test their influence in buildings. The data obtained from the questionnaires were then incorporated into the wayfinding model that was developed in this thesis. Following are the features that distinguish this wayfinding model from any other implemented in an evacuation/circulation model:

- Application of graph search algorithms such as the Yen's algorithm to generate a choice set of routes for the agents.

- The development and analysis of wayfinding surveys which analyse the influence of ten wayfinding criteria.

- The integration of the results from the surveys into the wayfinding model.

- Modelling the decision making ability of people using normalisation and the weighted sum model (see Chapter 7, Section 7.2.3.2)

- A wayfinding model that consists of many features such as non sequential wayfinding, sequential wayfinding with local-prescribed time estimation and sequential wayfinding with local-local prescribed estimation (see Chapter 7, Section 7.2.4)

The main goal of the thesis was to answer Question 1 posed in Chapter 1 namely "How to represent human wayfinding in computer models". This question is answered by the following chapters: Chapter 2 analysed the existing literature on wayfinding, route choice and evacuation/circulation models; Chapter 3 looked at the wayfinding features in evacuation/circulation models by modelling the Station fire incident in buildingEXODUS; Chapter 4 described the spatial representation and choice set generation techniques developed for the wayfinding model; Chapters 5 and 6 described the questionnaires carried out in this thesis to determine the wayfinding factors and establish their relative importance; Chapter 7 provided details of the wayfinding model developed and its application on hypothetical and real buildings. The remainder of this section answers the questions posed in Chapter 1.

Question 1: How to represent human wayfinding in computer models?

A literature review of wayfinding models and wayfinding features in evacuation/circulation models was performed as described in Chapter 2. The wayfinding models studied such as Navigator, Traveller, Tour were very complicated and their purpose was to mimic the actual thought process of humans (see Chapter 2, Section 2.6). The wayfinding features in evacuation/circulation models on the other hand were very simplistic. The wayfinding model developed in this thesis is in between these two approaches: it is a sophisticated wayfinding model which efficiently models human wayfinding within evacuation/circulation models by considering the key factors that affect wayfinding.

In Chapter 3, a real incident was modelled using buildingEXODUS to identify the existing wayfinding features and to perform a requirements analysis for the wayfinding model to be developed. The limitations of the buildingEXODUS model were presented in Chapter 3, Section 3.6. Some of the limitations such as path assignment, wayfinding attributes for the agents have been implemented within the buildingEXODUS model. However, some of the features such as occupant redirection due to smoke has been left as future work. The Station nightclub enclosure is a simple enclosure with only one route for the different exits in the building. The wayfinding model in this thesis has been designed for more complicated enclosures where there is more than one route to the exits. In Chapter 7, this capability of the wayfinding model was demonstrated by considering three complex test cases with multiple routes to the same exit. The application and modification of the wayfinding model multi-floor buildings may be considered in future.

Path planning algorithms existing in the literature were studied to determine the best algorithm to provide a choice of routes to the agents in the wayfinding model. Yen's algorithm was the most suitable as it was capable of finding the K shortest paths. Novel algorithms (Algorithms 1 and 2) were also developed and their performance with the modified Yen's algorithm (Algorithm 3) was compared (see Chapter 4). Algorithm 3 was found to be the best algorithm in terms of the routes found and its computational order was similar (linear) to the order of the other algorithms as well.

Questionnaires were then designed to identify the key factors that influence wayfinding within buildings that should be included in the model. The relative importance of the wayfinding factors were established in Chapter 6, Section 6.5. These factors were then introduced into the wayfinding model as described in Chapter 7. Different distribution of weights for the wayfinding criteria were established in Section 7.4. The functioning of the wayfinding model has been demonstrated by applying it on hypothetical and real buildings in Section 7.5.

Question 2: How do existing evacuation/circulation models represent human wayfinding?

Chapter 2 looked at how the various evacuation/circulation models represent wayfinding. It was found that most of the models simplify the wayfinding process by assuming that all agents have perfect knowledge of the structure and hence take the shortest route to the nearest exit. The wayfinding process is also simplified to be an exit choice task where agents use complicated formulas to decide which exit to choose. Hence majority of the existing models consider only distance and time as factors influencing exit choice. Only one of the models (EVACSIM) had wayfinding features resembling the wayfinding model developed for this thesis.

The buildingEXODUS model has more sophisticated wayfinding features such as signage and was studied in more detail in Chapter 3. Several limitations in the wayfinding features in the buildingEXODUS model were identified in Section 3.6. Several existing features in the buildingEXODUS model were useful for the wayfinding model. Features such as spatial graph generation and movement models were utilised by the wayfinding model to apply the path planning algorithms and to have the agents moved physically from one target point to the next.

Question 3: How is the building space represented in wayfinding models?

An overview of the spatial representation techniques used in wayfinding models has been provided in Chapter 2,Section 2.2.2. All the techniques make use of graphs to represent space. The buildingEXODUS model already possessed the ability to create such spatial graphs. Among the spatial graphs, route graphs were determined to be the most suitable. The waypoint nodes in the route graphs were more useful for implementing local navigation of agents (which is handled by buildingEXODUS) and thus were removed to generate a simpler graph for the route choice set generation algorithms. This procedure has been described in Chapter 4, Section 4.2. Such a representation of space is similar to a coarse node representation. However, the coarse node wayfinding model then communicates with the fine node buildingEXODUS model assigning target nodes for the agents.

Question 4: How to generate a choice set of routes?

In Chapter 2, existing literature on path planning techniques and algorithms were analysed. There exist many algorithms to find optimal paths, but very few algorithms exist to generate a choice set of routes. Yen’s implementation of the K-shortest paths problem was found to be the best suited algorithm to generate a choice set of routes. However, a disadvantage of the Yen’s algorithm was that it would have to be run once for every pair of source and target nodes. Algorithm 1, was developed to solve this problem which creates a tree of paths to find all possible routes from all nodes in a graph to multiple destinations. Algorithm 1 had a major drawback since its run time and space complexity was exponential. Heuristics were introduced to make Algorithm 1’s run time and space complexity linear. Algorithm 2, was the quickest of the three algorithms. However, a major drawback of this algorithm is that it produces minimal routes and is especially not suitable for evacuation situations (See Chapter 4, Section 4.5). Finally, in Algorithm 3, the Yen’s algorithm was modified to be used for the connectivity graphs employed in this thesis. Algorithm 3 makes use of a modified Yen’s algorithm to determine the shortest path, the next shortest path and so on until K shortest paths are found. Algorithm 3, due to the nature of the Yen’s algorithm, is capable of finding the K shortest paths whose cost is non-decreasing. This important feature of Algorithm 3 makes it the best algorithm for complex geometries (see Chapter 4, Section 4.7).

Question 5: How to model the movement of the agents?

The actual physical movement of the agents is handled by the buildingEXODUS model. However, there is a constant communication between the wayfinding model and the buildingEXODUS model to control the movement of the agents (see Chapter 7, Section 7.3). At the start of the simulation buildingEXODUS passes the spatial information and location of the agents to the wayfinding model. The wayfinding model creates the connectivity graph, applies the sub optimal path planning algorithms, stores the routes in the room nodes and assigns an initial path to the agents in buildingEXODUS. The path is a list of target nodes and buildingEXODUS is responsible for moving the agents from one target node to the next. Two wayfinding modes were implemented in the building wayfinding model. In the non sequential wayfinding mode the agent simply move from one target node to the next. In the sequential wayfinding mode buildingEXODUS notifies the wayfinding model when an agent reaches a target node. The wayfinding model then revaluates the route options for this agent and assigns a new path if it is disadvantageous to stick to the current path. The buildingEXODUS model also alerts the wayfinding model similarly when agents get impatient and when agents learn the existence of a new exit through signage.

Question 6: What factors influence wayfinding in the built environment?

A hypothesis of this thesis is that the factors that influence wayfinding in the urban environment will also influence wayfinding in the built environment. However, the relative importance of the factors might vary. Hence, two surveys were designed and placed online. The results of the survey were analysed (see Chapters 5 and 6) and the weights were introduced into the wayfinding model (see Chapter 7, Section 7.3). The urban wayfinding literature has so far ignored cultural and genetic factors such as driving side and handedness of people. However, the first survey established that the driving side and handedness of people have a significant influence on the paths chosen. The second survey established that the influence of these factors is not quite as significant when compared with other important criteria such as time and distance. However, the simulation results performed in Chapter 7 show that even small weights such as 7.7% and 4.3% applied to ‘right handed’ paths and ‘left handed’ paths significantly influence the path choice of agents in the building wayfinding model. Inclusion of time rather than just distance in the agent redirection due to signage (see Chapter 7, Section 7.5.4) made a significant difference in the evacuation statistics of *The Station nightclub*.

Question7: How to model the decision making ability of people?

There are a number of factors affecting wayfinding decisions as described in Chapters 5 and 6 that people apply on a number of alternatives available such as the different paths in an environment. This is thus a classic Multi-Criteria Decision Analysis (MCDA) problem. Among the various MCDA methods, the Weighted Sum Model (WSM) was chosen as it is simple and best suited for the wayfinding model developed in this thesis (see Chapter 7, Section 7.2.3.2).

In the wayfinding model people make decisions at/in various situations. All agents make a decision at the very start of the simulation. Three wayfinding modes were implemented in buildingEXODUS namely non-sequential, sequential with local-prescribed time estimation and sequential with local-local time estimation (see Section 7.2.4). In the non-sequential wayfinding mode the agents stick to the initially chosen path. In the sequential wayfinding models the agents revaluate their paths at each target node. In addition there are certain circumstances under which agents can re-evaluate their paths: when they become impatient; when they gain knowledge of a new exit. Redirection due to smoke/hazards is left as a future work.

8.2 Results and major findings

The major result of this thesis has been the development of a wayfinding model that can be incorporated within circulation/evacuation modelling tools. The model has been developed using C++ and has been tested using buildingEXODUS. Whereas the other models simplify the wayfinding process by assuming that all agents are familiar with the building and hence take the shortest path to the nearest exit, the wayfinding model integrated in buildingEXODUS produces more sophisticated wayfinding behaviour. A choice set of routes is assigned to the agents in the simulation. Each agent in the model possesses his/her own wayfinding attributes and makes independent decisions on which path to take. They are capable of redirecting on experiencing congestion along the route or when they acquire knowledge of a new path.

In Chapter 3, a real incident ‘The Station fire’ was analysed using buildingEXODUS. The evacuation simulation was coupled with fire data obtained from the SMARTFIRE model. The coupled fire and evacuation results produced the most realistic recreation of the incident using computational tools. The main purpose of studying this incident was to: analyse the behaviour of people in real evacuation situations, study the existing wayfinding features in buildingEXODUS and identify key features required for the wayfinding model. The existing wayfinding features in buildingEXODUS were enumerated in Chapter 3, Table 3-9 and further features to incorporate were discussed in Chapter 3, Section 3.7. The difference between the modelling of this incident by NIST and this thesis has been described in Chapter 3, Section 3.6. The main difference being that NIST did not couple fire with evacuation modelling which has been performed in this thesis.

Most of the existing path planning algorithms deals with optimal path planning optimal in terms of some metric such as distance or time. However, past wayfinding studies show that there are other factors that affect wayfinding such as turns, decision points, etc. Hence the building wayfinding model required a choice set of routes for agents to choose from. An important hypothesis of this thesis is that the path choice is a combination of the wayfinding factors as described in Section 7.1.2.1. Hence it is important to provide a choice set of routes for agents to choose from. Also it is important to determine this choice set before the start of the simulation as determining this during the simulation would slow it down. For example consider 1000 agents in a complex building each performing an algorithm to determine their choice set of routes which would affect the CPU time thus slowing down the simulation. Therefore in this thesis this process has been simplified by pre processing the routes before the simulation starts. Another advantage of pre processing the routes before the start of the simulation is that they can be stored and reused again in multiple simulations of the same geometry. However, this means that paths need to be found from every room in the building. Therefore the choice set generation algorithms developed in this thesis (see Chapter 4) are run before the start of the simulation and determine a choice set of routes from every room in the building. The agents during the simulation on entering a room are assigned routes that exist from that room to the exits that they are aware of. The choice set generation algorithms developed in this thesis could be used in other domains such as operations research and robot path planning as well.

The surveys described in Chapters 5 and 6 test a unique set of criteria from a building evacuation/circulation modelling perspective. The results of the survey confirm the results of other similar studies and disprove some assumptions made in the urban wayfinding field. The surveys confirmed that the major factors influencing building wayfinding were distance and time. However, other factors such as turns, angle, shortest leg first and longest leg first also played an important role in the path selection of agents (see Chapter 7, Section 7.5). The results of these survey's are also expected to be beneficial for researchers in the circulation/evacuation modelling fields and also to building designers.

The influence of the various wayfinding criteria determined from the surveys was then implemented in the wayfinding model. The integration of the wayfinding model within buildingEXODUS has thus resulted in an evacuation/circulation model that can model the routes taken by occupants more realistically than before. The buildingEXODUS model passes the spatial information at the start of the simulation which is used by the wayfinding model to generate a connectivity graph and assign route choice sets to the agents. During the simulation there is constant communication between the fine node buildingEXODUS model and the coarse node wayfinding model. The buildingEXODUS model passes information such as the location of the agents, queue size and triggers events such as target node reached, new exit knowledge gained or congestion experienced. The wayfinding model listens and makes use of the information provided to assign a new route or target node to the agents. There is thus a coupling between the coarse node wayfinding model and the fine node buildingEXODUS model (see Chapter 7, Section 7.3).

The evacuation simulation results with and without the introduction of wayfinding were compared for four test cases in Chapter 7. Without the introduction of wayfinding it was found that all agents chose the shortest path regardless of the congestion experienced. However, with the introduction of wayfinding the agents choose all available routes thus decreasing the evacuation times and congestion despite increasing the average distance travelled by the agents.

The buildingEXODUS model possesses redirection due to signage and redirection due to congestion features. However, the wayfinding model implements these features with a modification. The agents recalculate the path to take whereas previously they recalculate the exit to take. The difference in the evacuation statistics brought about by this modification was demonstrated by the simulation of the Station Nightclub building in Chapter 7, Section 7.5.4.

The wayfinding model also incorporates features such as the memory of the route taken by the agents. This prevents the agent from revisiting places without having a good reason to do so. However, the agent is allowed to retrace a route if he experiences considerable congestion along the present route and he reckons it would be faster to choose an alternative route (see Chapter 7, Section 7.2.4.2). In the wayfinding model, agents are only assumed to have knowledge of the local congestion i.e., queues in the exits in his current room. The agents will not have knowledge of queues at other exits. However, at each room the agent has the choice of redirecting on encountering sufficient congestion along the current route. The extension of the wayfinding model to incorporate redirection due to hazards/smoke has been left for future research.

A wayfinding model has been developed in this thesis that is very effective and brings about significant differences in the evacuation simulation statistics (see Chapter 7, Section 7.5). The wayfinding model is based on actual data that has been collected in this thesis. Evacuation/circulation models as they exist model the exit choice of agents; the wayfinding model developed in this thesis differs by modelling path choice instead of exit choice. The integration of this wayfinding model within buildingEXODUS can thus be expected to produce more realistic results much closer to real human behaviour than other evacuation/circulation models.

9 Future Work

A sophisticated wayfinding model has been developed in this thesis which is more advanced than any other implemented in evacuation/circulation models that are available in the public domain or described in the journal publications. However, the model can certainly be expanded and improved. In this chapter the future work emanating from this thesis is suggested.

9.1 Modelling Assumptions

The surveys carried out in this thesis provided data of value for the building wayfinding model. However, a few assumptions were made in the wayfinding model such as the following which were not covered by the survey:

9.1.1 Estimation of the route preference criteria

In the wayfinding model it is assumed that all agents have perfect knowledge of the various route preference criteria such as distance and time. However, in reality it is unlikely for people to estimate these factors to such great accuracy. There has been some work in the past on how people estimate distance [Wiest and Bell, 1985]. Similar work needs to be carried out for the determination of the other wayfinding factors as well.

9.1.2 Path Choice

In the wayfinding model it is assumed that people randomly choose a path in the set of paths that are within 10 % of the least path score. This is in order to compensate for the accurate estimation of the values as discussed in the previous section. The value 10 here has been chosen arbitrarily and more research needs to be carried out to determine what this number should actually be.

9.1.3 Preference for the initial path

In the wayfinding model when an agent revaluates paths at each room, the initial (current) path score is decreased by 10 % in order to make it more preferable. However, more research needs to be done to determine the real preference people have for their current path under various conditions.

9.1.4 Penalty for turning back

When an agent revaluates paths, he/she is allowed to turn back and retrace his/her movement. However, turning back is penalised by increasing the path scores of those paths that involve retracing by 10 %. Again more research needs to be done to determine under what conditions people will retrace their paths.

9.1.5 Route revaluation

In the building wayfinding model agents re-evaluate routes at each room. This is probably too frequent. More research needs to be carried out to determine how/where/when people revaluate routes i.e. where decisions are made. Also in the wayfinding model all agents choose a complete path whenever a decision is involved. However, in the EVACSIM model agents choose the next target node to go to at each decision point. It would be interesting to compare how such a model compares with the wayfinding model developed in this thesis.

9.1.6 Decision Making

In the building wayfinding model, it is assumed that all agents consider all the routes in the route choice set to decide on a path to take based on ten route preference criteria (see Chapter 7, Section 7.1.2.1). They also have a complete path planned at the start. However, according to Passini [Arthur and Passini, 1992] there are two models of decision making: the optimizing model where people consider all options and chooses an optimal solution; and the satisficing model where an acceptable solution is chosen instead of the optimal based on some crude heuristics. In real life, the wayfinding decisions made by people can be an approximation of one of these models. All agents in the building wayfinding model make use of the concept of the optimizing model. However, more research needs to be performed on the percentage distribution of the number of people using the two models in real life.

9.1.7 Building Familiarity

The wayfinding model implemented in this thesis assumes that all agents are completely familiar with the building. Unfamiliarity of an occupant with a building is modelled simply by assuming that some occupants will have knowledge of certain exits. Fuzziness in the route knowledge may be introduced by randomly assigning knowledge of certain routes only. However, an interesting approach to model the wayfinding of people unfamiliar with a building would be to make agents choose the next location to go based on certain heuristics such as a directional knowledge. For example a person might not know the route to an exit but may know approximately that it is to the south and may start moving along that direction. This is similar to the sequential wayfinding model (see Chapter 7, Section 7.2.4.2) where people make a route decision at each decision point but in this case without having knowledge of the entire path to the exit. An interesting topic for future research would be: How does building familiarity/unfamiliarity affect wayfinding?

9.1.8 Wayfinding Factors

In this thesis, ten wayfinding factors were studied using surveys and implemented in the wayfinding model. These factors were identified as the most important cognitive aspects of wayfinding. In building wayfinding, another important factor is 'social factors'. For example, when evacuating a building due to fire, people first try to find their spouse/children/friends before finding their way out; people may blindly follow a crowd or an authoritative person. Further research is required to determine how 'social factors' affect route choice and how they can be included in this wayfinding model.

9.2 Questionnaire Assumptions

A number of assumptions were made in the surveys carried out for this thesis. A major limitation of the surveys carried out in this thesis is the use of a map based approach i.e. using a 2D plan. Using the map-based approach it was not possible to analyse the effect of people being unfamiliar with a building. Other techniques such as usage of virtual environment or real world experiments should be used in order to determine the effect of unfamiliarity with a building. Group effect, such as the influence of other people in a building can also be tested using these techniques. Another drawback of the map based approach is that, the participants are only being tested on their wayfinding behaviour on a map i.e. in an artificial situation which may be different from their wayfinding behaviour in the actual environment. However, from the comments of the participants it was observed that some had a vivid imagination and looked at this as a real exercise than just a map based questionnaire.

9.3 Spatial Representation

In the wayfinding model it was necessary to introduce internal exits in order to differentiate compartments. However, there exist techniques which can automatically recognise compartments without having to introduce an internal exit for each compartment [Srinivasan and Nockman, 1987]. More efficient methods of spatial representation that avoids the need to place an internal exit to separate compartments needs to be introduced.

The wayfinding model developed in this thesis has been integrated into the fine node buildingEXODUS model. The integration of the model within a coarse or continuous representation or a hybrid of fine, coarse and continuous space [Chooramun, et al., 2010] could be considered in future research.

9.4 Optimizing Evacuation Time

This thesis has only considered realistic modelling of human wayfinding behaviour. However, an interesting area of study would be optimal route assignment to reduce evacuation times using network flow theory [Ahuja, et al., 1993]. In network flow theory each arc has a capacity which in this research could be considered to be the maximum number of people an arc can accommodate. This feature could be utilised to assign optimal routes to the agents. In the wayfinding model implemented in this thesis, a corridor of width 2 meter will have the same preference as a corridor of width 4 meters. Future implementation should take the capacities of corridors/rooms into account.

9.5 Occupant redirection due to hazards

Occupant redirection due to hazards was identified as one of the requirements for the wayfinding model in Chapter 3. There exist data sets [Wood, 1990] [Bryan, 1996] on how people redirect due to smoke. The wayfinding model is capable of producing alternate route for agents to take when they encounter smoke i.e. agents could be modelled to take routes containing less hazards/smoke. However, due to time constraints this has not been implemented within the buildingEXODUS model. Also further research is required to determine how people wayfind under emergency circumstances.

9.6 Multi floor buildings

The building wayfinding model has been designed for single floor buildings alone. Provision to include multiple floors needs to be introduced. With the introduction multiple floors there is additional complexity involved by the introduction of stairs, escalators and elevators. This will lead to an even more sophisticated wayfinding model involving different modes of transport between floors.

9.6.1 Route Choice set Generation

Three algorithms were developed in this thesis to provide a choice of set of routes to the agents in the wayfinding model. Following are the future works related to the graph search algorithms used in this thesis:

9.6.1.1 Directed/Undirected graphs

The connectivity graph employed in this thesis is an undirected graph. However, it would be useful to make it a directed graph. For example escalators can only move in one direction; checkpoints at railway stations allow people in one direction only. Therefore, in future the connectivity graph would have to be made a directed graph where each arc has a direction. The Algorithm 3 which is a modification of the Yen's algorithm is capable of working with directed graphs. If buildingEXODUS which passes the spatial information to the wayfinding model can be made to pass the directional attribute of the arcs as well, then Algorithm 3 can accurately find paths in the directed connectivity graph. However, this will be considered for future research.

9.6.1.2 Computational Complexity

Algorithm 3 which is a modification of the Yen's shortest path algorithm was found to be the best algorithm in term of the number and quality of the routes determined (see Chapter 4, Section 4.7). However, the original implementation [Martins and Pascoal., 2003] performs vastly better than its modified version implemented in this thesis in terms of space/memory complexity. This is due to the additional attributes carried by the nodes and arcs in the wayfinding model. Optimizing Algorithm 3 for the connectivity graph used in the wayfinding model will be considered in future research.

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APPENDICES

Appendix A – Publications produced during the course of the Research Project

The work produced as part of this thesis has been published in three conference proceedings. The author of this thesis is either the first author or one of the co-authors of these publications. Table 1 shows the list of the publications and the corresponding chapters.

Table 1: List of publications and the corresponding chapters

#	Publications	Chapters
1	Galea, E.R., Wang, Z., Veeraswamy, A., Jia, F., Lawrence, P.J. and Ewer, J., 2009. Coupled Fire/Evacuation Analysis of The Station Nightclub Fire. Fire Safety Science, 9, pp.465-476.	Chapter 3
2	Veeraswamy, A., Lawrence, P.J. and Galea, E.R., 2009. Implementation of Cognitive Mapping, Spatial Representation and Wayfinding Behaviours of People within Evacuation Modelling Tools. Fourth International Symposium of Human Behaviour in Fire, Interscience Communications, pp. 501-512.	Chapter 7
3	Veeraswamy, A., Galea, E. and Lawrence, P., 2011. Wayfinding Behaviour within Buildings – An International Survey. 10th International IAFSS Symposium, University of Maryland, USA, 19-24, June 2011.	Chapter 5

The first page of each of these publications is presented in the rest of this section.

A.1 Coupled Fire/Evacuation Analysis of the Station Nightclub Fire.

This paper was presented in the Ninth International Symposium on Fire Safety Science, Karlsruhe Institute of Technology, Karlsruhe, Germany, September 21 – 26, 2008.

Coupled Fire/Evacuation Analysis of the Station Nightclub Fire

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ABSTRACT

In this paper, coupled fire and evacuation simulation tools are used to simulate the Station Nightclub fire. This study differs from the analysis conducted by NIST in three key areas; (1) an enhanced flame spread model and (2) a toxicity generation model are used, (3) the evacuation is coupled to the fire simulation. Predicted early burning locations in the full-scale fire simulation are in line with photographic evidence and the predicted onset of flashover is similar to that produced by NIST. However, it is suggested that both predictions of the flashover time are approximately 15 sec earlier than actually occurred. Three evacuation scenarios are then considered, two of which are coupled with the fire simulation. The coupled fire and evacuation simulation suggests that 180 fatalities result from a building population of 460. With a 15 sec delay in the fire timeline, the evacuation simulation produces 84 fatalities which are in good agreement with actual number of fatalities. An important observation resulting from this work is that traditional fire engineering ASET/RSET calculations which do not couple the fire and evacuation simulations have the potential to be considerably over optimistic in terms of the level of safety achieved by building designs.

KEYWORDS: fire investigation; CFD; compartment fires, egress, hazard evaluation

INTRODUCTION

On the night of February 20, 2003, a deadly fire occurred in The Station Nightclub at 211 Cowesett Avenue, West Warwick, Rhode Island, USA [1]. One hundred people lost their lives in the fire with more than two hundred other people being hurt from burn, respiratory insult and physical trauma. The National Institute of Standards and Technology (NIST) established a National Construction Safety Team (NCST) to determine the likely technical cause or causes of the building failure that led to the high number of casualties in the nightclub fire [1]. The fire was investigated using a real-scale experimental mock-up representing approximately 20% of the nightclub and was computationally studied [1, 2] using the Fire Dynamic Simulator (FDS) [3]. In the FDS simulations, the ignition of burnable surfaces was determined solely by its ignition temperature and the burning rate was determined by the heat of vaporisation and the received heat. The FDS simulation of the mock-up experiment was intended to calibrate the model, fixing key model parameters by matching simulation results with experimental data. These simulations suggested that a heat release rate (HRR) of 1500kW/m^2 and a maximum burning rate of 0.008kg/m^{2}s were appropriate for the initial burning locations and burnable surfaces respectively. These parameters were then used to investigate the full-scale nightclub fire by NCST [1, 2].

In the FDS simulations of the mock-up test and the actual nightclub fire a single ignition criterion (surface ignition temperature) was applied. This leads to the use of a high level of heat release rate at the prescribed burning locations in order to create a high temperature area to sustain continuous burning and fire spread. Furthermore, the initial burning area is sensitive to this HRR. In addition, the FDS calculations ignored the main toxic fire gases CO and HCN, which can have fatal effects on building occupants [1, 2]. Using the FDS simulations and a temperature tenability threshold of 120 ^{O}C to evaluate the effect of heat on escape capability, NIST derived an available safe egress time (ASET) of 90 sec based on the predicted lower layer temperatures in the fire simulation [1]. Several evacuation tools were used to analyse the required safe egress times (RSET) and the number of people that remained within the building at the determined ASET. However, as the evacuation simulation was not coupled to the fire simulation, the impact of fire hazards on the evacuating occupants was not directly considered.

In this study we investigate the nightclub fire by coupling the Computational Fire Engineering (CFE) tools, buildingEXODUS [4,5] and SMARTFIRE [6-9] in an attempt to address the issues identified above. The coupling is such that the fire predictions directly impact the performance of the evacuating population

FIRE SAFETY SCIENCE–PROCEEDINGS OF THE NINTH INTERNATIONAL SYMPOSIUM, pp. 465-476
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A.2 Implementation of Cognitive Mapping, Spatial Representation and Wayfinding Behaviours of People Within Evacuation Modelling Tools

This paper was presented in the Fourth International Symposium on Human Behavior in Fire, Robinson College, Cambridge, UK, 13 – 15 July 2009.

Human Behaviour in Fire Symposium 2009

IMPLEMENTATION OF COGNITIVE MAPPING, SPATIAL REPRESENTATION AND WAYFINDING BEHAVIOURS OF PEOPLE WITHIN EVACUATION MODELLING TOOLS

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ABSTRACT

Within the building evacuation context, wayfinding describes the process in which an individual located within an arbitrarily complex enclosure attempts to find a path which leads them to relative safety, usually the exterior of the enclosure. Within most evacuation modelling tools, wayfinding is completely ignored; agents are either assigned the shortest distance path or use a potential field to find the shortest path to the exits. In this paper a novel wayfinding technique that attempts to represent the manner in which people wayfind within structures is introduced and demonstrated through two examples. The first step is to encode the spatial information of the enclosure in terms of a graph. The second step is to apply search algorithms to the graph to find possible routes to the destination and assign a cost to the routes based on their personal route preferences such as "least time" or "least distance" or a combination of criteria. The third step is the route execution and refinement. In this step, the agent moves along the chosen route and reassess the route at regular intervals and may decide to take an alternative path if the agent determines that an alternate route is more favourable e.g. initial path is highly congested or is blocked due to fire.

INTRODUCTION

Within the building environment, wayfinding describes the process by which an individual located within a complex enclosure decides on a path or route in order to reach a goal location. Within the building evacuation context, wayfinding describes the process in which the individual attempts to find a path which leads them to relative safety, usually the exterior of the enclosure.

The process of wayfinding requires the individual to have a cognitive or mental map of the space. Cognitive mapping has been defined as the process by which an individual acquires, stores, recalls and decodes spatial information[1]. According to the Landmark, Route, Survey (LRS) model[2], cognitive mapping involves individuals first extracting key landmarks from the environment. Within the built environment, these landmarks may be internal exits, external exits, rooms, escalators, stairs, lifts, sculptures, etc. Route knowledge then develops as the individual associates landmarks with routes and a mental map of the required route is formed. Survey or configurational knowledge is said to have been attained when the map is more complete and the person can find a path from any point in a building to any other point even though he/she may not have traversed that path.

A.3 Wayfinding Behavior within Buildings – An International Survey

This paper was published in the Tenth International Symposium on Fire Safety Science, University of Maryland, USA, 19 – 24 June, 2011.

Wayfinding Behavior within Buildings – An International Survey

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ABSTRACT

A building wayfinding questionnaire study is presented which analyses the importance of a set of wayfinding criteria from a building evacuation perspective. The main path selection criteria tested in this questionnaire are handedness and length of the first leg of the path. The study involved 1166 participants from 36 countries. The results suggest that the handedness, a genetic factor, and the side of the road people drive on, a cultural factor, exert a significant influence on path choice. The results of this study clarify misconceptions existing in urban wayfinding studies regarding the importance of the length of the first leg of a path. Path selection criteria along with their relative rankings are suggested for inclusion in wayfinding algorithms used within evacuation models. It is not clear how large an effect these influences will have on evacuation analysis. This will be examined by introducing these factors into a new wayfinding algorithm recently introduced into the buildingEXODUS evacuation model.

KEYWORDS: wayfinding, escape routes, path selection, human behavior, human factors.

INTRODUCTION

Within the building environment, wayfinding describes the process by which an individual located within a complex enclosure decides on a path or route in order to reach a goal location. Within the building evacuation context, wayfinding describes the process in which the individual attempts to find a path which leads them to relative safety, usually the exterior of the enclosure. In most evacuation modeling tools, the process of wayfinding is either ignored or grossly simplified. In a recent review of 30 evacuation models wayfinding features were only mentioned in the context of two models [1]. On the whole, evacuation models assume that the simulated agents have complete knowledge of the structure and so follow a potential or distance map to their nearest exit – essentially selecting the path of minimum travel distance. Some models may even assume that a proportion of the occupants have partial knowledge of the structure and so are familiar with only some of the exits [2,3]. At least one model incorporates agent interaction with signage allowing agents completely unfamiliar with the structure to follow a signage chain leading to an exit [2,3]. Recently, there has been some effort to incorporate a modified form of urban wayfinding criteria within building evacuation models [4]. However, this may be questionable as the wayfinding process within buildings may be different to that within urban environments. If our computer models are to accurately represent the wayfinding process adopted by humans during building evacuation we must first understand how humans wayfind within such environments. Key to this is developing an understanding of the criteria used by humans in deciding which path to take.

The lack of sophistication in the manner in which wayfinding is treated within building evacuation models is due in part to the general lack of detailed knowledge concerning wayfinding within complex building layouts. While there are numerous wayfinding studies in urban environments [5–8], there is very little wayfinding research performed within complex building environments. Due to the difficulty in conducting wayfinding research, especially research which involves international participants, most of the research that is conducted makes use of surveys, questionnaires or virtual environments.

Golledge's urban wayfinding study [5,6] involved a sample of 32 adults, 16 male and 16 female. The sample was mostly students, with half the population being trained in geography. The participants in Golledge's study were asked to identify the path they would take on a map to get from an identified starting point to an identified end point. The maps used varied from uniform grids, to uniform grids with diagonals and grids with curved paths plus blockages. Participants were then asked to rank the criteria they used in selecting their path using a seven point scale; participants selected the criteria from a list of 10 provided. The criteria selected by the participants, in order of preference (with mean rating shown in brackets) are: shortest distance (4.2), least time (4.1), fewest turns (3.6), most scenic/aesthetic (3.5), first noticed (2.5),

Appendix B – The Station Nightclub Simulation Results

A: Scenarios with instant response times

The scenarios in this section assume ideal conditions; for instance all occupants responding instantly, all exits are functioning perfectly.

Scenario A1: Nearest Exit with instant response times

Occupants exit via the nearest exit with instant response times

Kitchen Exit	Bar Door	Main Door	Platform Door	Total Evacuation Time	Evacuation time for 420 people	People Left After 90 seconds
0	23	211	206	188.92	170.48	158

Scenario A2: Optimum Exit with instant response times

Occupants make optimal use of the available exits with instant response times

Kitchen Exit	Bar Door	Main Door	Platform Door	Total Evacuation Time	Evacuation time for 420 people	People Left After 90 seconds
0	113	214	113	115.15	105.20	80

Scenarios A3: Signage scenarios with instant response times

Occupants make use of the exit signs to exit from the building with instant response times. Occupants are assigned 100% knowledge of main exit and 0% knowledge of other exits.

Scenario A3(i): Signage scenarios with instant response times(30m VCA)

Kitchen Exit	Bar Door	Main Door	Platform Door	Total Evacuation Time	Evacuation time for 420 people	People Left After 90 seconds
0.0	96	241	103	140.92	129.88	132

Scenario A3(ii): Signage scenarios with instant response times(15m VCA)

Kitchen Exit	Bar Door	Main Door	Platform Door	Total Evacuation Time	Evacuation time for 420 people	People Left After 90 seconds
0.0	95	237	107	139.29	127.51	126

Scenario A3(iii): Signage scenarios with instant response times(10m VCA)

Kitchen Exit	Bar Door	Main Door	Platform Door	Total Evacuation Time	Evacuation time for 420 people	People Left After 90 seconds
0.0	56	301	83	163.50	153.37	160

B: Scenarios with real response times

Occupants are assigned real response times as determined from the facts of the incident

Scenario B1: Nearest Exit Usage with real response times

Kitchen Exit	Bar Door	Main Door	Platform Door	Total Evacuation Time	Evacuation time for 420 people	People Left After 90 seconds
0	23	210	207	216.72	198.59	220

Scenario B2: Optimum Exit Usage with real response times

Kitchen Exit	Bar Door	Main Door	Platform Door	Total Evacuation Time	Evacuation time for 420 people	People Left After 90 seconds
0.0	114	214	112	143.36	135.1	207

Scenarios B3: Signage scenarios with real response times

Occupants make use of the exit signs to exit from the building with real response times. Occupants are assigned 100% knowledge of main exit, 0% knowledge of other exits.

Scenario B3(i): Signage scenarios with real response times(30m VCA)

Kitchen Exit	Bar Door	Main Door	Platform Door	Total Evacuation Time	Evacuation time for 420 people	People Left After 90 seconds
0.0	72	242	126	164.16	150.37	230

Scenario B3(ii): Signage scenarios with real response times(15m VCA)

Kitchen Exit	Bar Door	Main Door	Platform Door	Total Evacuation Time	Evacuation time for 420 people	People Left After 90 seconds
0.0	71	236	132	157.82	147.55	234

Scenario B3(iii): Signage scenarios with real response times(10m VCA)

Kitchen Exit	Bar Door	Main Door	Platform Door	Total Evacuation Time	Evacuation time for 420 people	People Left After 90 seconds
0.0	50	281	109	180.01	168.41	230

C: Scenarios reconstructing the real scenario without Fire

The scenarios considered so far do not include windows as exits. Scenarios C reconstruct the real incident by introducing windows as exits.

Scenario C1: Realistic case with instant response times(Signage)

All doors always open (including kitchen door), all doors remain open all through the simulation (except platform door); Windows open at time = (real open time) – 30 seconds; Signage to direct; 100% main exit knowledge; 0% other exit knowledge; Assign 100% attractiveness to windows, VCA 15m.

Kitchen Door	Bar Door	Main Door	Platform Door	Bar-room Windows	Sun-room Windows	People left after 90 seconds	Total Evacuation time	Evacuation time for 420 people
18	33	121	59	63	146	60	110.62	101.84

Scenario C2: Realistic case with real response times(Signage)

All doors always open (including kitchen door), all doors remain open all through the simulation(except platform exit); Windows open at real times; Signage to direct; 100% main exit knowledge; 0% other exit knowledge; Assign 100% attractiveness to windows, VCA 15m.

Kitchen Door	Bar Door	Main Door	Platform Door	Bar-room Windows	Sun-room Windows	People left after 90 seconds	Total Evacuation time	Evacuation time for 420 people
23	22	118	64	55	158	165	142.41	133.09

Scenario C3: Realistic case with real response times(Potential Maps)

All doors always open (including kitchen door), all doors remain open all through the simulation(except platform exit); Windows open at real times; People are directed to the exits based on the exit potentials.

Kitchen Door	Bar Door	Main Door	Platform Door	Bar-room Windows	Sun-room Windows	People left after 90 seconds	Total Evacuation time	Evacuation time for 420 people
22	75	151	43	60	45	153	118.29	110.02

D: Scenarios Altering the Geometry of the Nightclub without Fire

The scenarios considered so far do not include windows as exits. Scenarios D reconstruct the real incident by introducing windows as exits. This set of scenarios can be compared with Scenario C2. Scenarios D show the impact of altering the geometry of the nightclub and how this affects the total evacuation time.

Scenario D1: **Alteration case with the single door leading to the main double door removed.**

The main door which was a double door was restricted by a single doorway in the corridor leading to the ticket taker area. In this scenario the single doorway is removed thus allowing people to access the main double door without the flow of people being hampered by the single door.

Kitchen Door	Bar Door	Main Door	Platform Door	Bar-room Windows	Sun-room Windows	People left after 90 seconds	Total Evacuation time	**Evacuation time for 420 people**
23	22	137	63	48	148	166	137.78	129.30

<u>Scenario D2</u>: **Alteration case with real response times and the main door corridor removed**

The corridor connecting the main door to the ticket taker area proved to be serious impairment. A crowd crush occurred in this corridor within about 1 minutes and 42 seconds after the start of the fire. In this scenario the effect of removing this corridor is examined.

Kitchen Door	Bar Door	Main Door	Platform Door	Bar-room Windows	Sun-room Windows	People left after 90 seconds	Total Evacuation time	**Evacuation time for 420 people**
22	15	162	64	66	112	154	128.56	117.17

<u>Scenario D3</u>: **Alteration case with real response times and an extra door replacing the Kitchen door.**

In this scenario the effect of replacing the kitchen door with another double door of the same size as of the main door is examined. This extra door is designed as an emergency door and is placed about 3 meters from the kitchen door. It is assigned 0% attractiveness and occupants gain knowledge of this exit through 2 signs. One sign placed right above the door and the other placed at the dining area.

Extra Double Door	Bar Door	Main Door	Platform Door	Bar-room Windows	Sun-room Windows	People left after 90 seconds	Total Evacuation time	**Evacuation time for 420 people**
105	21	102	64	47	101	99	123.26	114.59

<u>Scenario D4</u>: **Alteration case with real response times and an extra door replacing the Kitchen door and main door cleared.**

This scenario examines the effect of adding a double door and eliminating the single door leading to the main double door

Extra Double Door	Bar Door	Main Door	Platform Door	Bar-room Windows	Sun-room Windows	People left after 90 seconds	Total Evacuation time	**Evacuation time for 420 people**
114	20	130	64	38	74	82	117.56	107.04

<u>Scenario D5</u>: **Alteration case with an extra door and the main door corridor removed.**

In this scenario the effect of removing the main door corridor coupled with the addition of an extra door is examined.

Extra Double Door	Bar Door	Main Door	Platform Door	Bar-room Windows	Sun-room Windows	People left after 90 seconds	Total Evacuation time	**Evacuation time for 420 people**
117	38	150	61	43	55	70	119.187	105.53

E: Scenarios with real response times and fire

Scenario E1: Nearest Exit with real response times and fire

Kitchen Exit	Bar Door	Main Door	Platform Door	Total Evacuation Time	Evacuation time for 420 people	People Left After 90 seconds	Fatalities
0.0	23	91	70	114.47	167	256	256

Scenario E2: Optimum Exit with real response times and fire

Kitchen Exit	Bar Door	Main Door	Platform Door	Total Evacuation Time	Evacuation time for 420 people	People Left After 90 seconds	Fatalities
0.0	73	94	70	115.33	236	203	203

Scenarios E3: Signage scenarios with real response times and fire

Occupants make use of the exit signs to exit from the building with real response times and fire. Occupants are assigned 100% knowledge of main exit, 0% knowledge of other exits.

Scenario E3(i): Signage scenarios with real response times and fire(30m VCA)

Kitchen Exit	Bar Door	Main Door	Platform Door	Total Evacuation Time	Evacuation time for 420 people	People Left After 90 seconds	Fatalities
0.0	40	90	70	116.24	258	241	241

Scenario E3(ii): Signage scenarios with real response times and fire(15m VCA)

Kitchen Exit	Bar Door	Main Door	Platform Door	Total Evacuation Time	Evacuation time for 420 people	People Left After 90 seconds	Fatalities
0.0	38	94	69	116.28	257	239	239

Scenario E3(iii): Signage scenarios with real response times and fire(10m VCA)

Kitchen Exit	Bar Door	Main Door	Platform Door	Total Evacuation Time	Evacuation time for 420 people	People Left After 90 seconds	Fatalities
0.0	33	99	68	116.42	257	241	241

F: Scenarios reconstructing the real incident with Fire

The scenarios considered so far do not include windows as exits. Scenarios F reconstruct the real incident with fire and include windows as exits.

Scenario F1: Realistic case with instant response times(Signage)

All doors always open (including kitchen door), all doors remain open all through the simulation (except platform door); Windows open at time = (real open time) – 30 seconds; Signage to direct; 100% main exit knowledge; 0% other exit knowledge; Assign 100% attractiveness to windows, VCA 15m.

Kitchen Door	Bar Door	Main Door	Platform Door	Bar-room Windows	Sun-room Windows	People left after 90 seconds	Total Evacuation time	Fatalities
19	35	130	60	54	108	84	114.4	35

Scenario F2: Realistic case with real response times(Signage)

All doors always open (including kitchen door), all doors remain open all through the simulation(except platform exit); Windows open at real times; Signage to direct; 100% main exit knowledge; 0% other exit knowledge; Assign 100% attractiveness to windows, VCA 15m.

Kitchen Door	Bar Door	Main Door	Platform Door	Bar-room Windows	Sun-room Windows	People left after 90 seconds	Total Evacuation time	Fatalities
23	26	98	63	10	31	234	115.48	189

Scenario F3: Realistic case with real response times (Potential Maps)

Kitchen Door	Bar Door	Main Door	Platform Door	Bar-room Windows	Sun-room Windows	People left after 90 seconds	Total Evacuation time	Fatalities
19	61	90	32	54.8	31	217	115.25	153

G: Scenarios Altering the Geometry of the Nightclub with Fire

In this set of scenarios, the effects of altering the geometry of the nightclub are examined. All the scenarios in this group use signage to direct the occupants. This set of scenarios can be compared with Scenario F2. Scenario F2 predicts the fatalities by reconstructing the incidents of the fire as close as possible. Scenarios G show the impact of altering the geometry of the nightclub and how this affects the fatalities count.

Scenario G1: **Alteration case with the single door leading to the main double door removed.**

The main door which was a double door was restricted by a single doorway in the corridor leading to the ticket taker area. In this scenario the single doorway is removed thus allowing people to access the main double door without the flow of people being hampered by the single door.

Kitchen Door	Bar Door	Main Door	Platform Door	Bar-room Windows	Sun-room Windows	People left after 90 seconds	Total Evacuation time	Fatalities
22	24	123	63	10	32	219	114.82	167

Scenario G2: **Alteration case with real response times and the main door corridor removed**

The corridor connecting the main door to the ticket taker area proved to be serious impairment. A crowd crush occurred in this corridor within about 1 minutes and 42 seconds after the start of the fire. In this scenario the effect of removing this corridor is examined.

Kitchen Door	Bar Door	Main Door	Platform Door	Bar-room Windows	Sun-room Windows	People left after 90 seconds	Total Evacuation time	Fatalities
22	23	149	62	27	34	193	116.75	122

Scenario G3: **Alteration case with real response times and an extra door replacing the Kitchen door.**

In this scenario the effect of replacing the kitchen door with another double door of the same size as of the main door is examined. This extra door is designed as an emergency door and is placed about 3 meters from the kitchen door. It is assigned 0% attractiveness and occupants gain knowledge of this exit through 2 signs. One sign placed right above the door and the other placed at the dining area.

Extra Double Door	Bar Door	Main Door	Platform Door	Bar-room Windows	Sun-room Windows	People left after 90 seconds	Total Evacuation time	Fatalities
101	23	89	63	5	31	158	115.25	126

Scenario G4: **Alteration case with real response times and an extra door replacing the Kitchen door and main door cleared.**

This scenario examines the effect of adding a double door and eliminating the single door leading to the main double door

Extra Double Door	Bar Door	Main Door	Platform Door	Bar-room Windows	Sun-room Windows	People left after 90 seconds	Total Evacuation time	Fatalities
115	22	122	62	6	23	137	115.25	91

Scenario G5: **Alteration case with an extra door and the main door corridor removed.**

In this scenario the effect of removing the main door corridor coupled with the addition of an extra door is examined.

Extra Double Door	Bar Door	Main Door	Platform Door	Bar-room Windows	Sun-room Windows	People left after 90 seconds	Total Evacuation time	Fatalities
68	28	149	62	21	35	138	116.92	76

Table B.1: Opening and closing times of the different doors and windows in the nightclub. ∞ denotes that the door after opening remained open.

Exits	Opening Time (seconds)	Closing Time (seconds)
Kitchen Exit	60	∞
Bar Exit	45	∞
Main Exit	30	< 102 seconds(Crowd Crush)
Platform Exit	29	< 85 seconds(Blockage due to flames)
Sunroom Windows(4)	78, 100, 110, 120	∞
Barroom windows(3)	80, 80, 80	∞

Appendix C – Toxicity Models in buildingEXODUS

There are two toxicity models implemented within buildingEXODUS which are the FED models of Purser [Purser, 2008] and Speitel [Speitel, 1995]. Purser's model considers the toxic and physical hazards associated with elevated temperature, HCN, CO, CO_2 and low O_2 and estimates the time to incapacitation [Galea, et al., 2006]. While the Purser model is the most popularly used FED model, Speitel has developed an alternative model. A major difference between the two models is the equations used for the heat contribution to the FED calculation which will be explained further in the next section.

There are two main attributes considered in the FED models – FIH and FIN.

FIH Attribute

The FIH attribute measures the occupant's cumulative exposure to heat. The initial value of FIH is zero. An occupant is said to be incapacitated (unable to move due to the effect of hazards) due to heat exposure when FIH equals one. The FIH attribute considers the combined effect of two factors – (i) Convected heat (FIH_c) and (ii)Radiative heat (FIH_r).

(i) Convected Heat

A major difference between Purser's and Speitel model is the equations used to calculate the convected heat. In the equations in this Appendix, t is the exposure time in minutes and T is the temperature in ^{0}C.

In Purser's model the following formula is used:

$$FIH_c = t * 2.0 * 10^{-8} * T^{3.4}$$ **Equation 1**

In Speitel's model the following formula is used:

$$FIH_c = t * 2.4 * 10^{-09} * (T\,^0C)^{3.61}$$ **Equation 2**

The Purser model predicts incapacitation at considerably lower temperatures than the Speitel model. For example a one minute exposure to 185^{0}C results in incapacitation using Equation 1 whereas using Equation 2, temperatures in excess of 240^{0}C is required to produce the same effect.

(ii) Radiative Heat

The radiative heat is calculated using the following formula:

$$FIH_r = q^{1.33} / D_r * t * 60.0$$ **Equation 3**

Where q is the radiative flux (kW/m^2) and D_r is the radiative denominator. D_r is the Dose of radiation required to cause the desired effect of – pain threshold or incapacitation.

The D_r value required for "pain threshold" is 80 which is equivalent to a thermal radiation exposure of 2.5 kW/m^2 for 24 seconds. This threshold denotes the effect of an occupant receiving a cumulative dose of thermal radiation required to cause the onset of pain and as a result is rendered incapable of continuing to evacuate effectively.

The D_r value required for "incapacitation threshold" is 1000 which is equivalent to a thermal radiation exposure of 8.25 kW/m^2 for one minute. This threshold is representative of an occupant receiving a cumulative dose of thermal radiation causing severe pain and as a result is rendered incapable of continuing to evacuate effectively.

The FIH attribute is then calculated as follows:

$$FIH = FIH_c + FIH_r$$ **Equation 4**

FIN Attribute

The FIN attribute measures the occupant's combined exposure to HCN, CO, CO_2 and low O_2. The initial value of FIN is zero. The travel speed of an agent is a function of the FIN attribute. As the FIN increases, the occupant's travel speed decreases. The occupant is said to be incapacitated due to exposure to gases when FIN equals one. The Purser's FED model uses the following formula to calculate FIN:

$$FIN = FICO + (FICN + FLD) * VCO_2 + FIO$$ **Equation 5**

Where FICO is the concentration of CO in ppm, FICN is the concentration of HCN in ppm, FLD is the Fractional Effective Dose, FIO is low O_2 in ppm and

$$VCO_2 = e^{(CO_2 / 5.0)}$$ **Equation 6**

is a multiplicative factor which measures the increased uptake of CO, HCN due to CO_2 induced hyperventilation.

Both the Purser and Speitel models incorporate a factor that takes into account the increased respiration rate that results from the presence of CO_2. In Purser's model, the hyperventilation factor, VCO_2 (see Equation 6) is used to represent the increase in uptake of CO and HCN and in the Speitel model it serves a similar function for CO, HCN, HCL, HF, HBr, NO_2 and Acrolein.

While the hyperventilation effect induced by CO_2 has a considerable effect in circumstances where the subject is oblivious of the fire such as a sleeping victim, it is not clear if it should be factored into evacuation models in its present form. The VCO_2 has a significant impact on the results of a simulation and may lead to severe over estimation of the number of fatalities. In buildingEXODUS, there are two options for VCO_2 – "1" or "purser".

The following equation (modification of Equation 5) is used when the VCO_2, purser option is chosen:

$$FIN = (FICO * VCO_2) + ((FICN + FLD) * VCO_2) + FIO$$ **Equation 7**

Therefore with Purser option selected, VCO_2 influences FICO, FICN and FLD values

The following equation is used when the VCO_2, 1 option is chosen:

$$FIN = FICO + ((FICO + FLD) * VCO_2) + FIO$$ **Equation 8**

With the VCO_2 option selected, VCO_2 influences only FICN and FLD values.

In addition to these factors buildingEXODUS also incorporates the irritant model originally developed by Purser [Purser, 2008] to take into account the influence of irritant gases such as: HCL, HBr, HF, SO_2, NO_2, Acrolein and Formaldehyde [Galea, et al., 2006]. Smoke concentration also affects the mobility of an occupant in the buildingEXODUS model. The travel speed or mobility decreases as the smoke concentration increases. The mobility of an occupant is given by the following formula based on the work of Jin [Jin, 1978] [Jin and Yamada, 1989]:

$$Mobility = -2.08K^2 - 0.38K + 1.06$$ **Equation 9**

Appendix D – Distance Map Algorithm

```
1 FOR each exit node in connectivity graph
2   Clear the NodesToExploreVector
3   Clear the ExploredNodesVector
4   Assign cost (CurrentExitNode, -1) for all nodes in the connectivity graph
5   Add CurrentExitNode to the NodesToExploreVector
6   WHILE NodesToExploreVector is not empty
7     CurrentNode = Node with the lowest cost from the NodesToExploreVector
8     Move CurrentNode to ExploredNodesVector
9     NeighbourNodesVector = neighbours of CurrentNode
10    FOR each NeighbourNode  in NeighbourNodesVector
11      NewCost = Cost of CurrentNode + distance between CurrentNode and
12                NeighbourNode
13      IF Cost of NeighbourNode  is 0.0 or greater than NewCost
14         Assign cost (CurrentExitNode, NewCost) to the NeighbourNode
15         Add NeighbourNode  to NodesToExploreVector
16      END IF
17      END FOR
18   END WHILE
19 END FOR
```

Figure C.1: Algorithm for creating the distance map for all exits in a connectivity graph

Algorithms 1 and 2 (see Chapter 4) developed in this thesis depend on the distance map to have an estimate of the optimal cost from each node in the graph to the goal (exit) node. A separate distance map is generated for each exit node in the graph. The algorithm to create this distance map is shown in Figure C.1. This algorithm is similar in concept to the Dijkstra algorithm [Dijkstra, 1959]. At the end of this algorithm all the nodes in the connectivity graph have a value which represents the shortest distance to each exit in the geometry.

This algorithm starts by initially assigning a cost of -1 to all nodes in the geometry for a particular exit. This is done in line 4 of the pseudo-code shown in Figure C.2. There are two vectors in this algorithm, NodesToExploreVector and ExploredNodesVector which are implemented as vector data types in C++. The nodes whose costs are to be determined are placed in the NodesToExploreVector. During each iteration of this algorithm the node with the lowest cost in the NodesToExploreVector is assumed to have its cost finalised and hence is moved into the ExploredNodesVector.

The distance map algorithm starts by adding the exit node to the NodesToExploreVector with its cost being set to zero. In the simulations once agents reach an exit node, they are assumed to have exited the geometry and hence exit nodes have zero distance.

The following steps are carried out untill the NodesToExploreVector becomes empty at which stage all nodes in the connectivity graph have been assigned the correct (lowest) cost for the exit under consideration. For each iteration the node with the lowest cost in the NodesToExploreVector is chosen as the CurrentNode (Line 7). This node is then added to the ExploredNodes Vector (Line 8) and deleted from the NodesToExploreVector. The neighbour nodes of the CurrentNode are then examined in the FOR loop starting at Line 10. The new cost (CostNew) for each neighbour node is calculated assuming the CurrentNode to be the parent (Line11). The new cost value is calculated as the sum of the parent node cost, the distance between the node and the parent node.

If the cost of the neighbour node is -1, this is the first time a cost has been assigned to it and hence the cost of this neighbour node is replaced by NewCost. If the cost of the neighbour node is greater than NewCost, then the CurrentNode is a better parent and hence the neighbour node is assigned NewCost. If the cost of the neighbour node is not -1 and is less than NewCost then the cost of the neighbour node is not improved by CurrentNode and hence no change is made. Since the CurrentNode has the lowest possible cost value, the costs assigned to the NeighbourNode should be the lowest though the Current Node. However the NeighbourNode's may have a lower cost through another node which will be corrected subsequently till it reaches the lowest value when it becomes the CurrentNode. This NeighbourNode is then added to the NodesToExploreVector. This process is repeated for each NeighbourNode of the CurrentNode. The whole process is repeated till the NodesToExploreVector becomes empty at which point all the nodes connected to this exit have the lowest cost from that exit in terms of distance and time. This is then repeated for all the exits in the connectivity graph.

E.2 Participant Information Sheet

Participant Information Sheet

Occupant Wayfinding Behaviour in Buildings

Thank you for agreeing to participate in this study. This study is being conducted by the University of Greenwich and your participation in this study is helping to improve building safety.

THE QUESTIONNAIRE:

- As part of this study, you will be asked to fill out a questionnaire.
- While you are under no obligation to answer any of the questions we would appreciate if you could provide an answer to all of the questions.
- If you have any problems in completing the questionnaire please ask the research assistant and they will explain the question.
- There are no right or wrong answers.
- The entire process should take about 5 minutes of your time.

YOUR ANSWERS:

- The answers you provide to the questionnaire will be analysed and the data stored.
- We will keep the data for research purposes and some of the analysed data may be published in journals and conference proceedings and presented in various public forums.
- Your name and any unique identifying personal details will not be associated with your questionnaire.
- The questions have been designed to collect information regarding the decisions people make while finding their way out of a building.

RIGHT TO WITHDRAW:

- The public survey in which you are about to participate, involves simple questions and answers and should present no difficulties to you.
- However, if at any time you wish to withdraw from the questionnaire, please inform the member of staff and you will be free to leave.

CONFIDENTIALITY:

- We request that you do not discuss the detailed nature of the questionnaire with any one likely to participate in the survey.

For further information about this survey please feel free to contact:

Prof Edwin Galea (Research Director)
Fire Safety Engineering Group,
University of Greenwich,
30 Park Row,
Greenwich, London SE10 9LS,
Tel: 0208 331 8730
Email: ge03@gre.ac.uk

Anand Veeraswamy (PhD Student)
Fire Safety Engineering Group
University of Greenwich,
30 Park Row,
Greenwich, London SE10 9LS,
Tel: 0208 331 8404
Email: va18@gre.ac.uk

E.3 Participant Consent Form

Title of Research: Occupant Wayfinding Behaviour in Buildings	
Investigator's name:	
To be completed by the participant (delete as necessary)	
1. Has the researcher explained the study to you?	YES/NO
2. Have you had an opportunity to ask questions and discuss this study?	YES/NO
3. Have you received satisfactory answers to all your questions?	YES/NO
4. Do you understand that you do not have to complete the questionnaire	YES/NO
5. Do you agree to take part in this study?	YES/NO
Signed	Date
Name in block letters	
Signature of investigator	Date

This Project is Supervised by: Prof. Edwin Galea
Contact Details (including telephone number): **University of Greenwich, Fire Safety Engineering Group, Room QM355, Queen Mary Building, 30 Park Row, Greenwich, London, SE10 9LS** **Telephone number : 0208 331 8730 (Direct Line) Email :** E.R.Galea@gre.ac.uk

E.4 Questionnaire 1 and 2

The questionnaires carried out in this thesis were placed on the internet and can be accessed at http://fseg.gre.ac.uk/wayfinding/index.asp. Initially Questionnaire 1 (Part 1 and Part 2) were taken by 400 participants. After analysing the results of the Questionnaire 1, Questionnaire 2 was designed. However, Questionnaire 2 was merged with Questionnaire 1. In this section the merged form of the Questionnaires are presented. Part 1 consisting of Questions 1 – 6 are demographic questions which will be used in the analysis of both questionnaires. Part 2 consisting of Questions 7 – 13 form the Questionnaire 1. There are two sets questions (Questions 14 – 18) in Questionnaire 2 – Questionnaire 2a and Questionnaire 2b. Questionnaire 2a will be taken by participants who have a preference for right-hand paths and Questionnaire 2b will be taken by participants who have a preference for left-hand paths. The last two questions, Questions 19 – 20 will be taken by all participants.

Wayfinding Survey: Participant Information

This study is being conducted by the Fire Safety Engineering Group (FSEG) of the University of Greenwich. The study concerns human route preferences during wayfinding within building environments. Your participation in this study will contribute to improving our understanding of human route choices within buildings and hence improve building safety. For More information on this research please click the More Information Button.

THE QUESTIONNAIRE

As part of this study, you will be asked to fill out a questionnaire. Some of the questions ask what decision you would make in a given hypothetical scenario. All questions relate to route choices in a building and participant demographics.

There are fourteen questions relating to route choices and six questions relating to personal demographics

The entire process should take about 10 minutes of your time.

YOUR ANSWERS:

The answers you provide to the questionnaire will be analysed and the data stored.

We will keep the data for research purposes and some of the analysed data may be published and shown in public fora. Any unique identifying personal details will not be associated with your questionnaire. The questions have been designed to collect information which will help us in our understanding of human behaviour during normal and evacuation scenarios.

RIGHT TO WITHDRAW:

The public survey in which you are about to participate, involves simple questions and answers and should present no difficulties to you. However, if at any time you wish to withdraw from the questionnaire, close the window/tab of the webpage and no data will be sent.

The Questionnaire consists of three parts:

PART 1:

In the first part of the questionnaire you will be asked six demographic questions.

PART 2:

In the second part you will be asked to select a path leading to an exit in a hypothetical building. There are 5 questions in Part 2. You will also be asked to identify the main factors that influenced your path selection decisions.

PART 3:

In the third part of the questionnaire you will again be asked to select a path leading to an exit in a hypothetical building. There are 5 questions in Part 3. You will also be asked to rate the main factors that influenced your path selection decisions.

Tick/Click on this box if you understand the above information and agree to take part in the questionnaire

If you have any difficulties concerning completing this questionnaire please contact:

Anand Veeraswamy (PhD Student)

University of Greenwich,
Fire Safety Engineering Group,
Room 265, Queen Mary Building,
30 Park Row,
Greenwich, London SE10 9LS,
Tel: 0208 331 8404
Email: A.Veeraswamy@gre.ac.uk

For all other queries or comments please contact:

Prof Edwin Galea(FSEG Director)

University of Greenwich,
Fire Safety Engineering Group,
Room 355, Queen Mary Building,
30 Park Row,
Greenwich, London SE10 9LS,
Tel: 0208 331 8730
Email: E.R.Galea@gre.ac.uk

E.5 Demographic Questions for both Questionnaires

PART 1

Question 1
What is your Gender?
Male Female

Question 2
You are

Left handed Right handed

Question 3
What is your age? ---
.

Question 4
a) What country were you born in? Please select a Country

b) What country do you currently reside in? Please select a Country

c) What is your email address?
.

Question 5
Do you have any physical condition which would inhibit you participating in physical exercise? E.g. wheelchair user

Yes
No
If yes, please specify(maximum 200 characters)

Question 6
Is your profession related to fire safety?

Yes
No
If yes, please specify(maximum 200 characters)

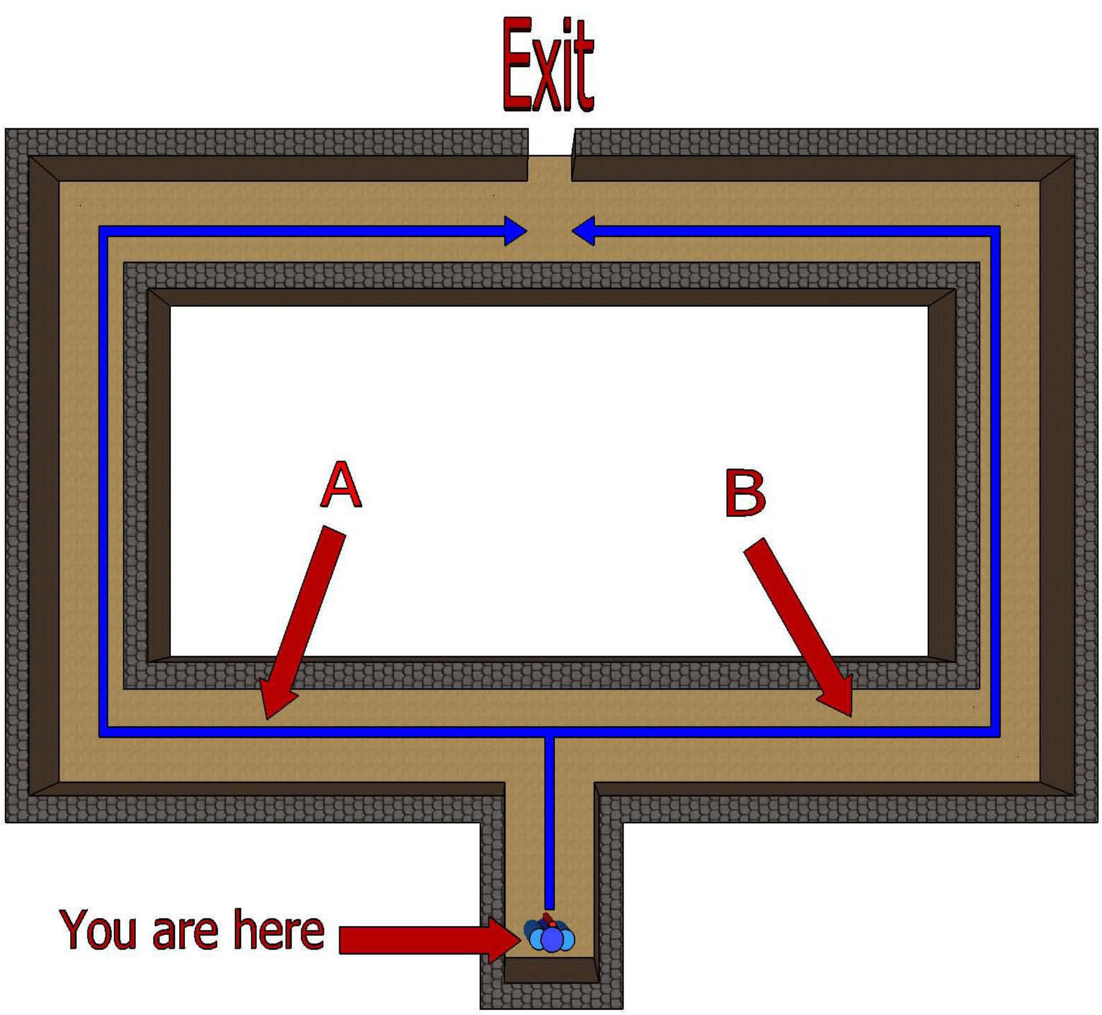
E.6 Questionnaire 1

PART 2

Question 7

Situation:

You are in the building shown below.
Your initial location is indicated by the arrow labelled You are here .
You are completely familiar with the building layout.
The only exit is located on the opposite side of the building labelled EXIT .
You have a choice of two alternative paths leading to the exit.
BOTH PATHS ARE OF EQUAL LENGTH



Question 7A: Which path would you choose to exit from this building under NORMAL, NON-EMERGENCY CIRCUMSTANCES?

Path A Path B

Please briefly state why you preferred the selected path.(maximum 200 characters)

Question 7B: Please rate the preference for the path you selected

The chosen path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 7C: Please rate the preference for the Alternate path

The alternate path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 7D: Imagine that you are now in an emergency evacuation situation in the same building. You can hear the fire alarm and you can see that both paths appear to have a small amount of smoke. Which path would you now choose?

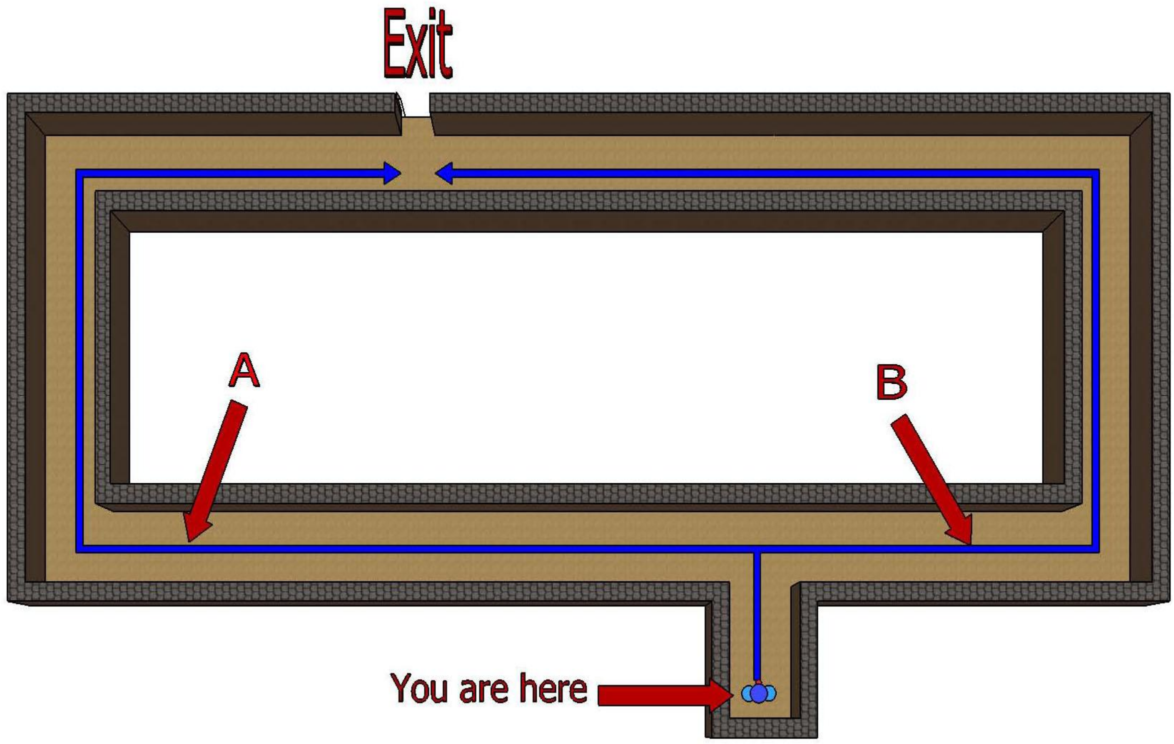
Path A Path B

If you chose a path different from the one you chose in 7A, please state what made you change the path?(maximum 200 characters)

Question 8

Situation:

You are in the building shown below.
Your initial location is indicated by the arrow labelled You are here.
You are completely familiar with the building layout.
The only exit is located on the opposite side of the building labelled EXIT.
You have a choice of two alternative paths leading to the exit.
BOTH PATHS ARE OF EQUAL LENGTH



Question 8A: Which path would you choose to exit from this building under NORMAL, NON-EMERGENCY CIRCUMSTANCES?

Path A Path B

Please briefly state why you preferred the selected path.(maximum 200 characters)

Question 8B: Please rate the preference for the path you selected

The chosen path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 8C: Please rate the preference for the Alternate path

The alternate path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 8D: Imagine that you are now in an emergency evacuation situation in the same building. You can hear the fire alarm and you can see that both paths appear to have a small amount of smoke. Which path would you now choose?

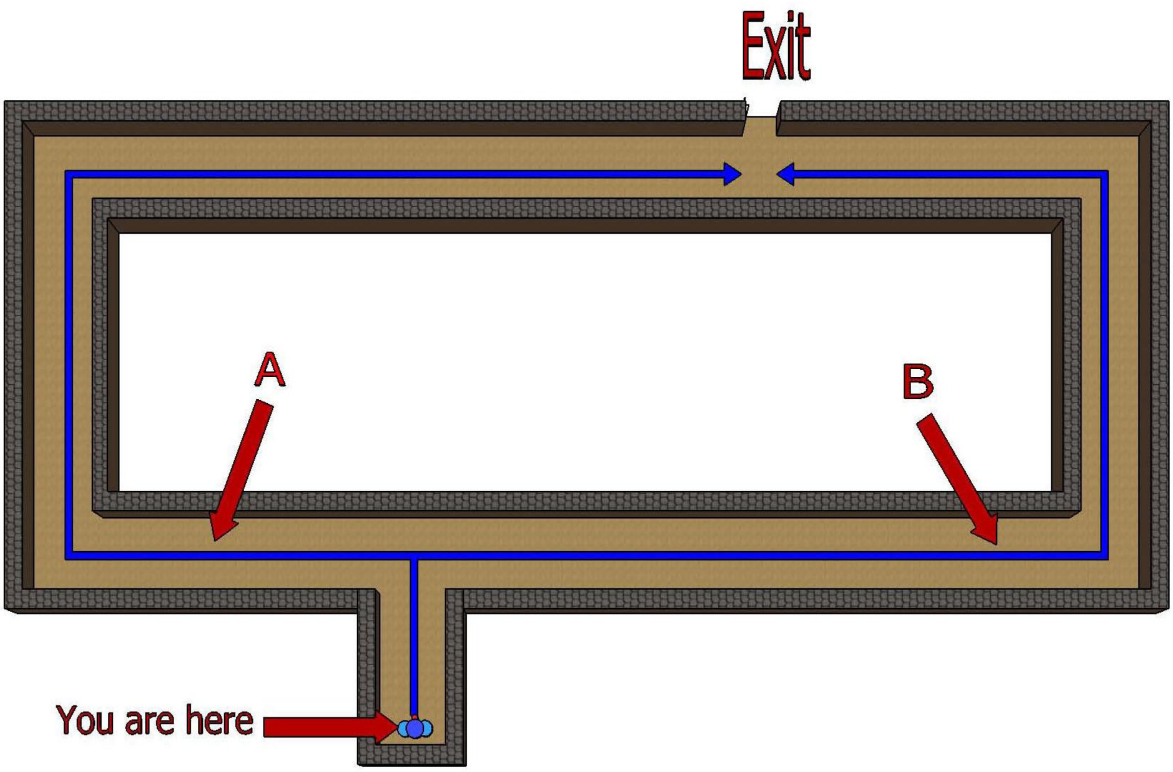
Path A Path B

If you chose a path different from the one you chose in 8A, please state what made you change the path?(maximum 200 characters)

Question 9

Situation:

You are in the building shown below.
Your initial location is indicated by the arrow labelled You are here .
You are completely familiar with the building layout.
The only exit is located on the opposite side of the building labelled EXIT .
You have a choice of two alternative paths leading to the exit.
BOTH PATHS ARE OF EQUAL LENGTH



Question 9A: Which path would you choose to exit from this building under NORMAL, NON-EMERGENCY CIRCUMSTANCES?

Path A Path B

Please briefly state why you preferred the selected path.(maximum 200 characters)

Question 9B: Please rate the preference for the path you selected

The chosen path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 9C: Please rate the preference for the Alternate path

The alternate path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable

4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 9D: Imagine that you are now in an emergency evacuation situation in the same building. You can hear the fire alarm and you can see that both paths appear to have a small amount of smoke. Which path would you now choose?

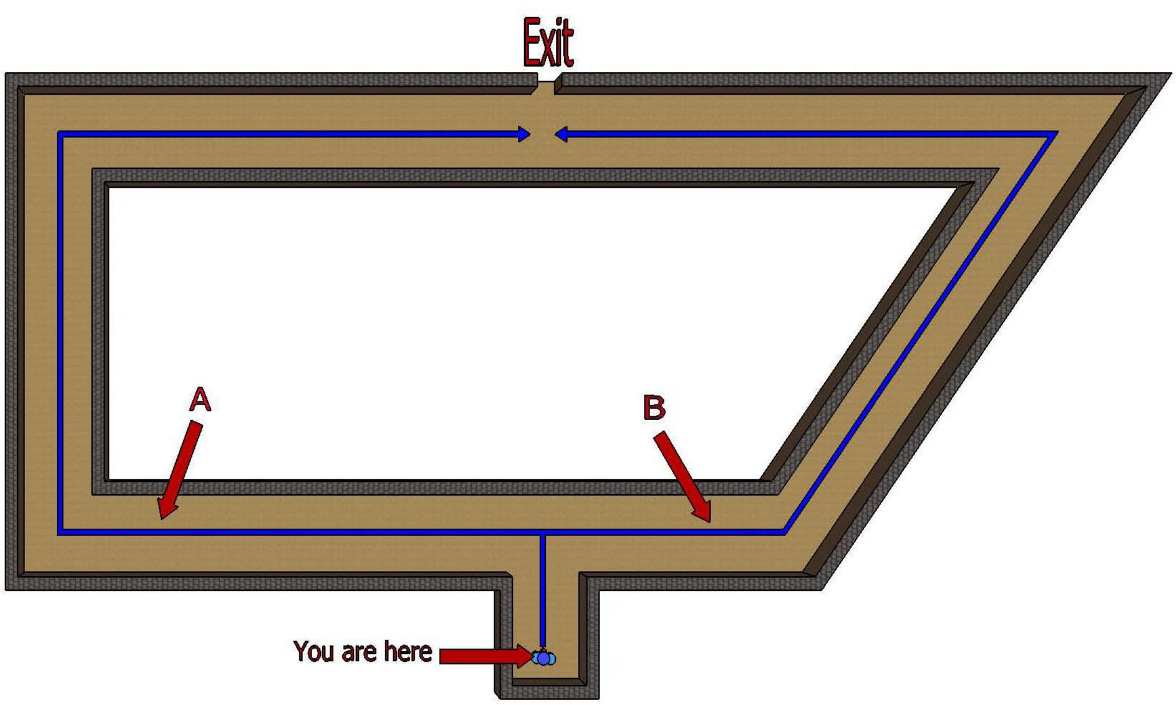
Path A Path B

If you chose a path different from the one you chose in 9A, please state what made you change the path?(maximum 200 characters)

Question 10

Situation:

You are in the building shown below.
Your initial location is indicated by the arrow labelled You are here .
You are completely familiar with the building layout.
The only exit is located on the opposite side of the building labelled EXIT .
You have a choice of two alternative paths leading to the exit.
BOTH PATHS ARE OF EQUAL LENGTH



Question 10A: Which path would you choose to exit from this building under NORMAL, NON-EMERGENCY CIRCUMSTANCES?

Path A Path B

Please briefly state why you preferred the selected path.(maximum 200 characters)

Question 10B: Please rate the preference for the path you selected

The chosen path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 10C: Please rate the preference for the Alternate path

The alternate path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 10D: Imagine that you are now in an emergency evacuation situation in the same building. You can hear the fire alarm and you can see that both paths appear to have a small amount of smoke. Which path would you now choose?

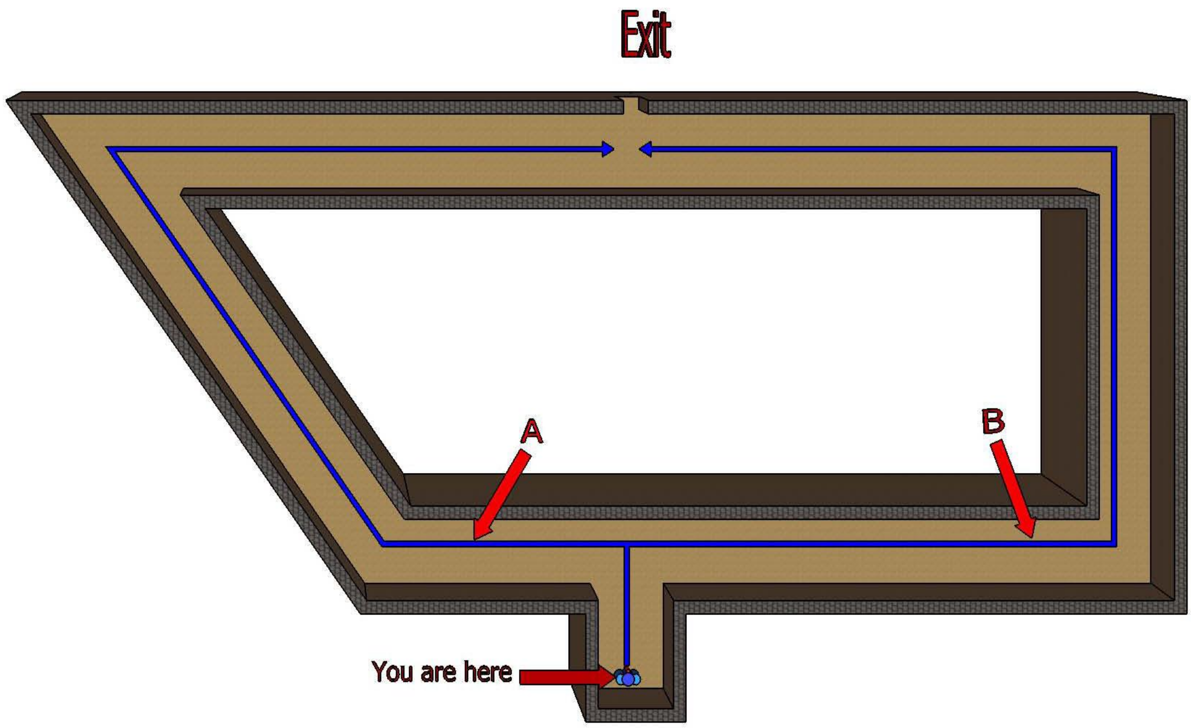
Path A Path B

If you chose a path different from the one you chose in 10A, please state what made you change the path?(maximum 200 characters)

Question 11

Situation:

You are in the building shown below.
Your initial location is indicated by the arrow labelled You are here .
You are completely familiar with the building layout.
The only exit is located on the opposite side of the building labelled EXIT .
You have a choice of two alternative paths leading to the exit.
BOTH PATHS ARE OF EQUAL LENGTH



Question 11A: Which path would you choose to exit from this building under NORMAL, NON-EMERGENCY CIRCUMSTANCES?

Path A Path B

Please briefly state why you preferred the selected path.(maximum 200 characters)

What factors influenced your path selection?

Question 12

For this exercise, please think about what factors influenced your path selection in the second part of the questionnaire.
Please circle the factors that influenced your path selection. You may choose more than one.

I prefer to take the path with the longest first leg
I prefer to take the path with the shortest first leg
I have a preference to take paths on my left
I have a preference to take paths on my right
I have a preference to take the clockwise path
I have a preference to take the anticlockwise path
I choose the path which appeared to be the most direct
I choose randomly

Question 13

Please state any other factors that you thought affected your path selection process (maximum 200 characters)

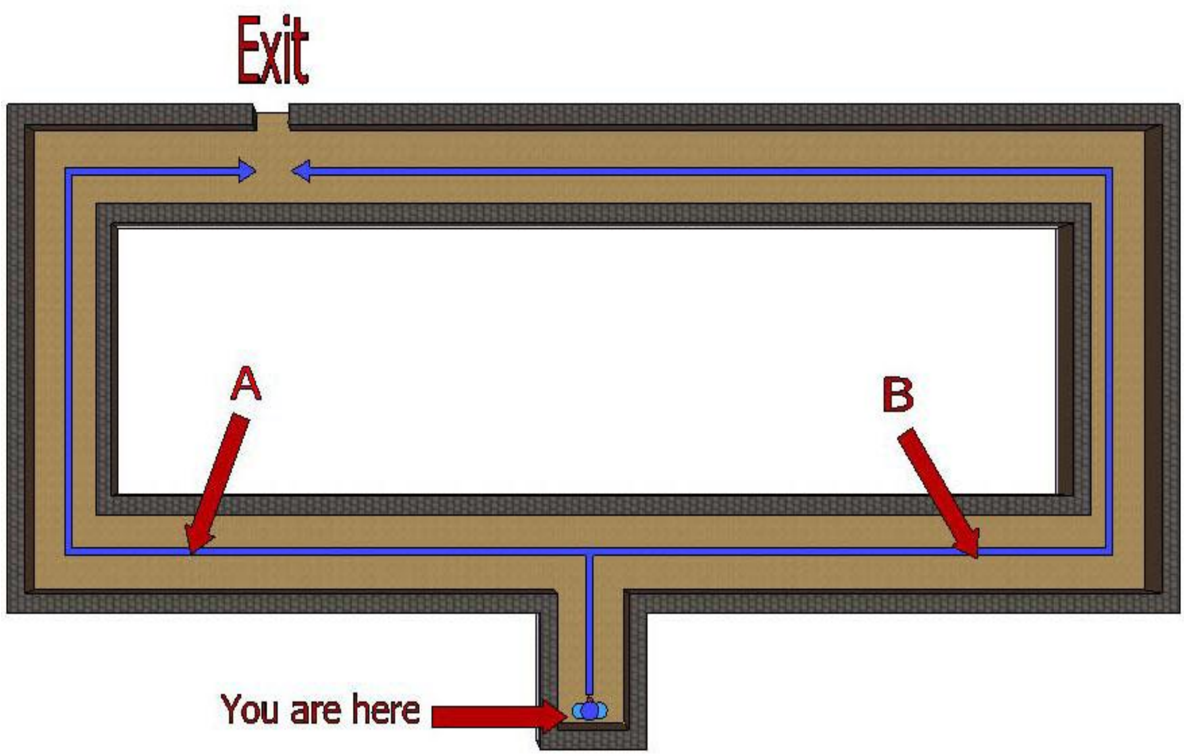
E.7 Questionnaire 2a

PART 3

Question 14

Situation:

You are **alone** in the building shown below.
Your initial location is indicated by the arrow labelled You are here.
You are completely familiar with the building layout.
The only exit is located on the opposite side of the building labelled EXIT.
You have a choice of two alternative paths leading to the exit.
Path B is longer than Path A



Question 14A: Which path would you choose to exit from this building under NORMAL, NON-EMERGENCY CIRCUMSTANCES?

Path A Path B

Please briefly state why you preferred the selected path.(maximum 200 characters)

Question 14B: Please rate the preference for the path you selected

The chosen path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable

4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 14C: Please rate the preference for the Alternate path

The alternate path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 14D: Imagine that you are now in an emergency evacuation situation in the same building. You can hear the fire alarm and you can see that both paths appear to have a small amount of smoke. Which path would you now choose?

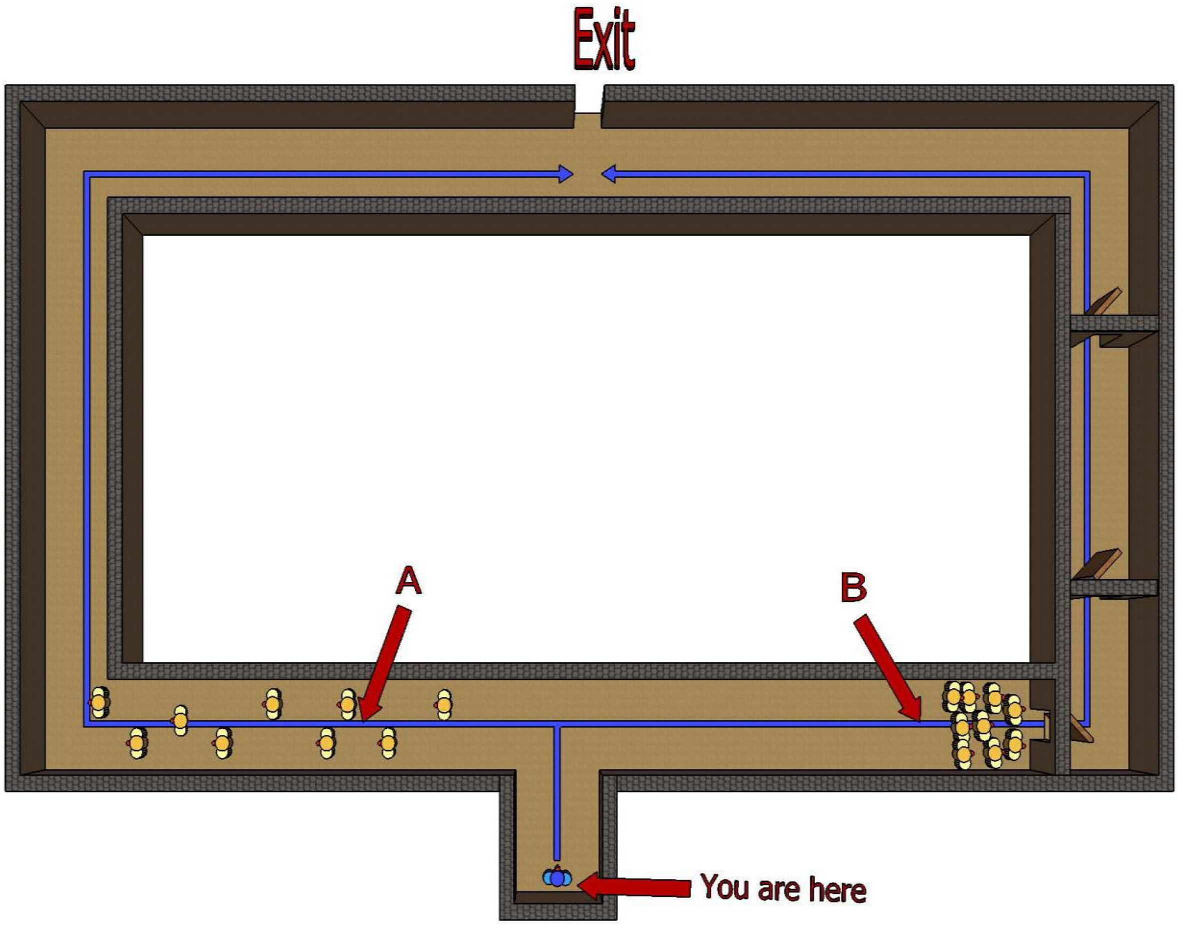
Path A Path B

If you chose a path different from the one you chose in 14A, please state what made you change the path?(maximum 200 characters)

Question 15

Situation:

You are in the building shown below.
Your initial location is indicated by the arrow labelled You are here .
You are completely familiar with the building layout.
The only exit is located on the opposite side of the building labelled EXIT .
You have a choice of two alternative paths leading to the exit.
BOTH PATHS ARE OF EQUAL LENGTH
There are equal numbers of people represented by the yellow objects along each path.
Path B has 3 internal doors.



Question 15A: Which path would you choose to exit from this building under NORMAL, NON-EMERGENCY CIRCUMSTANCES?

Path A Path B

Please briefly state why you preferred the selected path.(maximum 200 characters)

Question 15B: Please rate the preference for the path you selected

The chosen path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 15C: Please rate the preference for the Alternate path

The alternate path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 15D: Imagine that you are now in an emergency evacuation situation in the same building. You can hear the fire alarm and you can see that both paths appear to have a small amount of smoke. Which path would you now choose?

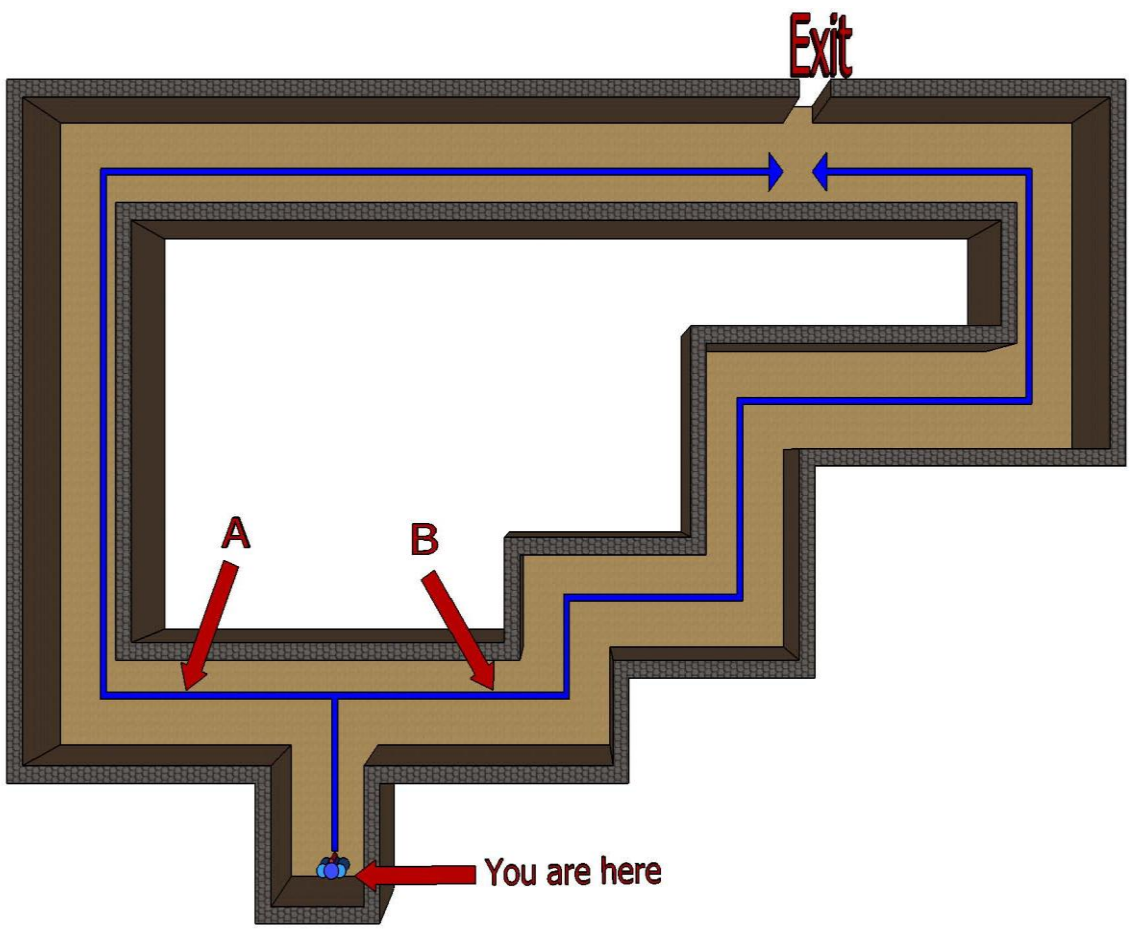
Path A Path B

If you chose a path different from the one you chose in 15A, please state what made you change the path?(maximum 200 characters)

Question 16

Situation:

You are **alone** in the building shown below.
Your initial location is indicated by the arrow labelled You are here .
You are completely familiar with the building layout.
The only exit is located on the opposite side of the building labelled EXIT .
You have a choice of two alternative paths leading to the exit.
BOTH PATHS ARE OF EQUAL LENGTH
PATH A HAS 2 BENDS AND PATH B HAS 6 BENDS.



Question 16A: Which path would you choose to exit from this building under NORMAL, NON-EMERGENCY CIRCUMSTANCES?

Path A Path B

Please briefly state why you preferred the selected path.(maximum 200 characters)

Question 16B: Please rate the preference for the path you selected

The chosen path was
1. Highly Undesirable

2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 16C: Please rate the preference for the Alternate path

The alternate path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 16D: Imagine that you are now in an emergency evacuation situation in the same building. You can hear the fire alarm and you can see that both paths appear to have a small amount of smoke. Which path would you now choose?

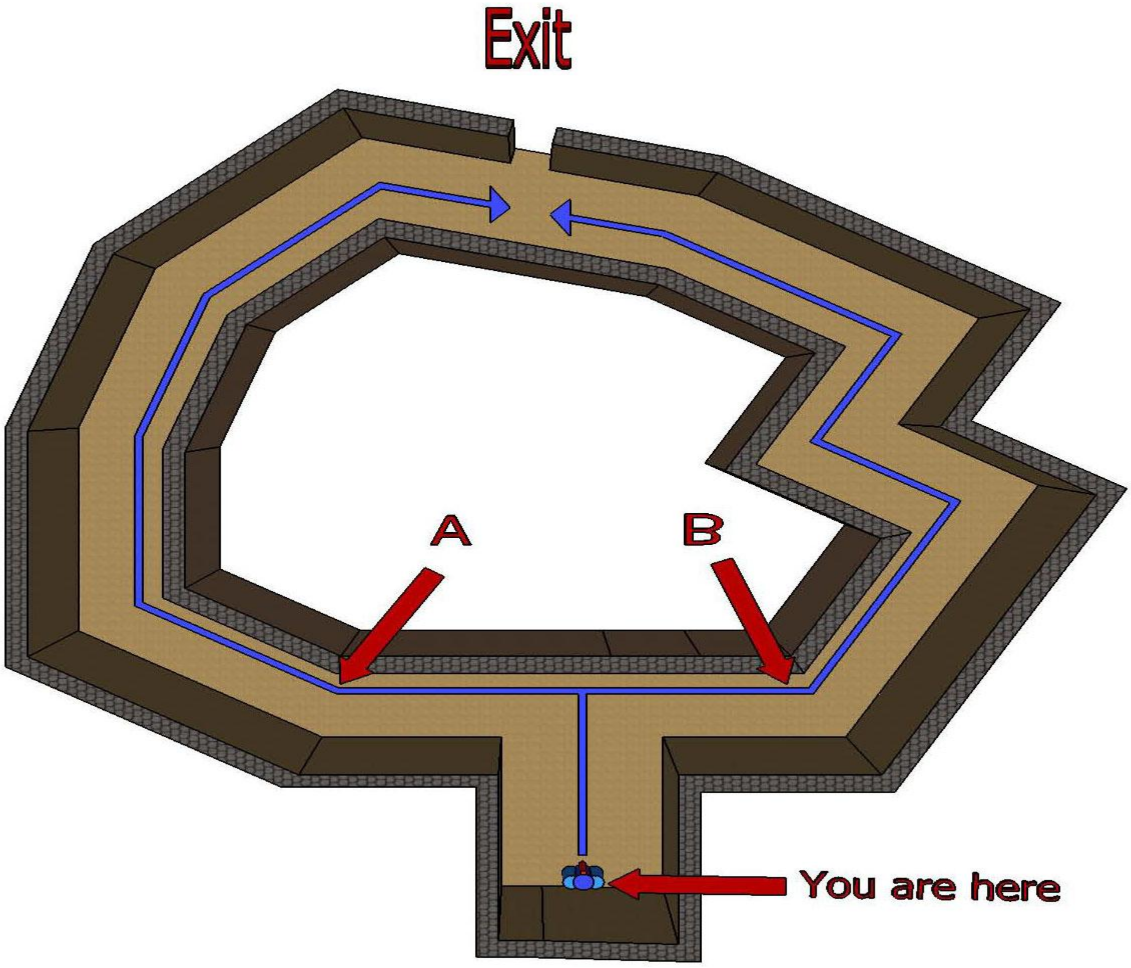
Path A Path B

If you chose a path different from the one you chose in 16A, please state what made you change the path?(maximum 200 characters)

Question 17

Situation:

You are **alone** in the building shown below.
Your initial location is indicated by the arrow labelled You are here.
You are completely familiar with the building layout.
The only exit is located on the opposite side of the building labelled EXIT.
You have a choice of two alternative paths leading to the exit.
BOTH PATHS ARE OF EQUAL LENGTH
BOTH PATHS HAVE THE SAME NUMBER OF BENDS
PATH B HAS SHARPER BENDS



Question 17A: Which path would you choose to exit from this building under NORMAL, NON-EMERGENCY CIRCUMSTANCES?

Path A Path B

Please briefly state why you preferred the selected path.(maximum 200 characters)

Question 17B: Please rate the preference for the path you selected

The chosen path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 17C: Please rate the preference for the Alternate path

The alternate path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 17D: Imagine that you are now in an emergency evacuation situation in the same building. You can hear the fire alarm and you can see that both paths appear to have a small amount of smoke. Which path would you now choose?

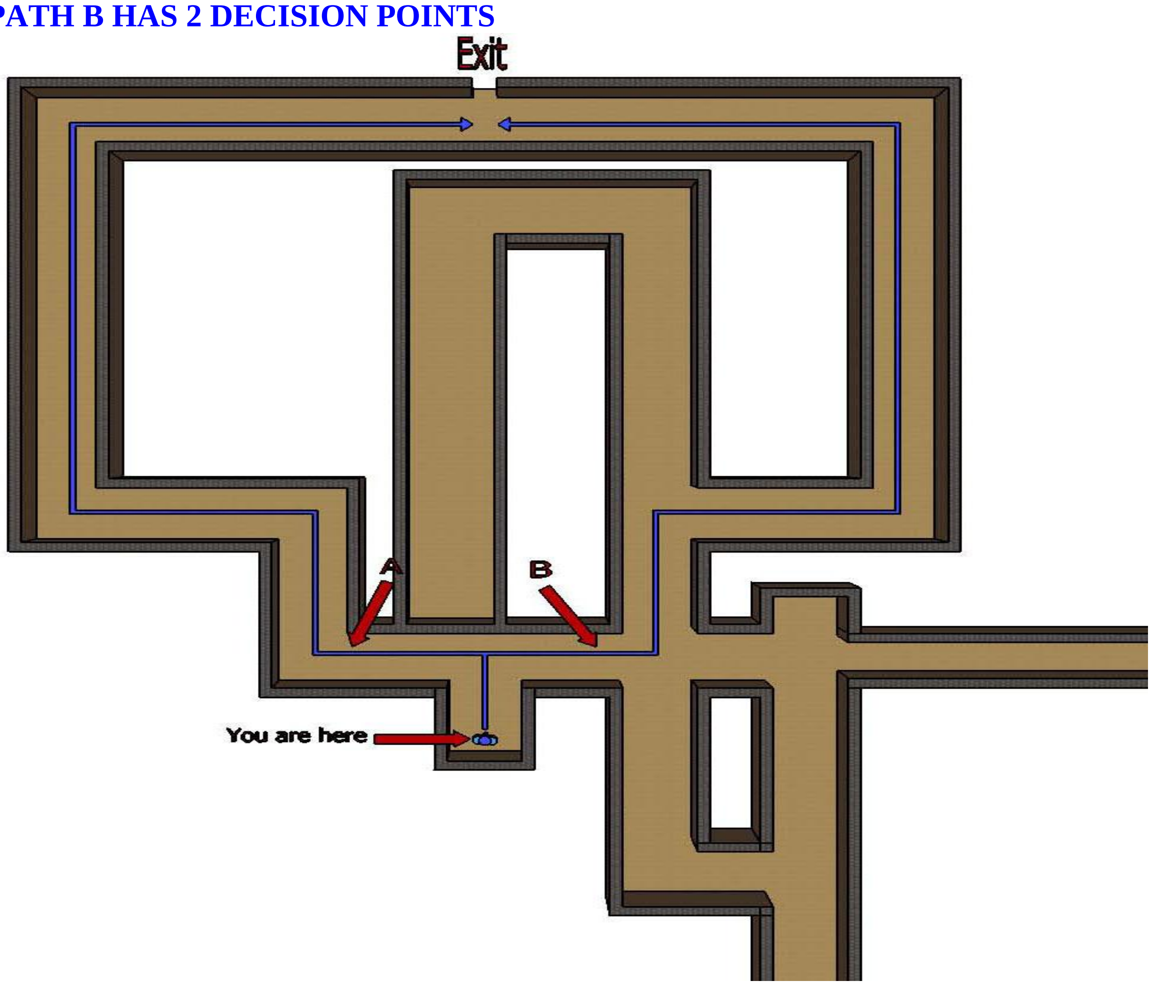
Path A Path B

If you chose a path different from the one you chose in 17A, please state what made you change the path?(maximum 200 characters)

Question 18

Situation:

You are **alone** in the building shown below.
Your initial location is indicated by the arrow labelled You are here .
You are completely familiar with the building layout.
The only exit is located on the opposite side of the building labelled EXIT .
You have a choice of two alternative paths leading to the exit.
BOTH PATHS ARE OF EQUAL LENGTH
BOTH PATHS HAVE THE SAME NUMBER OF BENDS
PATH B HAS 2 DECISION POINTS



Question 18A: Which path would you choose to exit from this building under NORMAL, NON-EMERGENCY CIRCUMSTANCES?

Path A Path B

Please briefly state why you preferred the selected path.(maximum 200 characters)

Question 18B: Please rate the preference for the path you selected

The chosen path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 18C: Please rate the preference for the Alternate path

The alternate path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 18D: Imagine that you are now in an emergency evacuation situation in the same building. You can hear the fire alarm and you can see that both paths appear to have a small amount of smoke. Which path would you now choose?

Path A Path B

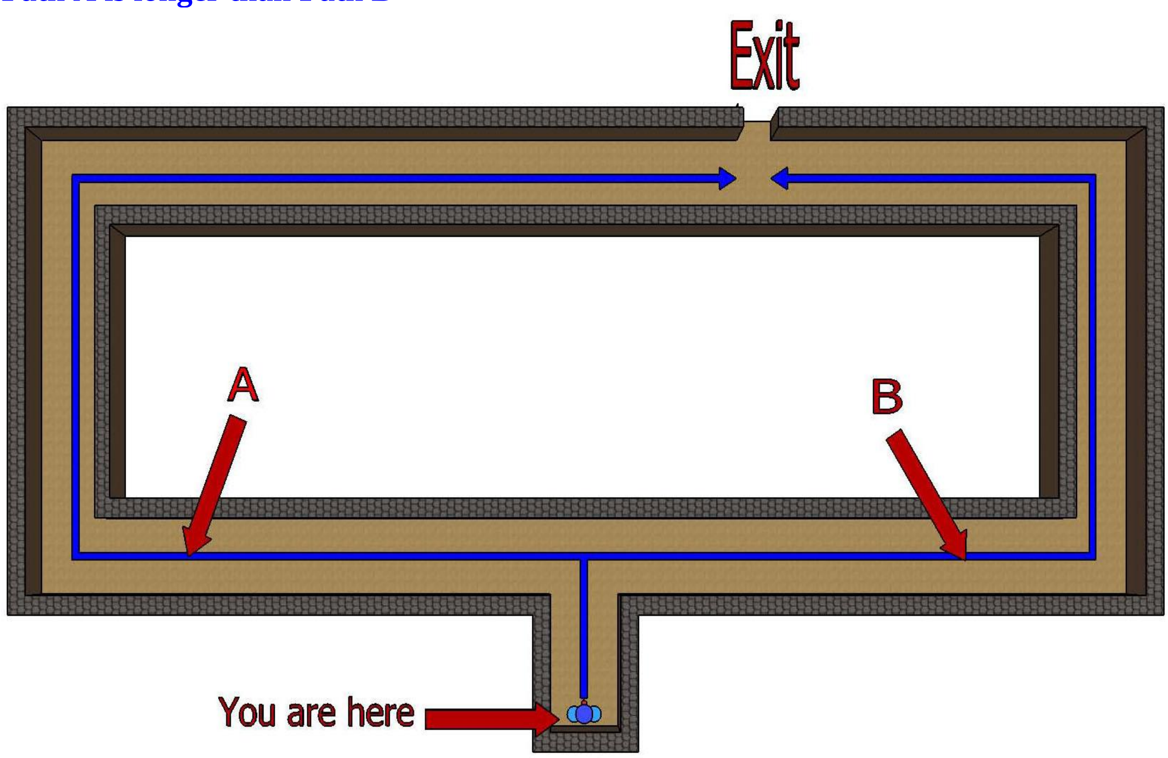
If you chose a path different from the one you chose in 18A, please state what made you change the path?(maximum 200 characters)

E.8 Questionnaire 2b

PART 3

Question 14

Situation:
You are **alone** in the building shown below.
Your initial location is indicated by the arrow labelled You are here.
You are completely familiar with the building layout.
The only exit is located on the opposite side of the building labelled EXIT.
You have a choice of two alternative paths leading to the exit.
Path A is longer than Path B



Question 14A: Which path would you choose to exit from this building under NORMAL, NON-EMERGENCY CIRCUMSTANCES?

Path A Path B

Please briefly state why you preferred the selected path.(maximum 200 characters)

Question 14B: Please rate the preference for the path you selected

The chosen path was
1. Highly Undesirable
2. Very Undesirable

3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 14C: Please rate the preference for the Alternate path

The alternate path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 14D: Imagine that you are now in an emergency evacuation situation in the same building. You can hear the fire alarm and you can see that both paths appear to have a small amount of smoke. Which path would you now choose?

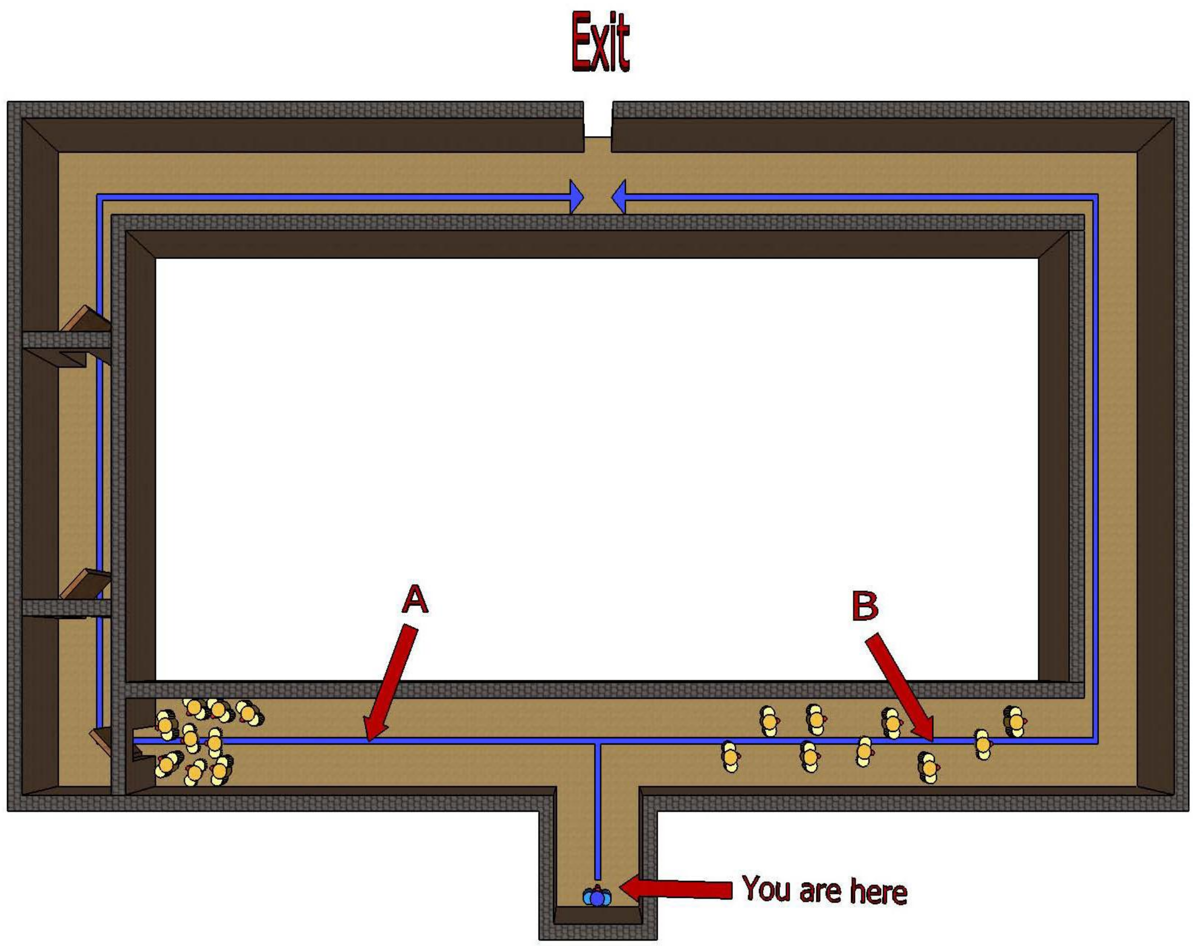
Path A Path B

If you chose a path different from the one you chose in 14A, please state what made you change the path?(maximum 200 characters)

Question 15

Situation:

You are in the building shown below.
Your initial location is indicated by the arrow labelled You are here .
You are completely familiar with the building layout.
The only exit is located on the opposite side of the building labelled EXIT .
You have a choice of two alternative paths leading to the exit.
BOTH PATHS ARE OF EQUAL LENGTH
There are equal numbers of people represented by the yellow objects along each path.
Path A has 3 internal doors.



Question 15A: Which path would you choose to exit from this building under NORMAL, NON-EMERGENCY CIRCUMSTANCES?

Path A Path B

Please briefly state why you preferred the selected path.(maximum 200 characters)

Question 15B: Please rate the preference for the path you selected

The chosen path was

1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 15C: Please rate the preference for the Alternate path

The alternate path was

1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 15D: Imagine that you are now in an emergency evacuation situation in the same building. You can hear the fire alarm and you can see that both paths appear to have a small amount of smoke. Which path would you now choose?

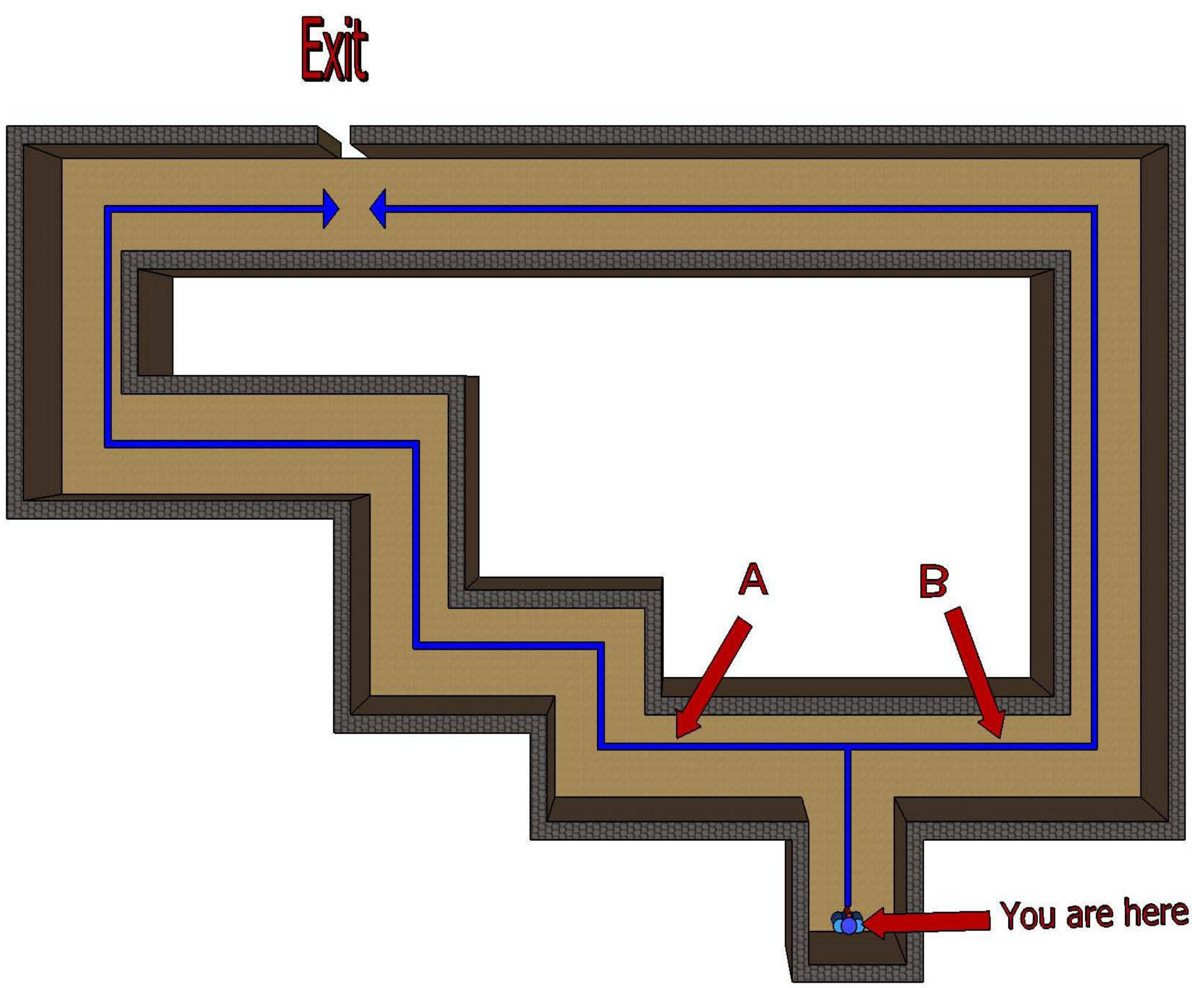
Path A Path B

If you chose a path different from the one you chose in 15A, please state what made you change the path?(maximum 200 characters)

Question 16

Situation:

You are **alone** in the building shown below.
Your initial location is indicated by the arrow labelled You are here .
You are completely familiar with the building layout.
The only exit is located on the opposite side of the building labelled EXIT .
You have a choice of two alternative paths leading to the exit.
BOTH PATHS ARE OF EQUAL LENGTH
PATH B HAS 2 BENDS AND PATH A HAS 6 BENDS.



Question 16A: Which path would you choose to exit from this building under NORMAL, NON-EMERGENCY CIRCUMSTANCES?
Path A Path B

Please briefly state why you preferred the selected path.(maximum 200 characters)

Question 16B: Please rate the preference for the path you selected

The chosen path was
1. Highly Undesirable

2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 16C: Please rate the preference for the Alternate path

The alternate path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 16D: Imagine that you are now in an emergency evacuation situation in the same building. You can hear the fire alarm and you can see that both paths appear to have a small amount of smoke. Which path would you now choose?

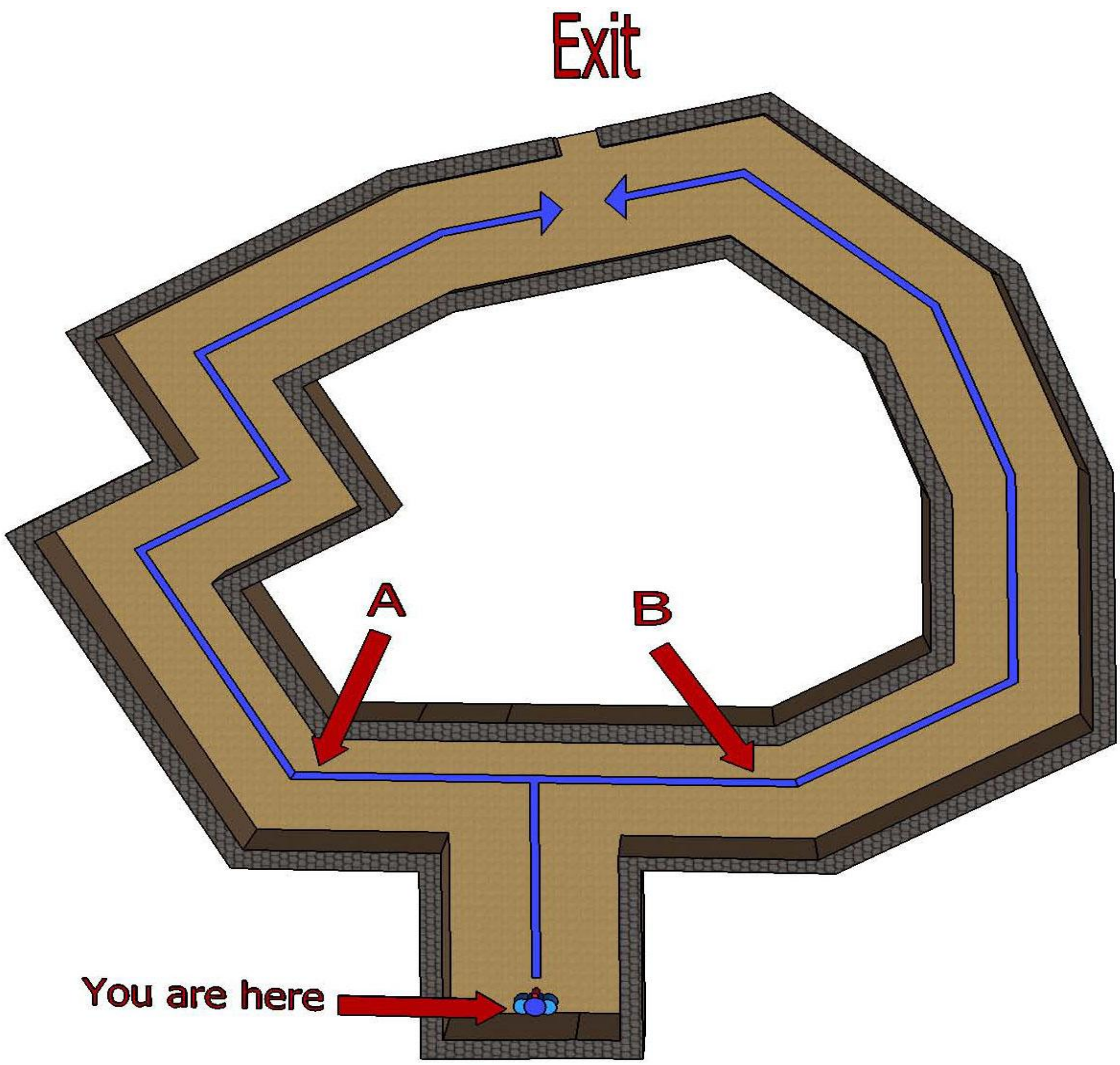
Path A Path B

If you chose a path different from the one you chose in 16A, please state what made you change the path?(maximum 200 characters)

Question 17

Situation:

You are **alone** in the building shown below.
Your initial location is indicated by the arrow labelled You are here .
You are completely familiar with the building layout.
The only exit is located on the opposite side of the building labelled EXIT .
You have a choice of two alternative paths leading to the exit.
BOTH PATHS ARE OF EQUAL LENGTH
BOTH PATHS HAVE THE SAME NUMBER OF BENDS
PATH A HAS SHARPER BENDS



Question 17A: Which path would you choose to exit from this building under NORMAL, NON-EMERGENCY CIRCUMSTANCES?

Path A Path B

Please briefly state why you preferred the selected path.(maximum 200 characters)

Question 17B: Please rate the preference for the path you selected

The chosen path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 17C: Please rate the preference for the Alternate path

The alternate path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable

6. Highly Desirable

Question 17D: Imagine that you are now in an emergency evacuation situation in the same building. You can hear the fire alarm and you can see that both paths appear to have a small amount of smoke. Which path would you now choose?

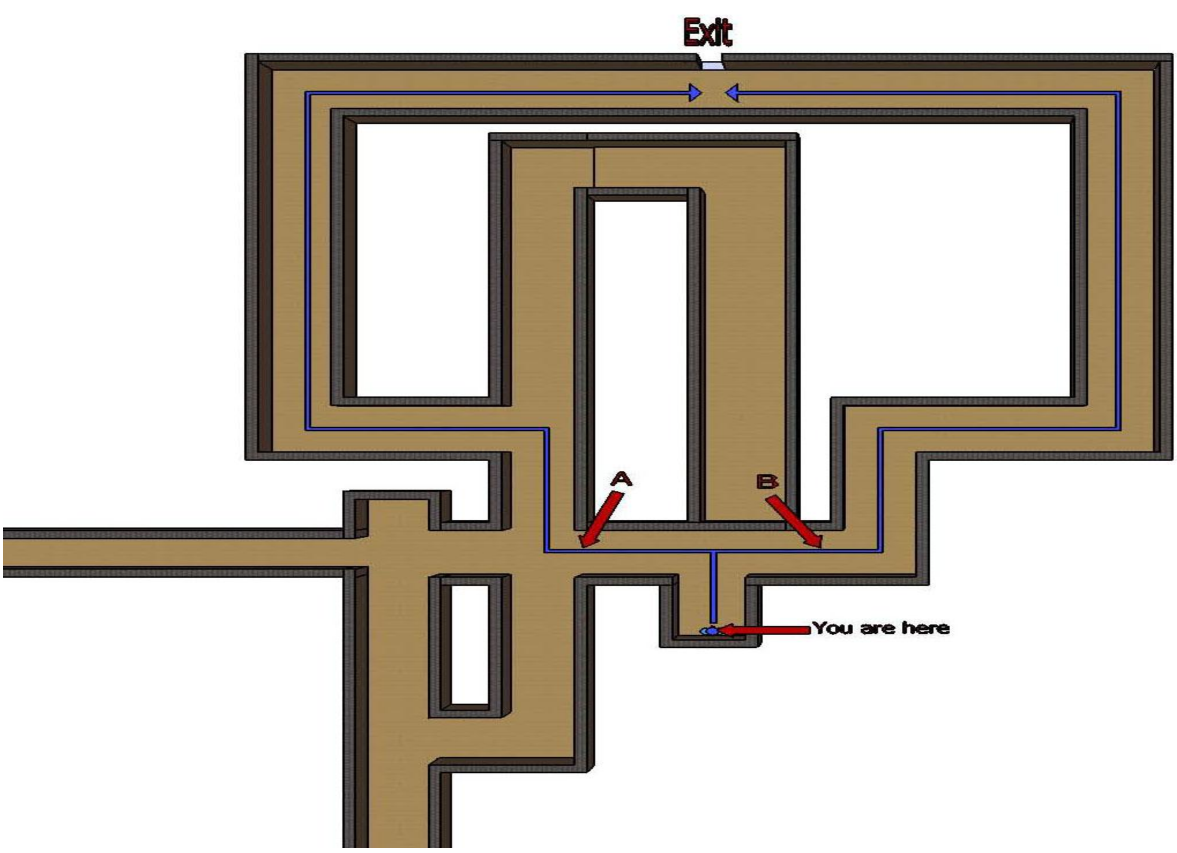
Path A Path B

If you chose a path different from the one you chose in 17A, please state what made you change the path?(maximum 200 characters)

Question 18

Situation:

You are **alone** in the building shown below.
Your initial location is indicated by the arrow labelled You are here .
You are completely familiar with the building layout.
The only exit is located on the opposite side of the building labelled EXIT .
You have a choice of two alternative paths leading to the exit.
BOTH PATHS ARE OF EQUAL LENGTH
BOTH PATHS HAVE THE SAME NUMBER OF BENDS
PATH A HAS 2 DECISION POINTS



Question 18A: Which path would you choose to exit from this building under NORMAL, NON-EMERGENCY CIRCUMSTANCES?

Path A Path B

Please briefly state why you preferred the selected path.(maximum 200 characters)

Question 18B: Please rate the preference for the path you selected

The chosen path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 18C: Please rate the preference for the Alternate path

The alternate path was
1. Highly Undesirable
2. Very Undesirable
3. A Little Undesirable
4. A Little Desirable
5. Very Desirable
6. Highly Desirable

Question 18D: Imagine that you are now in an emergency evacuation situation in the same building. You can hear the fire alarm and you can see that both paths appear to have a small amount of smoke. Which path would you now choose?

Path A Path B

If you chose a path different from the one you chose in 18A, please state what made you change the path?(maximum 200 characters)

Question 19

A number of factors which may influence your choice of route through a complex building are listed in the pull down menus in the table below.
Please rank these factors in order of importance to you, where 1 is the most important, 2 is the second most important, etc.
If you consider a factor to be irrelevant, DO NOT assign a rank to that factor.
Please rank these factors separately for Routine Conditions and for Emergency Conditions.

Order Of Importance	Factors Affecting Route Choices Under:	
	Routine Conditions	Emergency Conditions
1 (Most Important)	------------------------------	------------------------------
2	------------------------------	------------------------------
3	------------------------------	------------------------------
4	------------------------------	------------------------------
5	------------------------------	------------------------------
6	------------------------------	------------------------------
7	------------------------------	------------------------------
8	------------------------------	------------------------------
9 (Least Important)	------------------------------	------------------------------
	Click To Reset	Click To Reset

Question 20

Please state any other factors that you think may influence your route selection process and rank their importance using the same scale as above (maximum 200 characters)