MODELLING THE IMPACT OF SIGNAGE SYSTEMS ON PEDESTRIAN AND EVACUEE BEHAVIOUR

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DECLARATION

I certify that the work contained in this thesis, or any part of it, has not been accepted in substance for any previous degree awarded to me, 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 the contents are not the outcome of any form of research misconduct.

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ABSTRACT

The ability to use signage information to wayfind and determine the location of facilities within buildings is an important component in the successful use of the space. In reality, there are various types of signs (routes, services, location, etc.) for general circulation and evacuation procedures, which normally form a chain along the intended route that leads to the desired target location within the premises or a place of safety; the signs do not work in isolation. Despite the importance of signage information in helping occupant identify and follow the intended route, the effectiveness of signage, depending on the design of the signage system, the environmental conditions and the viewer attributes, etc. have been generally ignored in most evacuation/pedestrian models. A few evacuation models such as PEDROUTE, buildingEXODUS and MASSEgress do have a representation of emergency exit signs allowing agents to detect signs and use this information to find a way out of the structure. However, this is mostly based on the detection and interaction with a single sign. Representing the interaction between agents and a series of signs is crucial to properly simulate people's wayfinding behaviour, especially in an unfamiliar environment.

The work presented in this thesis is about a new signage-based navigation model developed specifically to improve the representation of the interaction between agents and series of signs in evacuation modelling (and potentially circulation modelling). The enhancement to evacuation modelling in terms of the agent wayfinding through this work includes: combining signage (with direction) and navigational graph to expand agent's visual perception of the environment and sense of direction, introducing a preliminary form of cognitive understanding of the building layout through memory and providing individual level decision-making capability for wayfinding in both familiar and unfamiliar environments. The new model allows the simulation of the agent's active wayfinding behaviour through detecting the signs in a chain to follow the intended route. The model also allows the agents to build up and use individual navigational experiences to search a way out when there is imperfect signage information (e.g. an incomplete signage chain) or even a lack of signage information.

The new signage-based navigation model was implemented within the buildingEXODUS evacuation simulation tool using C++ programming language. The model can also potentially be implemented within other evacuation and circulation simulation tools to allow the study of

the effectiveness of signage systems in a built environment. The enhanced capability of the new model has been verified through a series of verification cases and the improvement over the existing signage model within buildingEXODUS has been demonstrated through evacuation analysis performed over a hypothetical evacuation scenario.

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Chapter 1 Introduction

1.1 Background and research motivation

This thesis is about a new signage-based navigation model developed specifically to improve the representation of the interaction between the agents[1] and series of signs within software-based evacuation (and potentially circulation models). The model allows the simulated agents to perceive and follow escape route signage, which identifies the location and direction of the means of escape and guides them to a final exit or a place of safety from the premises. The model also allows the agents to build up individual navigational experiences and search a way out when there is inadequate signage information or even a lack of signage information.

Currently, in England and Wales the Regulatory Reform (Fire Safety) Order, 2005, which covers fire safety in non-domestic premises, requires adequate means of escape to be provided for all building occupants. Within the EU, similar requirements are given in the 89/654/EEC Directive that covers safety and health at the workplace. Means of escape is a safe route or routes that are provided for occupants to travel from any spot within the premises to a place of safety [BS 5499-4:2013, BS 9999:2017]. The design of the means of escape routes takes into account the use of the building, occupancy characteristic, travel distances, exit capacity and the risk profile associated. It is generally required that alternative escape routes should be provided to compensate the possibility of losing an escape route due to fire, smoke or fumes. Moreover, multiple escape routes should be provided to meet the requirement of evacuating the maximum number of occupants may be present within the available safe-escape time (ASET) [ISO/TR 13387-8:1999, ISO/TR 16738:2009]. Finally, the routes from each place within the premises should normally have the shortest travel distance to a place of safety.

The escape routes planned for a building can pose a wayfinding difficulty to the occupants. This is because firstly, it is often not possible to have direct sight of an exit or the open air at most place within a building. In general, with the increasing size of the building and complexity

[1] In this thesis, the term occupant is used in discussion of real-world matters, and the term agent is used in discussion of simulations.

of the building's layout, the available escape routes can form a complex network. Within the network, escape routes can have changes in level and/or direction, and the routes can cross each other and open areas. Secondly, it is often optimistic to assume that everyone is familiar with the building layout. Even people who are a regular user of a building may still be unfamiliar with the escape routes designated for use in an emergency.

The solution to the wayfinding difficulty in buildings is to implement an escape route signing system that provides simple and clear identification of the means of escape [BS 5499-4:2013, BS EN ISO 7010]. The Regulatory Reform (Fire Safety) Order, 2005 requires that

> "*in order to safeguard the safety of relevant persons … emergency routes and exits must be indicated by signs;…*".

And more specifically, the essential building fire safety standard BS 9999:2017 [BS 9999:2017] indicates that

> "*Fire safety signs and signing systems form an integral part of the overall fire safety strategy of a building …. Clearly visible and unambiguous signage is essential for speedy escape, particularly in buildings where many of the occupants might be unfamiliar with the building layout.*"

The principles of designing and setting up an escape route signing system in a building have been set out in relevant national and international standards, such as BS 5499-4, BS 5499-10, BS ISO 3864-1, BS EN ISO 7010. In essence, the signs should indicate the primary escape routes within the building and each route normally requires a series of signs that form a signage chain along the route [Filippidis *et al.*, 2008]. By correctly identifying the signage symbol, reading the text and following the direction of the escape route signs, the occupants, who may be unfamiliar with the premises and possibly under conditions of stress, can escape from any place in the building to a place of safety using a planned escape route without assistance. In summary, exit signs and signage system[2], which assist people in finding their way out, are an

[2] There are five types of safety signs based on the safety meaning they represent. These are prohibition signs, mandatory sign, hazard signs (warning signs), fire equipment signs (fire safety signs) and safe condition signs

essential part of the fire safety strategy of a building. They are particularly important in the event of an emergency such as a fire where an efficient and safe evacuation from the building is needed, given time is precious and some of the occupants might be unfamiliar with the building layout.

Signage systems, as a solution to wayfinding difficulty, are now widely used in buildings to provide general information and safety messages to the occupants and assist them in wayfinding during both circulation and evacuation. However, the effectiveness of signage remains unclear and undefined, despite the extensive guidance on the planning and designing of signage systems [Xie, 2012]. It is often assumed by designers, engineers and building officials that if the signage systems, which comply with the design and installation criteria, are present in a building, the occupants will perceive and interpret the signs, and follow the message conveyed by the signs [Benthorn & Frantzich, 1999]. Several high profile disasters, such as the Beverly Hills Supper Club fire in 1977 [Best, 1977], the Scandinavian Star Disaster in 1990 [The Scandinavian Star Disaster of 7 April 1990], the Cook County Administration Building fire in 2003 [James Lee Witt Associates, 2004], the Station Nightclub Fire in 2003 [Grosshandler *et al.,* 2005a, 2005b] have demonstrated that the exits were not used evenly which in turn indicated that escape route signs were not as effective as they should. Research into the effectiveness of signage also revealed that people may not perceive and follow the signage information even when it is readily available [Weisman, (1985), McClintock *et al.,* (2001), Xie *et al.,* (2011), Xie, (2012)]. Correctly estimating the effectiveness of signage systems in buildings and improving the design of signage systems as an aid for wayfinding becomes a critical issue for building fire safety.

The rapid development of computer simulation and pedestrian modelling techniques enables researchers to study occupant's movement and behaviour in normal circulation and emergency evacuation [Gwynne *et al.,* 1999; Kuligowski *et al.,* 2010]. These techniques provide a virtual representation of a real-world scenario based on research and empirical data by using pre-defined rules. The pedestrian/evacuation models also play an important role in determining the

(BS5499-1:2002, BS ISO 3864-1:2011). This research focusses on safe condition signs especially the escape route signs signifying the location of exit and direction of egress route [BS 5499-4:2013, BS EN ISO 7010].

structure's safety issues because it affirms the results provided by performance-based codes [Tavares and Galea, 2009].

The aim of simulating techniques is to model the pedestrian/evacuation scenarios to provide results close to real-world such as determining the adequate time for the occupants to evacuate safely. Due to this, the demands of pedestrian/evacuation have been increased in research and work within the Fire Safety Engineering industry [Ko *et al.,* 2007]. Furthermore, today's complex demands of design spaces challenge the prescriptive design codes and hence, designers and regulators choose the performance-based approach and evacuation models [Tavares and Galea, 2009].

These evacuation models provide an ideal platform to simulate the interaction between agents and signs and estimate how signage systems may facilitate an evacuation [Gwynne *et al.,* 1999; Kuligowski *et al.,* 2010]. However, most of the simulation models lack the capability to represent the interaction between the agents and signs, especially series of signs [Filippidis *et al.,* 2003], in normal circulation and emergency evacuation. This is because most simulation models focus on estimating the evacuation efficiency of a structure in a relatively ideal situation, where it is commonly assumed in modelling and simulation that the agents are aware of the internal connectivity, the location of exits and their targets, ignoring agent's wayfinding process using external source of information, such as signage systems.

Wayfinding is a navigation process that involves receiving, storing and processing directional information [Arthur and Passini 1992]. Some evacuation simulation models [buildingEXODUS (Filippidis *et al.,* 2001, 2003, 2006, 2008; Xie *et al.,* 2007, Galea *et al.,* 2011), PEDROUTE (PEDROUTE V5 Manual), MASSEgress (Pan 2006) and Chu *et al.,* 2015] have the capability of representing signage and allow agents to find an escape direction through detecting and following signs. However due to the lack of an understanding of structure layout and space connectivity, the agents have limited capability to use the signage information in a successive wayfinding process to a final exit point. For instance, in the existing signage model in buildingEXODUS, if an agent detects a sign, he will be directed to a designated spot rather than moving in the signage direction [Filippidis *et al.,* 2006, 2008]. If the agent following a signage direction fails to detect the next sign in the signage chain or find an exit, the agent will execute arbitrary backtracking, searching behaviour [Filippidis *et al.*, 2006, 2008] or even random walk in MASSEgress [Pan 2009]. This can potentially result in the agent being trapped in unrealistic milling movement. Lastly, these models require an agent to be assigned a target to navigate the surrounding space.

In this thesis, a new signage-based navigation model is proposed and implemented to address the above issues and improve the representation of the interaction between the agents and signage in wayfinding. The improvement is achieved through the introduction of agent's spatial awareness, individual memory and exit route decision making using the perceived space and signage information.

In the new model, the agents' spatial awareness is built upon a highly abstract network called navigational graph [Chooramun, 2011]. The navigational graph is composed of waypoints located at places where the boundary curves inward and lines connecting the waypoints that are visible to each other. By looking at the adjacent visible waypoints and the associated lines, the agents obtain a sense of space connectivity within their range of vision. Then combining the signage visibility [Filippidis *et al.*, 2001, 2003, 2006, 2008; Xie *et al.*, 2007] and the navigational graph, the agents are able to follow the direction indicated by the signs, i.e. the direction of the escape routes.

Agent memory is introduced to create an individual navigational experience. The memory stores agent's acquired wayfinding information including visited places and perceived signs. The information is used in exit route selection to differentiate visited and unvisited spaces and routes. This allows the agents to avoid repeatedly visiting the space where they could not find viable exits. In addition, the memory allows the agents to explore spaces without always relying on an assigned target. This is particularly useful in modelling the agent exploring an unvisited space.

The model developed through this research allows the designers, engineers and researchers to examine the interaction between occupant and signage in a building in a more accurate and effective way. The effectiveness of evacuation signage systems in guiding people's evacuation can be better estimated and thus it could potentially lead to safer buildings by improving the design of the signage systems. Furthermore, this work could also be of aid in the development of smart buildings [Wong *et al.*, 2005; Buckman *et al.,* 2014] and intelligent signage systems [Galea *et al.*, 2016, 2017].

The research conducted in this thesis is interdisciplinary and researchers from various fields may find this work useful. Chapter 2 provides a comprehensive review of wayfinding and the factors affecting wayfinding, which can be an interest to the researchers who are interested in wayfinding and human behaviour. Chapter 3 discusses the evacuation modelling in depth which can be useful to model developers. The design and implementation of the new signage-based navigation model are explained in Chapter 4 which should be useful to evacuation/circulation model developers. In Chapter 5 the new model is verified through component testing and qualitatively validated which again should be useful to evacuation/circulation model developers. The capability of the new signage model demonstrated in Chapter 6 should interest model designers, engineers to develop an understanding between different procedural, structural and signage designs.

The new signage model developed in this thesis can be applied to other evacuation models subject to some conditions (see Section 4.7 in Chapter 4). Hence, model developers can use the same notions and techniques to implement a signage model suitable for their model.

1.2 Research questions

In order to improve the representation of the interaction between the agents and signage systems (chain signage or signage network), the following research questions are raised.

Question 1: How do people perform wayfinding in a built environment?

(Q1.1): How does the signage system influence people's wayfinding in a built environment?

(Q1.2): What are the factors influencing the effectiveness of signage?

Question 2: How does the impact of signage on evacuation performance is represented in existing models?

(Q2.1): What are the limitations of the existing models?

(Q2.2): What are the aspects of modelling that can be improved?

Question 3: How to expand the representation of human visibility without significantly increasing the demand for computational power?

(Q3.1): What are the existing approaches in evacuation and circulation models for modelling agent's visibility?

(Q3.2): How to improve and utilise the representation of human visibility to better represent agent spatial awareness?

Question 4: How to efficiently represent and store the information agent perceived to form an understanding of building layout?

(Q4.1): How to store agent's wayfinding experience?

(Q4.2): How the stored wayfinding experience can be used to build up individual navigation experience?

Question 5: How the introduction of spatial awareness and individual navigation experience can improve the modelling of wayfinding behaviour in an evacuation and circulation?

(Q5.1): How to represent occupant's decision-making process based on their perception of the environment and individual navigation experience?

1.3 Research objectives

This research is an attempt to develop a framework, which will allow the user to simulate wayfinding scenarios using chain signage on cognitive enabled occupants. In order to fulfil the main objectives, this research is proposed to:

- Analyse advanced research on signage and the representation of the interaction between the agents and signage in currently available evacuation and circulation models.

- Examine how people in real world perform wayfinding and interact with signage.

- Analyse the current understanding and need of signage systems in addition to how occupants interact with the signage system.

- Investigate the wayfinding characteristics employed in various evacuation and circulation models to analyse the strengths and weaknesses of current procedures.

- Review evacuation modelling in general and gain practical knowledge of the buildingEXODUS evacuation model [Galea *et al.*, 2011]. The buildingEXODUS evacuation model was a suitable choice for test platform due to its sophisticated features, availability and technical support.

- Based on the research gaps identified, to develop a novel signage-based navigation model featuring agent's sense of space connectivity and direction, memory and decision-making mechanism.

- Demonstrate the new model implemented within buildingEXODUS by modelling the evacuation scenarios over a hypothetical structure.

1.4 Contribution

This study has developed an improved signage model for modelling the agent's wayfinding behaviour for evacuation modelling and potentially circulation modelling. The signage model uses the combination of signage visibility and navigational graph to allow an agent to construct a cognitive sense of the environment so that he can actively plan and execute a wayfinding strategy in an evacuation. This provides a distinctive method of evacuation modelling, which expands the way of modelling the agent's wayfinding behaviour.

In terms of key contributions of this thesis, in Chapter 2 and Chapter 3, a comprehensive analysis of wayfinding, the factors influencing wayfinding, interaction between the occupants and signage, and current techniques used in evacuation modelling have been presented. This review identified the gaps in the knowledge and created the foundation of the new signage-based navigation model proposed and developed in this thesis.

The main contribution of this thesis is the development of a new signage-based navigation model. The new model enhances the evacuation modelling by combining signage visibility and navigational graph to expand agent's visual perception of the environment and sense of direction, introducing memory to store the navigation experience and providing individual level decision-making capability for wayfinding.

1.5 Structure of the thesis

This thesis contains seven chapters. Apart from this introduction chapter, the others are summarised as follows:

Chapter 2 (Literature Review): This chapter identifies the gaps in knowledge and creates a basis for areas that require further development and research. The chapter begins with a detailed review on the current understanding of wayfinding and the role of signage system in wayfinding. The review also covers the interaction between occupants and signage system.

Chapter 3 Evacuation Modelling: This chapter discusses the evacuation modelling in general along with the review of three selected evacuation models emphasising on the wayfinding process and the modelling of the interaction with signage is also presented.

Chapter 4 Design and Development of the New Signage-based Navigation Model: This chapter describes the design and implementation of the new signage-based navigation model. The structure of the framework and algorithmic procedures are described.

Chapter 5 Verification and Validation of the New Signage-based Navigation Model: This chapter demonstrates a series of component test cases to ensure the appropriate working of the implemented algorithms. The new model is also validated qualitatively against one of the demonstration cases in BS 5499-4:2013.

Chapter 6 The Demonstration Case: This chapter presents one demonstration case. A comparison with the simulation results produced by the buildingEXODUS signage model is presented.

Chapter 7 Conclusions and Future work: This chapter summarises the entire work and suggests the future research work.

Chapter 2 Literature Review

2.1 Introduction

In this chapter, a comprehensive review of the existing literature about human wayfinding in a familiar and an unfamiliar built environment is conducted to examine the research questions raised in Chapter 1 (Section 1.2) in order to identify the knowledge gaps.

Wayfinding is a process in which occupants find their way from their current location to their desired destination [Golledge, (1999); Conroy, (2001)]. This thesis mainly focuses on the impact of signage on the agents' wayfinding behaviour during evacuation scenarios. This chapter is divided into three parts which are presented in Section 2.2, Section 2.4 and Section 2.5 respectively.

The first part (Section 2.2) explains the occupants' decision-making process and reviews the history of wayfinding studies. Wayfinding is a spatial problem-solving process [Arthur and Passini, 1992]. A wayfinding task consists of three tasks namely decision making, decision execution and information processing. During wayfinding, occupants create a mental map or cognitive map which is a mental representation of the occupant's surrounding environment. The cognitive map is normally created based on occupants' perception and past memory. Perception allows occupants to become aware of their surrounding through their senses. Memory is the recollection of their remembered spatial information. Perception and memory enable occupants to execute wayfinding decisions.

The second part (Section 2.4) discusses the importance of safety signage explained in regulations and national/international standards. The third part (Section 2.4) focuses on signage as the main influencing factor of wayfinding. This section discusses the current understanding of the interaction between signage and occupants in a built environment (Section 2.5). Three stages are involved in occupants' interact with signage, i.e. signage visibility (Section 2.5.1), perception (Section 2.5.2) and interpretation and taking action (Section 2.5.3).

2.2 Evacuation and wayfinding

In an ideal evacuation scenario, when the fire alarm goes off all occupants start to evacuate the building with no time delay and confusion. In this scenario, all occupants are assumed to be fit with full mobility (no movement disabilities) and eventually, the evacuation process concluded safely. In a real evacuation, occupants perform various activities before and during evacuation and some of them may have disability [Bryan, (2002); Hall, (2004)].

To assess and ensure an adequate level of safety of a structure, a safety engineer utilises prescriptive or performance-based methodologies. The prescriptive methods are a set of predefined set of rules which allow the design to be just considered safe [Approved Document B, 2006]. The performance-based design is performed using the quantitative assessments of egress efficiency of the structure and requires an estimation of ASET (Available Safe Egress Time) and RSET (Required Safe Egress Time). ASET and RSET are then compared with each other to assess the level of the safety of the design. For a building to be safe, ASET should be higher than the RSET. Evacuation models (e.g. buildingEXODUS, MASSEgress, PathFinder) and movement calculations are employed to determine the RSET value which tends to focus on the physical movement of the occupants and oversimplify and underestimate the human decision-making behaviour [Gwynne *et al.*, 2017]. The essence of evacuation modelling and current techniques used in evacuation modelling are discussed in detail in Chapter 3.

In general, a conceptual decision-making model is required to be implemented within the evacuation models and movement calculations in order to more credibly represent egress behaviour [Gwynne *et al.*, 2016]. A conceptual model encompasses empirical data and theories from various emergency scenarios including fire scenarios [Kuligowski *et al.*, 2017]. Existing studies on evacuee decision-making explain particular aspects of evacuee during emergency scenarios such as fire. A brief discussion of the existing conceptual models is presented below.

According to Blumer, [1969], any decision taken in a particular scenario is a direct result of a decision-making process. The decision-making process of an occupant consists of a series of sub-processes which enable an occupant to execute a decision. In the past, several studies of evacuations have demonstrated that an occupant before taking a decision perceives cues from the surrounding, comprehends the cues, evaluates the associated risk and lastly executes a decision based on the comprehended information [Mileti and Beck, 1975; Tong and Canter, 1985; Mileti and Sorensen, 1990; Bryan, 2002]. For each phase of the process, there are defined factors which can impact each stage of the process. These factors are:

- Factors that impact whether the occupant perceives the cue from the surrounding.
- Factors that impact what kind of comprehension an occupant form based on the cue.
- Factors that impact the decision to be taken based on the acquired information.

Figure 2.1 depicts this behavioural process of an occupant.

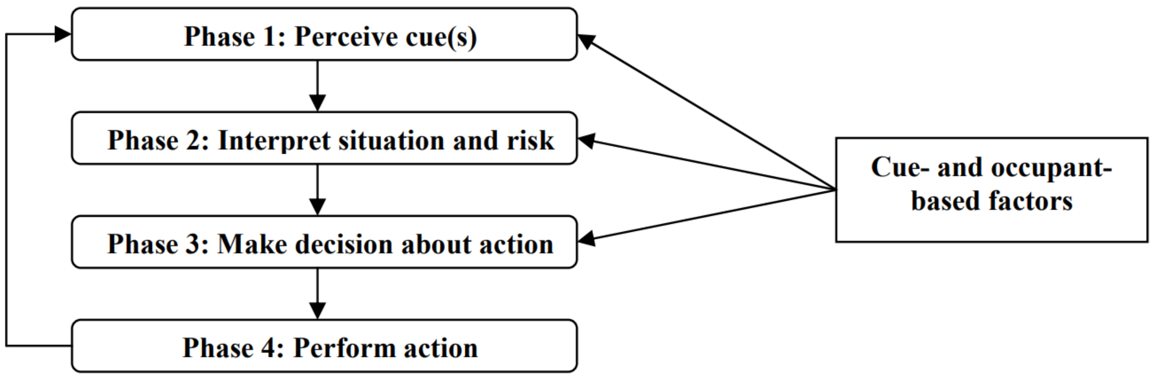


Figure 2.1: An occupant's behavioural process in an emergency scenario [Kuligowski, 2009].

From Figure 2.1, Phase 1 is a perception phase through which an occupant perceives the external (for instance smoke, debris, heat) and social cues (hearing other occupants, seeing others) from the surrounding environment [Kuligowski, 2009]. In Phase 2, an occupant attempts to interpret the cues received from Phase 1. In Phase 3, an occupant takes a decision based on his/her interpretations of the cues. Lastly, in Phase 4, an occupant may execute a decision he/she decided in Phase 3.

Breaux *et al.*, [1976] argued that occupant's past experience, the current state of mind and physiological factors can trigger the decision-making process. Breaux *et al.*, [1976] recognised three stages of their model. First, recognition/interpretation second, behaviour and third the result of the action. Similarly, the work of Canter, [1980], Tong and Canter, [1985] and Canter *et al.*, [1992] developed a decision-making model representing the order of activities an occupant performs in an evacuation scenario. According to this model, an occupant's decision-making process consists of four stages (see Figure 2.2). First, perceiving the cues; second, interpreting the cues; third, decision making based on the cues and fourth, taking action based on the selected decision. While this model was helpful in understanding occupant's decision-making, at the same time, this model lacked the specifics on the influence of the information received on particular sub-processes and their following impact on action stage [Gwynne *et al.*, 2016].

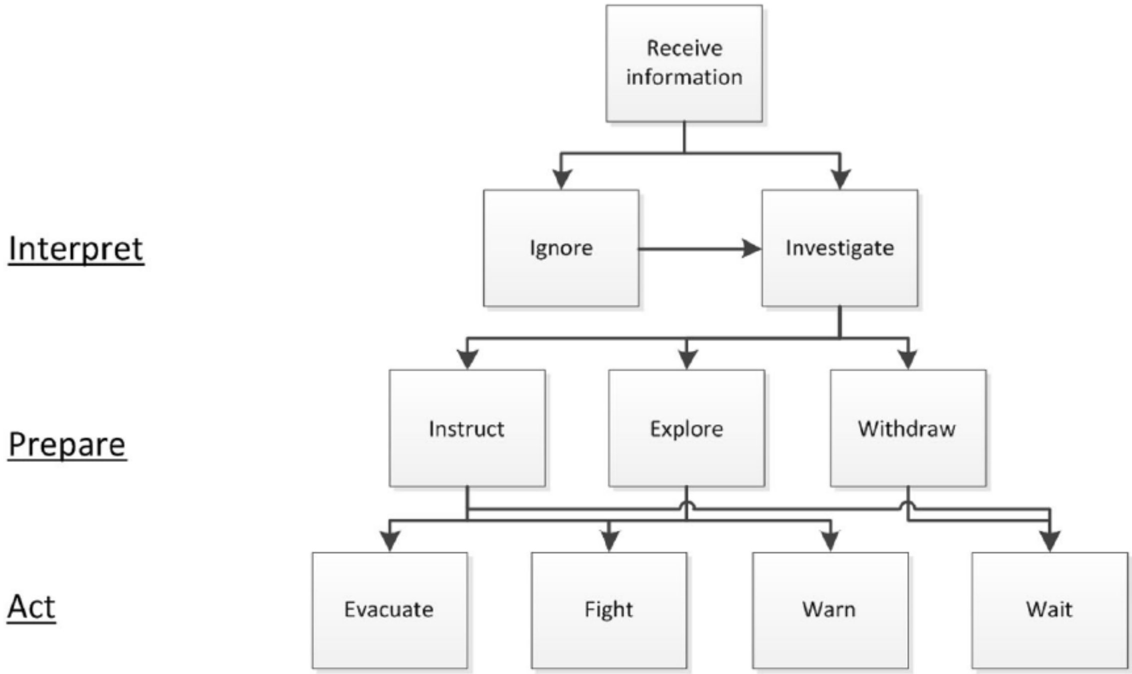


Figure 2.2: An occupant's behavioural model in fire [Canter, 1980; Tong and Canter, 1985; Canter *et al.*, 1992 and Gwynne *et al.*, 2016].

Protective Action Decision Model (PADM) [Lindell and Perry, 2004] is a framework based on five decades of empirical studies explaining the occupant's decision-making in emergency scenarios. According to PADM framework, if an occupant perceives an indication of a threat, the occupant will suspend their normal task and will either search for further information, involve in problem-solving tasks to ensure the safety of others, help other occupants to reduce their stress or recommence their normal activity [Lindell and Perry, 2004]. These actions can take place when an occupant completes pre-decisional processes which include, first an occupant must receive the cue(s) from the surrounding, second, the occupant must pay attention to the cue(s) and third, occupant should comprehend the cue(s) [Kuligowski, 2011]. After the pre-decisional processes are completed sequentially, the principle of decision-making model consists of the following five important questions [Lindell and Perry, 2004; Kuligowski, 2011]:

1. *Whether there is a real threat that I need to pay attention to?*
   - If yes, then the occupant believes there is a threat and action may be required.

2. *Do I need to take protective action?*
   - If yes, then the occupant starts searching for possible protective strategies.

3. *What can be done to achieve protection?*
   - The occupant begins searching process for possible protective action strategy.

4. *What is the best method of protection?*
   - If yes, then the occupant selects one of the strategies developed in the previous step and begins planning a protective action strategy.

5. *Does protective action need to be taken now?*
   - If yes, the occupant starts following the plan developed in the previous stage.

If at any stage through the process, an occupant is unable to answer a question, the occupant is likely to search for additional information, how to obtain the required information and what action to be taken on the acquired information [Kuligowski *et al.*, 2017]. An occupant concludes the process by implementing an action to reach a place of safety. An action can consist of behaviours namely evacuate, fight, wait and warn [Canter, 1980; Tong and Canter, 1985; Canter *et al.*, 1992 and Gwynne *et al.*, 2016]. If the occupant decides to evacuate, he/she may perform wayfinding to navigate from current location to a place of safety as swiftly and safely as possible [Brunyé *et al.*, 2010].

In summary, PADM provides a comprehensive framework encompassing the processes in which an occupant takes action to reach a place of safety. However, PADM does not discuss the factors that would influence various stages of the process, the variety of behaviours that are likely to be executed at each step and specifics related to an emergency scenario such as fire [Kuligowski *et al.*, 2017]. Figure 2.3 depicts the PADM framework.

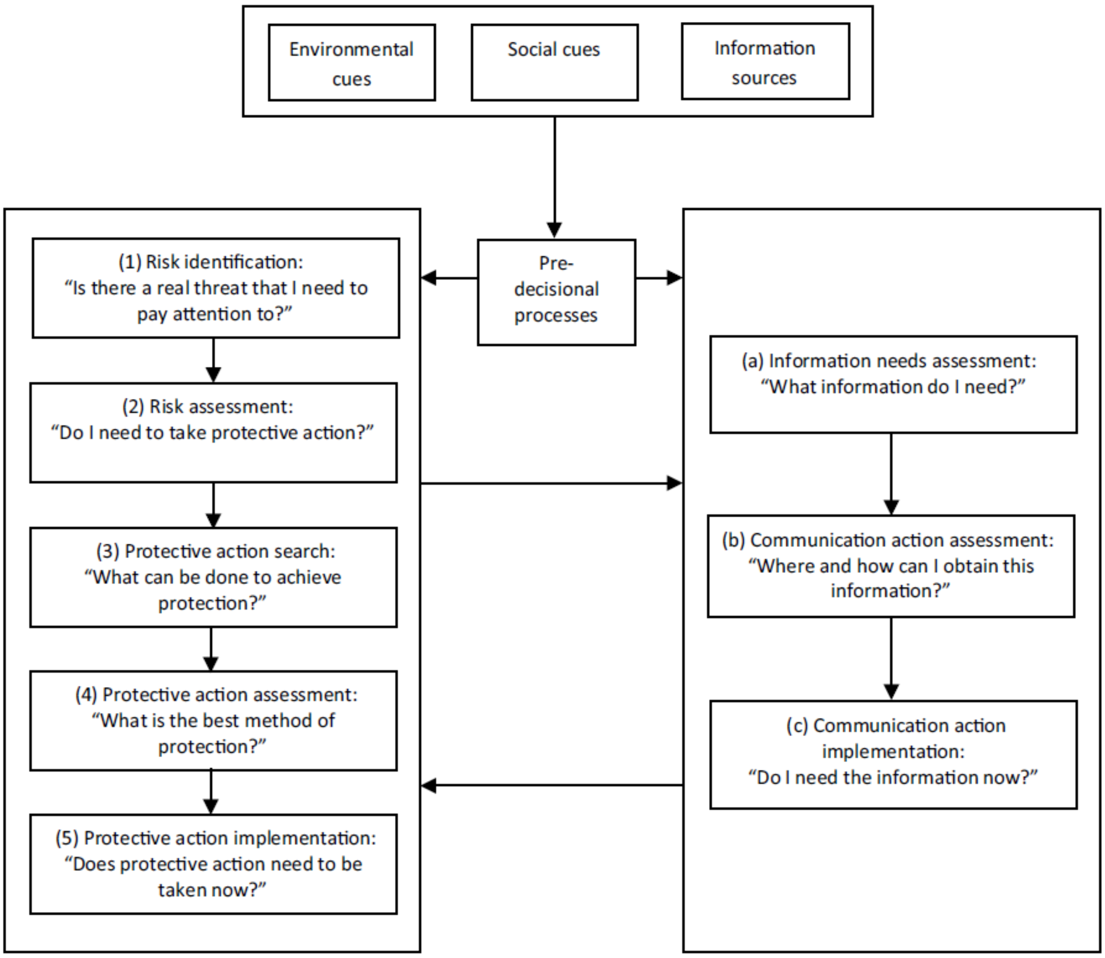


Figure 2.3: The Protective Action Decision Model (PADM) [Lindell and Perry, 2004].

These conceptual models of evacuee behaviour provide an insight into how occupants act in an emergency scenario. One of the action occupants may perform is to evacuate from the structure. An evacuation from a building is a process which requires an understanding of wayfinding, including how occupants perform wayfinding under different conditions and what are the factors which can affect wayfinding performance. Wayfinding is a process in which occupants find their way from their current location to their desired destination [Golledge, (1999); Conroy, (2001)]. Wayfinding can be influenced by various human factors and environmental factors. The human factors include previous familiarity with the structure

[Gärling *et al.,* (1983); Sime, (1985); Benthorn & Frantzich, (1999); Shields & Boyce, (2000)], social communication [Tenbrink *et al.,* 2011], spatial orientation [Lynch, (1960); Arthur and Passini; (1992); Casakin *et al.,* (2000)], cognitive mapping [Tolman, (1948); Seigel and White (1975) and Kuipers *et al.,* (2003)], route strategies [Golledge, (1995a) and (1995b)], culture [Lawton, (2001); Levinson, (2003); Frank, (2006)], gender [Schmitz, (1999); Kato &Takeuchi, (2003); Lawton *et al.,* (1996); Brown *et al.,* (1998)], age [Barrash (1994); Wilkniss *et al.,* (1997); Moffat *et al.,* (2001)] and special needs [Dutton, (2003); Wu *et al.,* (2005); Sohlberg *et al.,* (2007); Chang *et al.,* 2010]. The environmental factors include spatial differentiation [Weisman, (1981); Abu-Ghazzeh, (1996); Conroy, (2001); Montello and Sas (2006)], visual access [Weisman, 1981], layout complexity [Seidel, (1982); Montello and Sas (2006)], signage [BS 5499-4:2013; BS 5499-10:2014; BS EN ISO 7010; BS 9999:2017; BS ISO 3864-1; BS EN ISO 7010] and smoke [Jin, (1978); Jin and Yamada, (1989); Brennan, (1995)]. This thesis mainly focuses on the impact of signage on the agents' wayfinding behaviour during evacuation scenarios.

The following sections discuss wayfinding and the factors influencing wayfinding in detail.

According to Passini's [1984], wayfinding is a process where an occupant tries to reach a destination. As Arthur and Passini [1992] puts it,

"Wayfinding is a continuous spatial problem-solving process under uncertainty".

According to Arthur and Passini [1992], the term "*wayfaring"* has been into existence since the 16th century, but Lynch [1960] was the first person who formally defined wayfinding in the context of mental map or image of the environment. He argued that an individual possesses a mental image of the surrounding environment which is a crucial need for wayfinding. Since Lynch was an urban planner, his work was influential in studying the city and its elements like paths, edges, landmarks, nodes and districts and less on individual's wayfinding behaviour. His study also lacked the consideration of the impact of signage on wayfinding behaviour.

In the early 1970s emphasis was made to understand the key process of what people do to find their way and how people do that. Kaplan [1976], Downs and Stea, [1977] argued that to understand how people wayfind, the fundamental process of wayfinding needs to be learned. Therefore, a new concept of wayfinding was introduced which no longer concentrated only on spatial orientation and embodied all perceptual, cognitive and decision-making processes required for navigation. Perceptual process allows the occupants to become knowledgeable of their surroundings through their senses. The cognitive process determines an understanding of occupant's perception. And decision making involves taking decisions based on their cognition.

Using the new understanding of wayfinding, various researchers defined the wayfinding in their respective studies. According to Passini's [1984] definition of wayfinding

"To reach a destination represents a wayfinding task",

the task of wayfinding is achieved using various cues provided by signage, directions, maps and other occupants' activity. Passini also contested that an occupant while wayfinding receives cues from the environment which create a mental map or cognitive map which eventually assist the person in wayfinding task. Cognitive map refers to an image or mental representation of the environment that every occupant tries to create in their mind. An individual creates this mental image or cognitive map using the perception and the past memory regarding the structure. Perception of an occupant allows them to become aware of their surrounding through their senses and memory is the recollection of their remembered spatial information. Perception and memory when combined enable an occupant to interpret the wayfinding information and helps them to navigate further in the structure.

According to Brunyé *et al.*, [2010], the aim of wayfinding is to navigate from one point to another point as swiftly and easily as possible. They further argued, the process of wayfinding is achieved by assessing the spatial relationship between the origin and target location, recognising and comparing path options and selecting the optimal path to move. However, the target location and path choices may change under pedestrian and evacuation wayfinding. Wayfinding in routine circulation and emergency scenario differs according to destination. In a routine circulation, an occupant's priority is to reach their desired destination (for instance, finding a flight gate in an airport) [Fewings, 2001]. If the occupant is familiar with the structure, the occupant can take the shortest known route to reach their destination [Hirtle and Gärling, 1992]. Or, if the occupant is unfamiliar with the structure, the occupant may ask for directions from other people [Tenbrink *et al.*, 2011] or follow non-emergency signage to reach their destination. In an emergency situation, the occupant's priority and destination is to reach a place of safety possibly as soon as possible [Farr *et al.*, 2009]. Given the occupant is familiar with the structure, the occupant may prefer to take the shortest route to evacuate the structure or at least that route which reduces the time to reach safety. If the occupant is not fully familiar with the structure, then the occupant may use escape route signing system to find an emergency exit.

To understand wayfinding, it is required to carefully analyse [Brunyé *et al.*, 2010]

"how people perceive and understand environment", "how people locate themselves in an environment and how they use the information in the decision making and decision execution processes".

Arthur and Passini [1992] provided a framework, describing wayfinding as the process of navigation to a desired location in familiar or unfamiliar built structures, compromising of the following three processes:

- **Decision making** allows an occupant to use a viable route.

- **Decision execution** translates the decision into behaviour at the required place.

- **Information processing** process is further divided into two categories, i.e. environment perception and cognition (see Figure 2.4). Environment perception provides an insight of the surrounding environment by which an occupant becomes aware of their surrounding environment and cognition provides a mental action of understanding the perception.

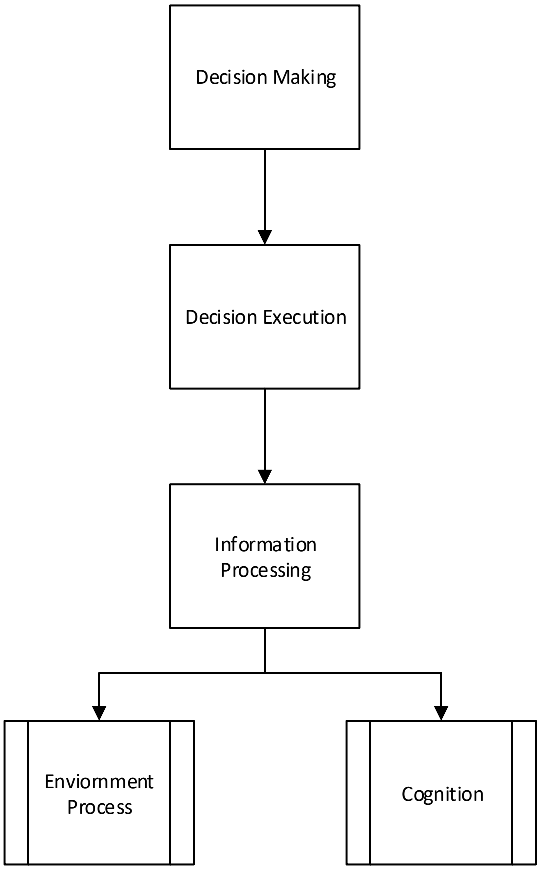


Figure 2.4: Wayfinding framework provided by Arthur and Passini [1992].

Decision Making and Decision Execution

In order to reach the destination, an occupant has to make various wayfinding decisions along the route based on perception and past memory [Arthur and Passini 1992]. If the destination is unfamiliar, an occupant has to decide what particular route to take to reach their destination. An occupant may have to make decisions sequentially at locations where there is a risk of confusion such as an intersection with multiple possible routes [Veeraswamy, 2011].

Decision making is equally important even if an occupant is familiar with the structure. An occupant may have to choose a particular route among multiple available routes. Under this kind of scenario, the occupant may choose to take the shortest available route [Hirtle and Gärling, 1992] [Golledge, 1995a and 1995b]. The occupant can change their decision if they face any obstruction or find a more advantageous route during their pursuit.

Arthur and Passini [1992] describe two decision making behavioural models namely, the optimising model and the satisficing model. The optimising model allows an occupant to consider all options and then chooses an optimal solution. Whereas, in the satisficing model, an occupant retains an acceptable solution without seeking the optimum solution. The authors further stated that the satisficing model is more inclined towards complex decision making. Hence, in a real world scenario, some occupants will select the satisficing model whereas the others will select the optimising model.

Decision making is a mental solution to a wayfinding problem; however, decision making cannot physically move an occupant to their destination [Arthur and Passini, 1992]. Hence, after making decisions, decisions must be converted into action or behaviour.

According to Arthur and Passini [1992],

"*The key to understanding the way decisions are executed lies within the compositions of the decisions itself*".

An occupant, while executing a decision, compares a mental picture of their desired target with what they perceive in the surrounding. If the mental picture matches the perceived image, the decision can be executed. If the mental picture does not match the perceived image, the decision cannot be executed and therefore requires further problem solving and decision making.

If an occupant is taking a previously known route, decision making is no longer required; however, the decision execution still takes place. For example, an occupant easily navigates from one known place of structure to another. Nevertheless, if during the navigation, an occupant finds an obstruction, such as blockage of a known route, the occupant has to rethink their approach to make a suitable decision [Arthur and Passini, 1992].

Through memory, an occupant can learn previously used routes which help them in decision execution [Arthur and Passini, 1992]. The perceived image from each decision stored in the memory should match the mental image. The matching process can occur using two operations, recall and recognition. Both actions are an important part of decision execution [Arthur and Passini, 1992].

Recognition is remembering a particular route among the presence of various routes whereas recall is remembering a particular route in the absence of all other routes. The process of executing decisions is based on recognition [Arthur and Passini, 1992]. The recognition and recall actions require memory. Occupants during wayfinding use their memory for recognition and recall previously selected routes and executed decisions.

It is assumed that while an occupant executing their wayfinding decision, they constantly compare the predicted decision images with the perceived images [Arthur and Passini, 1992]. If a mismatch of the images occurs, the occupant may react with surprise. For instance, the route to reach a park is blocked or the service road is missing. This will compel the person to execute the decisions more consciously than before. Hence, they may like to develop a new strategy to complete the wayfinding task.

Information Processing

Information processing is a series of operations performed by occupants to understand and memorise the spatial information. Information processing consists of perception and cognition [Arthur and Passini, 1992]. Perception is the ability to perceive information through the senses and cognition is the ability to understand and use spatial information.

The process of perception is based on scanning and glancing [Arthur and Passini, 1992]. In a complicated building, an occupant scans the environment using their eyes (senses). According to Neisser [1967], this is called pre-attentive perception. During this phase, an occupant usually glances at the particular feature for a tenth of a second [Adachi and Araki, 1989]. Arthur and Passini [1992] argued that the image obtained from the short glance is stored in short-term visual memory which has limited storage potential. Hence, in complex-built environments where various informational / environmental noise, such as advertising, multi-media (non-guidance) signage, etc, are present, congestion in the scanning process may occur leading to information overload. Eventually, an occupant may miss the relevant information even they are looking at the information source.

Cognition is the mental ability to acquire insight and understanding. An occupant visiting a particular building frequently may have an insight of the building internal connectivity. The understating of the building connectivity is represented by a mental image or cognitive map. The cognitive map is explained in detail in Section 2.3.1.

2.3 Factors influencing wayfinding

When occupants are faced with a wayfinding task, it is important to understand the factors influencing their wayfinding process. There are two main categories of factors which can influence the wayfinding process namely, human factors and environmental factors [Golledge, 1995a] [Golledge, 1995b] [Conroy, 2001].

2.3.1 Human factors

Enclosure familiarity

Occupant's knowledge of the layout of a building is a vital factor in wayfinding. Gärling *et al.,* [1983] discussed the role of familiarity on occupant's orientation. An occupant can achieve familiarity through a previous visit to the building or understanding the maps. Occupant's familiarity with a building affects the paths they select for navigation. According to Sime [1985], Benthorn & Frantzich [1999] and Shields & Boyce [2000], the occupants prefer to leave the building by the same route they enter or the routes with which they are familiar. The higher the level of familiarity, the more confident occupant will feel during the navigation. Whereas an occupant who is unfamiliar with the building is more likely to follow the other people [Veeraswamy, 2011].

Social communication

Built environments tend to be more congested than the urban environments [Tenbrink *et al.*, 2011]. Hence, during wayfinding, social communication like asking other occupants for directions is an important factor in making a route choice [Tenbrink *et al.*, 2011]. Social communication is a complex factor affecting building wayfinding and may be considered in the future.

Spatial orientation

Lynch [1960] defined wayfinding using the concept of spatial orientation. Spatial orientation is defined as wayfinder's ability to create a cognitive map [Arthur and Passini, 1992]. A wayfinder is spatially oriented if they have an appropriate cognitive map of the physical world where they can locate themselves within a structure [Casakin *et al.*, 2000].

According to Farr *et al.*, [2012], a successful spatial orientation depends on people's spatial ability. Spatial ability depends on sensing and cognitive mechanisms to generate, store and retrieve the visual images of the environment. People's spatial ability varies as some people find it difficult to navigate than the others. Furthermore, another important factor for creating a successful spatial orientation is the clear graphical instructions used for giving directions to a wayfinder. Some people may prefer exact route descriptions, clear instructions and precise distances for wayfinding whereas the others favour approximations based on landmarks [Farr *et al.*, 2012].

Cognitive mapping

Tolman [1948] was the first person who used the word cognitive map. He conducted various experiments on rats finding food in a maze. The food was left inside the maze structure where a roaming rat found the food. After a few iterations of the experiment, it was found that the rat was going directly towards the food without any roaming and mistakes. During the process of searching for food, rats learned the part of the environment where food was not placed and ignored using the area on later stages. Tolman contested that rats were capable of creating a cognitive map of the physical world for wayfinding and by analogy humans also create a cognitive map of an environment for wayfinding.

Tolman argued the rats' decision was influenced by the appearance of the decision point, the subsequent target and the result of turning right or left at the decision point. The executed decision at each decision point was influenced by previous decisions taken by the rat at previous decision points.

According to Darwin [1873], animals might be able to manoeuvre using path integration. In words of Müller and Wehner, [1988] path integration is

"…animal is able to continuously compute its present location from its past trajectory and, as a consequence, to return to the starting point by choosing the direct route rather than retracing its outbound trajectory."

Furthermore, Golledge [1999] proved that humans, apes, some birds and some mammals utilise a map to aid their wayfinding.

By studying the research of Tolman [1948], Müller and Wehner, [1988] and Golledge [1999], human beings build cognitive map for wayfinding in a similar fashion. A person navigating in an unfamiliar environment can create a cognitive map using the route information [Siegel and White, 1975; O'keefe and Nadel, 1979] and path integration [Gallistel, 1990]. A person can learn route information by searching the space and creating associations between perceived images of the space. Using path integration, a person is able to locate himself/herself in the structure which allows him/her to estimate the remaining distance to reach a desired destination [Gallistel, 1990]. In each attempt of finding the desired destination, the cognitive map is updated. During wayfinding under time pressure and stress, if a person perceives a negative association with a particular route, the formation of his/her cognitive map will be affected [Ozel, 2001]. When a person becomes familiar with space, he/she is likely to use the shortest route to reach his/her desired destination [Hirtle and Gärling, 1992].

The difference between humans and animals cognitive map is rationality [Meilinger, 2008], self-consciousness [Meilinger, 2008] and intentionality [Tomasello, 1999]. According to Meilinger, [2008], in contrast to animals, humans are able to refine their cognitive map by using language and drawing. Humans can give verbal directions to themselves or to other people to explain the layout of a building. Using the verbal format, a person is able to express and share the cognitive map more efficiently as compared to animals such as rats or bees which only share vector information [Von Frisch, 1967]. Humans are also able to draw the mental image or cognitive map of a structure on a paper which can provide more confidence to a person in achieving a successful spatial orientation [Meilinger, 2008].

Downs and Stea [1973] defined cognitive mapping as the process by which a wayfinder perceives, stores, recalls and decodes spatial information. Cognitive map and cognitive mapping differ from each other. Where former is the overall mental image of the spaces and later refers to the rational process resulting in the formation of a cognitive map [Arthur and Passini, 1992].

Seigel and White [1975] presented the Landmark Route Survey (LRS) model which explains the process of creating an individual’s knowledge of the space. In LRS model, first, occupants identify the distinct landmarks in the surroundings such as internal doors, external exits, rooms, lifts and escalators [Veeraswamy, 2011]. Second, occupants connect the identified landmarks with each other to form a route. This perceived knowledge is called Route Level Knowledge. During wayfinding, when the route knowledge becomes more comprehensive and clearer through signage and communication, it is called Configurational Knowledge which implies that occupant can find their way from their current location to their desired target.

In the opinion of Kuipers *et al.*, [2003], the human cognitive map can be compared to a “skeleton” containing the distinct landmarks and travel paths connecting those landmarks. Proficient wayfinders, such as taxi drivers, utilises the “skeleton” to perform wayfinding by locating the nearest point on the “skeleton” from their current location and finds a route to their destination [Veeraswamy, 2011].

Route strategies

In everyday life, people perform wayfinding tasks on a regular basis. Sometimes, they have to make potentially complicated decisions within a limited time frame. In normal circulation, a poor decision can lead to waste of time and energy whereas in emergencies, the choice of routes becomes more important as selecting the best available route can signify the difference between life and death. To understand how different route strategies influence pedestrian route selection in an outdoor environment, Golledge [1995a and 1995b] used questionnaires and found the most frequently used heuristics (see Table 2.1).

Table 2.1: Ranking of commonly used criteria in route selection [Golledge 1995a and 1995b].

Rank	Criteria	Definition
1	Shortest Distance	A direct route with the shortest distance.
2	Least Time	Quickest route.
3	Fewest Turns	Route with minimum number of direction changes.
4	Most Scenic	Aesthetically pleasing route.
5	First Noticed	Route leading in the general direction of the exit
6	Longest Leg First	Selecting the route option that has the longest line of sight
7	Many Curves	Route involved several bends ranging from shallow to 90°degree.
8	Many Turns	Route with various number of direction changes.
9	Different from Previous	Different route from the usually or previously chosen one
10	Shortest-leg First	Selecting the route option with the shortest distance to the next decision point.

The result of Golledge's [1995a and 1995b] study showed that in normal circulation, occupants prefer direct (shortest distance), quick (least time), and easy to navigate (fewest turns) routes. Whereas, in an emergency scenario, occupants tend to prefer direct and quickest route to reach a place of safety [Feuz and Allan, 2012]. Conroy [2001], Dalton [2003] reported that people prefer to take routes that have a minimum deviation from the straight line as long as it leads them to the target location.

Culture

Farr *et al.,* [2012] reported the cultural backgrounds are responsible for the differences in how structures and spatial relations are developed. They further added different languages construct wayfinding experience differently and people speaking different languages perceive and contemplate about the world differently.

The respective research of Frank, [2006] and Levinson, [2003] shows that culture has a significant impact on how people perform wayfinding. The impact of culture on wayfinding is not only apparent in different countries with different languages but also noticeable in different areas within the same country [Frank, 2006. Lawton, [2001] assessed regional cultural differences in the United States through studying people's way of providing route descriptions. He reported for providing wayfinding directions, people in the Midwest provided basic route directions (e.g, go north, go south etc.) more than people from the Northeast. Lawton concluded that choice for providing basic directions increased with age which reflects their previous experience with the route.

Gender

Various studies have demonstrated that males and females have different wayfinding capabilities [Schmitz, (1999); Kato &Takeuchi, (2003); Lawton *et al.,* (1996); Brown *et al.,* (1998)].

During wayfinding, men are found to be more confident in locating themselves in the structure and in their overall wayfinding process [Harrell *et al.,* (2000), Lawton *et al.,* (1996), Harris, (1981), Miller and Santoni, (1986) and Ward *et al.,* (1986)]. Females also tend to have more wayfinding anxiety and uncertainty than males which may influence their wayfinding capability [Malinowski and Gillespie, (2001), Lawton and Kallai, (2002), Gabriel *et al.,* (2011)].

Age

Previous literature showed that aged people complete wayfinding tasks such as routes learning poorly as compared to young people [Barrash (1994); Wilkniss *et al.*, (1997); Moffat *et al.*, (2001)]. In tasks such as learning new place using the cognitive map, younger adults perform better than older people [Moffat and Resnick (2002); Driscoll *et al.*, (2003); Moffat *et al.*, (2006)]. Furthermore, various studies have demonstrated the negative effect on elderly people's wayfinding tasks [Bruce and Herman (1983); Evans *et al.*, (1984); Wilkniss *et al.*, (1997); Cushman *et al.*, (2008)]. These tasks include understanding and organising spatial features, landmark recall and recognition, landmark location identification and self-orientation.

Special needs

Cognitively impaired people struggle with understanding a map or signage [Chang *et al.*, 2010] to even spatial disorientation at unfamiliar spaces [Wu *et al.*, 2005]. People suffering from serious traumatic brain injury may not be able to remember the known routes or forgot their desired destination while wayfinding [Dutton, (2003); Sohlberg *et al.*, (2007)].

2.3.2 Environmental factors

In a complex built environment, occupants can struggle in finding an exit or their desired target because they may find difficult to trace their navigation which would be required to create an integrated overall route. According to Carlson *et al.*, [2010], a complicated structural environment, for instance, a hospital or a library can hinder people's wayfinding capability. The aesthetic and functional features of these complex structures can put a strain on occupant's wayfinding experience. The visible and configurational features of an environmental impact on wayfinding behaviour of occupants [Carpman and Grant, 2002]. If occupants in a complex structure fail to locate themselves within the space, they may feel negative and disoriented and may avoid visiting the particular structure again.

According to Montello and Sas [2006], the wayfinding process is different under different environmental conditions, for example, the relatively flat environment and the circular environment such as underground environments. Furthermore, Montello and Sas [2006] provided the distinction between two kinds of environments, built and natural. As the names suggest, the built environment refers to an environment created by human activity and the natural environment corresponds to an environment which evolved naturally without any human intervention. The human environment consists of built structures where wayfinding is assisted by you-are-here maps and signage systems. Unlike the natural environment, human environments are “regular” in shape with straight lines and right angles.

Environmental psychologist Wiesman [1981] discussed the experimental results of how occupants perform wayfinding. He argued that plan configuration is the most influential factor on wayfinding performance followed by spatial landmarks, architectural differentiation and lastly, signs and room numbers. The results of this research were later confirmed by Gärling *et al.,* [1983] and O’Neill [1991] in their respective research studies. Weisman [1981] argued that there are four major environmental factors that influence people’s wayfinding experience in a built environment. These are spatial differentiation, visual access, layout complexity and signage. Smoke is also an important factor which can influence the wayfinding process [Brennan, 1995, Jin, 1978, Jin and Yamada, 1989]. Following is the description of each of the environmental factor.

Spatial differentiation

Spatial differentiation signifies the degree to which aspects of the environment (including size, shape, colour, layout etc.) look different [Weisman (1981); Conroy (2001)]. Montello and Sas [2006] argued that differentiated components are distinct and easily remembered; hence they are more helpful in assisting people’s wayfinding. Abu-Ghazzeh [1996] conducted a study to examine the spatial orientation and wayfinding problems in a university setting. Abu-Ghazzeh reported that inadequate differentiation contributed significantly to spatial disorientation. Passini *et al.,* [2000] also reported that the lack of differentiation in different elements within a structure can lead to the mundane pattern which can pose wayfinding difficulties to a wayfinder. Therefore, differentiation is crucial as it helps a wayfinder in perceiving and comprehending the information offered by the environment [Appleyard 1969, Passini *et al.*, 2000].

Visual access

Visual access refers to the visibility of key location within a structure from various viewing points (Weisman [1981]). According to Gärling *et al.,* [1986], it is challenging to attain visual access in a complex structure. However, if large parts of a structure are clearly visible then wayfinders utilise their vision and depend less on stored spatial information [Gibson *et al.*, 1983]. Seidel [1982] also established that wayfinding is easy for passengers arriving at the air terminals where they have direct visual access to baggage claims. Dogu and Erkip [2000] conducted a study in a mall in Turkey to examine the factors that influence wayfinding. The result of this study demonstrated that participants found the mall containing shops positioned in a circular way to be helpful for smooth navigation. To provide the advantage of clear visual access to occupants, it was suggested that structures should be built in a circular way around the open space [Baskaya *et al.,* 2004].

Layout complexity

A complex structure layout can make wayfinding difficult. As Montello and Sas [2006] puts it

"A more articulated space, broken up into more different parts, is generally more complex, though the way the different parts are organized is critical".

Furthermore, some particular patterns can make people disorienting. For instance, oblique turns are more disorienting than orthogonal turns [Montello and Sas, 2006].

Seidel [1982] conducted a detailed study to investigate the influence of physical environment on a person's wayfinding performance. The study was conducted at Fort Worth Airport in Dallas where they concluded that the physical structure of the enclosure affects occupant's wayfinding capabilities. This study recommended that airport design should be linear rather than complex "torso-and-arms" design. Due to complex design of built structures such as airports, people may pay multiple visits to become familiar with the structure.

Signage

Large-scale building such as residential blocks, stadia, shopping centres, airport terminals etc., cater to the needs of human living and travelling activities. These massive and complex structures often pose a safety question: how efficient is their wayfinding design? Especially in an emergency situation, will the occupants be able to use the wayfinding design to reach a place of safety quickly and safely?

During an emergency evacuation, occupants may have a choice of emergency exits, side exits and main exits of the structure to use during the evacuation [Ronchi and Nilsson 2016]. However according to Sime [1985], Shields and Boyce [2000], Nilsson *et al.,* [2008] and Olander [2015], occupants tend to leave the structure using familiar exits which are generally the entry points of the structure. This behaviour may cause the reduced usage of emergency exits which in turn causes congestion around the main entrance and increases the evacuation time.

Wiesman [1981] and Hajibabai *et al.,* [2007] contested that designing a signage system is an important task, as it influences the wayfinding performance of occupants. Gärling *et al.,* [1986] argued that signage has a significant influence on occupant's wayfinding behaviour which must be included in the overall layout plan of a structure. An efficient signage system can reduce the occupant's wayfinding time whereas a poor signage system can contribute to occupant's wayfinding problems.

Signage system is commonly used to provide occupants with wayfinding information and enhance wayfinding efficiency in complex structures [BS 5499-4:2013, BS 5499-10:2014, BS EN ISO 7010, BS 9999:2017, BS ISO 3864-1 and BS EN ISO 7010]. Signage system is designed to ensure that from any place within a building, where the direct sight of an exit is not possible, and doubt might exist as to its location, a directional sign (or series of signs) is provided [BS 5499-4:2013].

Smoke

The presence of smoke can create a visual barrier and cause psychological damage which influences people's wayfinding and slow down an evacuation [Brennan, 1995, Jin, 1978, Jin and Yamada, 1989]. The occupant's response to smoke is impacted by usage and familiarity with the built environment. The principle factors which affect occupant's decision to move through smoke include recollection of exit location, ability to estimate required travel distance, the severity of smoke [Galea *et al.*, 2011], smoke density and presence or absence of heat [Bryan, 1996].

When an environment is filled with smoke, it is difficult for occupants to discern the surrounding. Hence, the wayfinding behaviour of people under normal conditions is not identical to people in smoke conditions. In the past, the study of the impact of smoke on occupant's wayfinding behaviour was constrained by the harmful effect of smoke and gases.

The impact of smoke on occupants' egress performance and behaviour has been studied by several researchers with different objectives [Jin, 1978, 1997; Jin & Yamada, 1985, 1989; Wright *et al.*, 2001a, 2001b; Frantzich & Nilsson, 2004]. The impact of smoke on occupant's wayfinding can be analysed through simulation tools. The representation of smoke and its impact is currently implemented in a few evacuation models, such as buildingEXODUS [Galea *et al.*, 2011] and FDS+Evac [Korhonen and Hostikka, 2008] based on the empirical data from [Jin, 1978, 1997].

2.4 Signage in building legislation and standards

In the UK and Wales, the current Regulatory Reform (Fire Safety) Order, 2005 requires that an appropriate means of escape must be provided to the building occupants. Similar requirements are posed in the EU through the 89/654/EEC Directive which describes the minimum requirements for safety and health at the workplaces. According to BS 5499-4:2013, means of escape is defined as

"Route forming part of the means of escape from any place in a premises to a final exit".

In general, it is required to have multiple planned escape routes in a building. This is to adhere to the specification of evacuating the potential maximum number of occupants within the available safe-escape time (ASET) [ISO/TR 13387-8:1999, ISO/TR 16738:2009]. It is also a requirement to compensate the possibility of losing part of the escape routes due to structural collapse, fire or smoke. Lastly, the escape routes from each place within the premises should normally have the shortest travel distance to a place of safety [BS 5499-4:2013].

While the planned escape routes can aid the occupants in an evacuation, they cannot be automatically recognisable to the occupants and easy to choose, especially those meant to be used in an emergency. A large-scale and complex building can have multiple escape routes which are difficult to decide the optimal choice. Furthermore, the multiple escape routes can form a complex network. Within the network, escape routes may involve changing direction or crossing an open space.

To address this wayfinding problem in buildings, escape route signing system is implemented which gives proper identification of the means of escape to allow people to escape without assistance, possibly under conditions of stress [BS 5499-4:2013, BS EN ISO 7010].

According to BS 9999:2017

"Fire safety signs and signing systems form an integral part of the overall fire safety strategy of a building".

Similarly, the Regulatory Reform (Fire Safety) Order 2005 explicitly prescribes the requirement for providing escape route signing system

"Emergency routes and exits must be indicated by signs."

According to the UK standards [BS 5499-4, BS 5499-10] and international standards [BS ISO 3864-1, BS EN ISO 7010], the escape route signage should provide a clear indication of the primary escape routes. Each escape route usually requires a series of signs to form a signage chain along the route. By aptly comprehending the signage information and following the direction of escape route signs, the occupants who are unfamiliar with the building can reach their desired target without assistance. Therefore, escape route signage system is a critical requirement of fire safety strategy of a building. The escape route signage system is even more important in emergency scenarios where some occupants may not be familiar with the building.

To ensure the effective use of escape route signage system, the UK standards [BS 5499-4, BS 5499-10] and international standards [BS ISO 3864-1, BS EN ISO 7010] provide guidelines to plan escape route signage including design and location of signs. The signage design should convey the signage information clearly and correctly so that building occupants can understand the signage information. The signage information consists of text and graphical symbol which should have a good level of legibility. The escape route signs should be positioned to complete an escape route by avoiding potential points of confusion. Additional signs should be installed where the direct sight of the line is not possible, and confusion might exists to its position [BS 5499-4:2013, BS 5499-10:2014]. The signs should be installed uniformly so that occupant can predict the location of the next sign along the escape route. In summary, escape route signage should be provided according to the relevant standards to achieve clear and uniform signage information to building occupants [BS 5499-4:2013, BS 5499-10:2014].

In spite of comprehensive relevant signage legislations and standards, the effectiveness of signage systems remains unclear and undefined [Xie, 2012]. Hence, it is generally assumed by designers, engineers and building officials that if the installed signage system meets the guidelines prescribed in relevant legislations and standards, occupants will be able to perceive and interpret the signs, and follow the message conveyed by the signs [Benthorn & Frantzich

1999]. However, in the past disasters such as the under-use of emergency exits in disasters such as Beverly Hills Supper Club fire in 1977 [Best 1977], the Scandinavian Star Disaster in 1990 [The Scandinavian Star Disaster of 7 April 1990], the Cook County Administration Building fire in 2003 [James Lee Witt Associates, 2004], the Station Nightclub Fire in 2003 [Grosshandler *et al.* 2005a, 2005b] it has been shown that escape route signs were not as effective as they should. According to research work on the effectiveness of signage by Weisman [1985], McClintock *et al.* [2001], Xie *et al.* [2011] and Xie [2012], occupants may not perceive and follow the direction of a sign when it is easily available. In summary, accurately evaluating the effectiveness of signage systems in buildings and improving the design of signage systems as an assistance for wayfinding have become an important issue for building fire safety.

The next section discusses the interaction between occupants and signage systems which involves three major components. These are visibility of sign, perception and lastly, interpretation and taking action.

2.5 Interaction between signage and occupants

The interaction between the occupants and signage system is a complex process which is influenced by several physical and psychological factors [Filippidis *et al.,* (2003, 2006, and 2008)]. These include the visibility of the sign, the probability that the occupant will perceive the sign and correctly interpret the signage information, and finally whether the occupant takes an action to follow the sign.

First and foremost, the sign must be physically visible to the occupants. The visibility of a sign is determined by the location of the sign, the size and design of the sign, the signage information quality, the internal configuration of the building, the levels of lighting (both of the sign and the environment), and the presence or absence of smoke [Filippidis *et al.,* 2006]. Filippidis *et al.,* [2003, 2006] divided the interaction between occupants and signage into three stages: recognition, interpretation and action (see Figure 2.5).

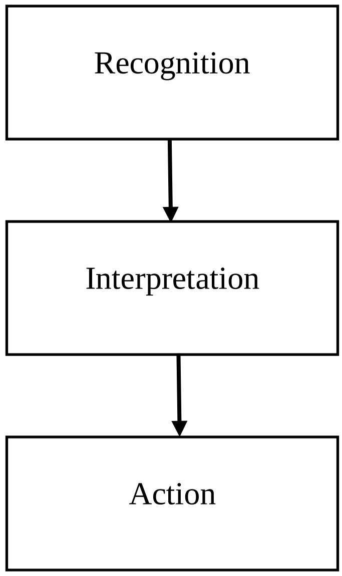


Figure 2.5: Three stages involved in the interaction between occupants and signage [Filippidis *et al.*, (2003, 2006)].

Recognition: A sign can potentially be recognised by an occupant depending on various conditions. Firstly, it is essential that the occupant is located within a definite extent of distance from the sign [Xie, 2011]. Secondly, the sign must be located inside the occupant's field of view [Xie, 2011]. Thirdly, the likelihood of perceiving a sign also depends on the internal complexity of a structure. For instance, airport terminals are often populated with various kinds of signs, from emergency evacuation and circulation signage to products advertisements. An occupant, in the midst of such abundance of signage, may lose the sight of their concerned sign [Filippidis *et al.*, 2003, 2006]. Fourthly, there is also a physiological effect due to the abundance of signage which can create information overload over an occupant posing difficulty to discern the sign. Hence, even if the sign is directly visible to the occupant, the occupant may fail to recognise the sign. Lastly, an occupant's attentiveness and the presence of mind becomes important especially in an evacuation scenario where recognising the correct sign leading to a place of safety is paramount [Arthur and Passini, 1992].

Interpretation: Interpretation of sign depends on occupant's cognitive characteristics like their own interpretation of sign and their desire to trust the information displayed. Occupant's education background and the language in which sign information is displayed also influence the interpretation of sign. There are some other occasions where occupants may choose to ignore the sign information; for instance, they may be well aware of the layout of the structure, or occupants can opt to not follow the signs due to full familiarity with the structure [Filippidis *et al.*, 2003, 2006, 2008].

Decision Execution: If the conditions permit the sign to be seen, the occupant's decision execution depends on their desire to believe and follow the signage information and the influence of other occupants and conditions [Xie, 2011].

In summary, to fully understand the interaction between signage and occupants, the following three aspects are essential to be examined in detail. First, visibility of sign and how occupants perceive the sign (phase 1); second, how occupants interpret the signage information (phase 2); lastly, how occupants make a decision to follow the sign (phase 3).

2.5.1 Visibility of sign

The understanding for visibility of sign has been evolved in last two decades. Signage standards [BS 5499-4:2013, BS 5499-10:2014] provide the guidance for design and position safety signage in a building. A crucial factor for planning a signage system is the physical range within which an occupant can discern the sign. To estimate this physical range, the relative signage standards defines maximum viewing distance of signage. The maximum viewing distance, I, is calculated based on the sign height, h, and an appropriate distance factor, z_0 [BS 5499-4:2013]. The maximum viewing distance of an escape route sign can be affected by the colour, contrast of the sign [BS 5499-4:2013], the illumination on the sign (externally illuminated sign) or the luminance of the sign (internally illuminated sign) and the presence of smoke [Jin 1978, 1985, 1997, 2008] between the occupant and the sign. In the current signage standards [BS 5499-4:2013, BS 5499-10:2014], the maximum viewing distance is calculated through the below formula.

$$I = z_0 h$$

The visibility of an escape route sign under smoke has been studied by Jin [1978, 1985, 1997] in details. Jin conducted the experiments to study the impact of various smoke on signage visibility and demonstrated that occupant's ability to discern escape route signs decreases with the increase of smoke concentrations and irritant level [Jin 1978, 1985, 1997]. Other factors which may influence the visibility of sign are the design of the signage system itself, the location of installed signage, occupant's eyesight and height [BS 5499-4:2013, BS 5499-10:2014].

Filippidis et *al.,* [2001, 2003, 2006] introduced the concept of Visibility Catchment Area (VCA) to depict the physical extent to which an agent can see the sign. The concept of VCA has been further explained in Chapter 3, Section 3.2.6.2. Initially, Filippidis et *al.,* [2001, 2003, 2006] proposed the semi-circular shape of the area within which an agent can discern the sign (see Figure 2.6, M1). The radius of this semi-circular area represents the maximum viewing distance. Due to lack of data, Filippidis et *al.,* [2001, 2003, 2006] assumed that an occupant located anywhere in the semi-circular area irrespective of their viewing angle can discern the sign (see Figure 2.6, M1). In later work of Filippidis *et al.*, [2006] it was realised that it is difficult to detect a sign at an angle 90º. However, due to lack of empirical data to understand the relative orientation between the occupant and sign, an arbitrary value of 5º (α) was removed from both sides of the semi-circular representation of the VCA (see Figure 2.6, M2). The shape of VCA was later revised by Xie et *al.,* (2007) who performed the theoretical and empirical analysis to examine the effect of viewing a sign from an angle. Xie et *al.,* (2007) argued that the maximum viewing distance for accurately discerning the sign is dependent on the viewing angle and the viewing angle is inversely proportional to the maximum viewing distance. In addition, it was suggested that the shape of VCA of a sign is a circle tangent to the surface of the sign (see Figure 2.6, M3).

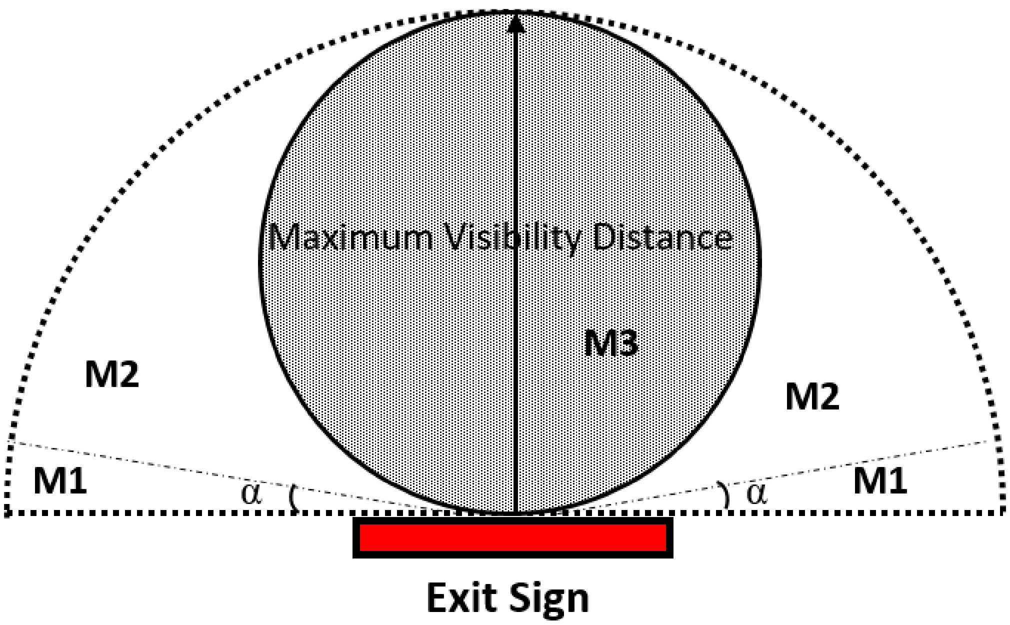


Figure 2.6: The shape of the VCA defined by Filippidis et *al.*, [2001, 2003, 2006] (M1), revised shaped of VCA defined by Filippidis *et al.*, [2006] (M2)and the circular shape of VCA defined by Xie *et al.*, [2007] theoretical model (M3).

In the current safety standard [BS5499-10:2014], the visibility of signage is estimated through the zone of influence which is defined as

"Viewing space which encompasses the eye positions of people from where the graphical symbol elements of a safety sign can be correctly identified, and a safety sign located."

The zone of influence is depicted in a shape of sphere (see Figure 2.7). The size of the sphere depends on the factor of distance z_0 [BS ISO 3864-1:2011]. The factor of distance is a relationship between the height of the sign (h) and viewing distance (l). An occupant located outside the zone of influence may be able to see the sign. BS5499-10:2014 suggests that an occupant located within or on the boundary of the zone of influence should be able to see the sign and interpret the sign information.

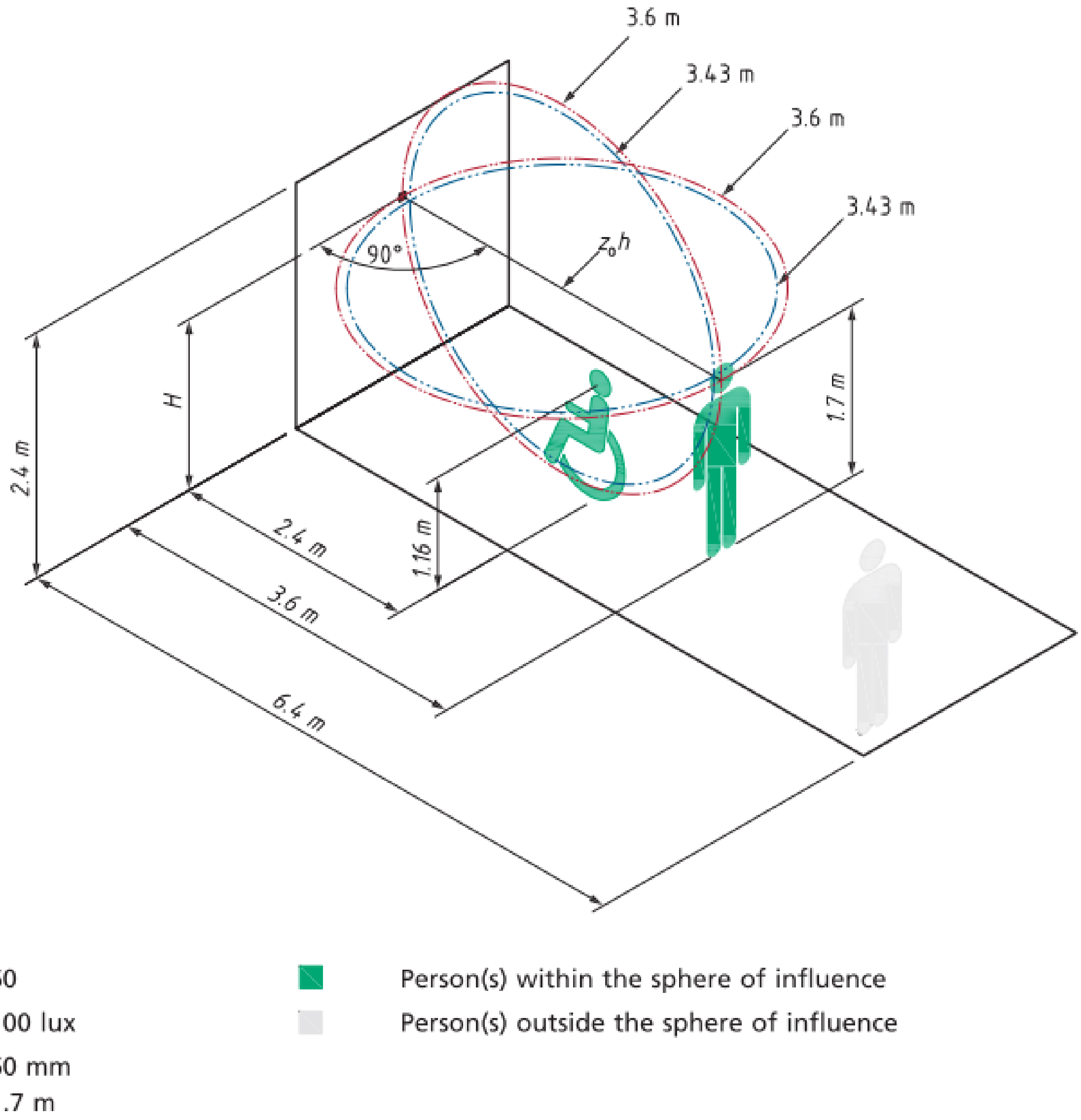


Figure 2.7: The Zone of Influence [BS5499-10:2014].

The zone of influence of a sign is influenced by the sign's location, size and position. Other important factors which also impacts the zone of influence are the angle of observation, the lighting conditions, and any visual obstructions. The observation angle is determined as the angle from the perpendicular to the sign [BS5499-10:2014]. As the occupant's observation angle moves further from the normal to the sign, the distance between the occupant and sign decreases. Figure 2.7 represents the zone of influence with horizontal and vertical rings of diameter z_0h. The sign is located at 1.7 m above the ground. The horizontal ring is located in the horizontal plane. The occupant's height is assumed to be 1.7 m. The occupant depicted in grey colour is standing outside the extent of zone of influence.

In summary, the definition of signage visibility has been developed gradually in last two decades. Initially, a single maximum viewing distance is used to define the physical range within which an occupant can discern the sign. In evacuation modelling, the signage visibility was defined using a concept called Visibility Catchment Area (VCA) to depict the physical extent to which an agent can see the sign [Filippidis *et al.*, 2001, 2003, 2006]. Based on the definition of maximum viewing distance, a semi-circular shape of the VCA was proposed. It was also assumed that an occupant located anywhere in the semi-circular area irrespective of their observation angle can discern the sign. In a later study, it was observed that it is difficult for an agent to detect a sign at an angle 90º. Hence, an arbitrary value of 5º was removed from both sides of the semi-circular representation of the VCA [Filippidis *et al.,* 2006]. A new shape of VCA was argued through theoretical analysis and experimental study to analyse the effect of viewing a sign from an angle [Xie *et al.,* 2007]. In this study, it was proved that the VCA has a circular representation.

In the current safety standard [BS5499-10:2014], a similar definition of signage visibility is adopted through the concept of the zone of influence which has a spherical shape. A zone of influence is an area within which an occupant can discern the sign and interpret the sign information.

2.5.2 Perception

Perception is the capability of occupants through which they sense the environment and become aware of their surroundings. During wayfinding, occupants perceive their surrounding environment and organised the perceived information as a mental image [Lynch, 1960].

There have been various studies in the past on occupant's perception and its impact on their movement [Gibson 1979, Sixsmith *et al*., 1988, Werner and Schindler 2004, Nilsson 2009]. Sixsmith *et al*., [1988] discussed "perceptual flow" and direction of travelling. They proposed that the occupants while navigating may fail to notice a clue as they may not face the direction in which indications were located. Werner and Schindler [2004] discussed that the positioning of different parts of the built environment plays a vital role in occupant's general understanding of the building. The authors argued with empirical evidence that an occupant's wayfinding performance and their spatial orientation in a structure depend partially on geometrical relations between different components of the structure. The authors further added that an efficient wayfinding structure should concentrate on the alignment of reference points which reduce the cognitive load and ease the wayfinding task.

Gibson [1979] is accredited for establishing a profound understanding of visual perception. He proposed a theoretical framework based on ecological psychology called the Affordance theory. This theory explains how individuals perceive the objects that they see. Gibson argued that people perceive objects as what they afford. For example, a sign is not simply seen as something that contains graphics and text, but also as something that affords navigation assistance. According to Nilsson [2009], the affordance is offered by the objects in relation to the completion of the perceiver's goal. In an emergency condition in a building, the goal of the occupants is to reach a place of safety in a minimum period of time using available means of escape. To support the safe egress, emergency exits should provide affordance in terms of distinct design, proper lighting in the environment and ease of use [Nilsson 2009]. However, the presence of affordance does not guarantee that the corresponding action will take place; rather it signifies the probability of the action [Xie, 2011]. The action depends on the process of visual perception and compliance. Xie [2011] illustrated when the occupants in a building try to evacuate using an exit, first and foremost they should see the exit. Second, they must recognise the exit as a means of safe egress. Signage as part of egress design is supplied to enhance the affordance offered by the exits.

Gibson's theory is important as it provides a sound framework for connecting occupant perception with occupant behaviour. However, Gibson's work also faced criticism for neglecting the role of cognition and memory during wayfinding [Raubal, 2001]. Cognition provides a mental action of understanding the perception of the surrounding environment and memory is the recollection of their remembered spatial information. Raubal further argued that Gibson's theory of affordance cannot explain the wayfinding process as it focusses on perception and ignores cognition. This is due to, firstly Gibson's work does not explain what kind of cognition is required during perception and how errors can be possible during perception phase. And secondly, the study explains the perception of a person without taking the person's memory into account.

Ozel [2001] discussed how negative labelling of emergency route influences the perception of occupants which eventually lead them to prefer other exit routes. Bickman *et al*., [1977] studied a fire incident in a nursing home. In this nursing home, the staff labelled three out of four exits as emergency exits and also implied with signs that emergency exits should be used only in emergencies. The nursing home patients were fined by the staff if they used emergency exits for routine movement. Bickman *et al*., [1977] concluded that during the real fire incident in the nursing home, only six out of more than hundred occupants used the labelled emergency exits. The occupants who did not use the emergency exits pointed out that the use of those exits was restricted. Due to time pressure, the occupants could not focus on the positive aspects of emergency exits such as being closer to a place of safety from their location, not leading to the fire area etc. Hence, the restriction placed on the usage of the emergency exits during normal scenarios may create a negative perception of them and therefore reduce the probability of them being used in emergencies.

Sixsmith *et al*., [1988], conducted wayfinding experiments in a shopping mall and contested that

"Given that way-finding has to be quick and efficient in the event of fire…fire doors should be readily available."

Thus, fire doors (emergency exits) must provide distinct and explicit information so that occupants under time pressure can perceive and take the fire (emergency) exit. Ozel [2001] argued that the clarity of cues is a major problem in identifying the fire exits which may add considerable confusion in occupant's perception while evacuating. The work of Sixsmith *et al*., [1988], included the use of murals which hid the visual cues for emergency exits. Hence, in the complex environment of a shopping mall with information overload, occupants found it difficult to discern the emergency exits. Sixsmith *et al*., [1988] concluded people have distinct images of emergency exits in their mind which are different from the actual doors in the environment. Firstly, this contradiction creates ambiguity and confusion. And secondly, an occupant's understanding of the environment sometimes discourages them to stress on minor details such as a door. For instance, in the shopping mall where Sixsmith *et al*., [1988] conducted the experiments, the exit doors were either on the endways or in the centre. The affordance of a passageway is to lead somewhere, alerting people to move straight. During this process, occupants overlooked and passed the emergency fire exit.

As Sixsmith *et al*., [1988], also mentioned the occupants *"looking but not seeing"* perspective, fewer occupants were successful in locating the nearest exit from their location. It becomes more apparent in the complex environment such as shopping centres, airports, supermarkets where the other factors such as lighting, structure architecture compound the difficulty to perceive the signage information. Hence, taking time pressure and stress into account, in the emergencies consistent exit cues must be easily available and clearly perceivable to the occupants [Ozel, 2001].

Filippidis *et al*., [2006], it was observed that it is more difficult to detect a sign when observing it at a large angle (90^0) to the perpendicular of the surface of the sign. Hence, Filippidis *et al.*, [2006] introduced a hypothetical relationship linking the visibility probability of resolving the sign and the relative orientation of the occupant and sign. According to this relationship, the visibility probability is highest at 0^o which means an agent is looking at the sign straight on providing the maximum possibility to detect the sign (see Figure 2.8). Similarly, the visibility probability is smaller at 90^o (the agent is viewing the sign side on) and diminish to 0 at 180^o (the agent is looking away from the sign) (see Figure 2.8).

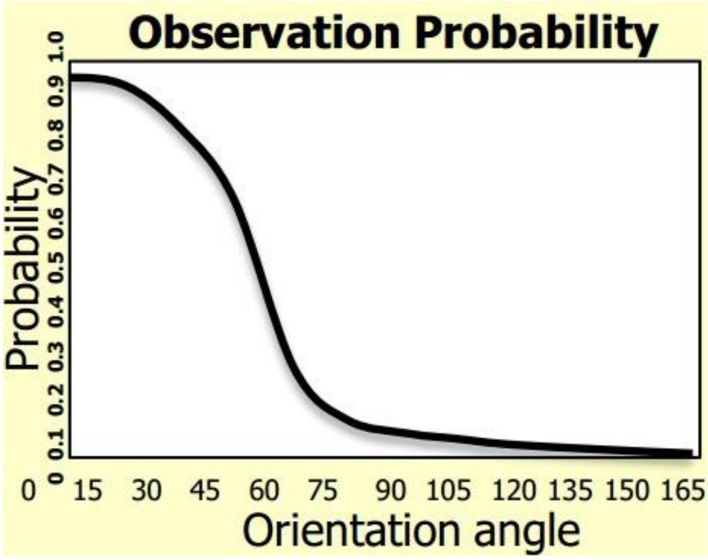


Figure 2.8: The hypothetical relationship between visibility probability and occupant's orientation angle.

A sign can be more effective if its affordance is enhanced in several ways such as increasing the size of the sign, making the sign more distinguishable by adding flashing lights and audio instructions [Xie *et al*., 2007]. Nilsson [2009] used the Theory of Affordance [Gibson, 1979] to investigate the factors which can influence the exit choice and advocated the use of green flashing lights at the emergency exits to encourage occupants to use the emergency exits. The results of this study showed flashing green light added to the standard emergency exit signage system increased the use of emergency exits.

2.5.3 Interpretation and taking action

For a sign to be effective in an evacuation or normal circulation, occupants not only have to perceive the sign, but they also have to interpret and take the action according to the information provided by the sign. This phase of signage interaction system depends partly on signage design and partly on how occupants perceive the current signage design [Xie, 2011].

The probability that occupant will perceive the sign depends on cognitive characteristics such as their own interpretation of sign and their desire to trust the information displayed [Xie *et al.,* 2012]. Occupant’s education background and the language in which sign information is written are also the important factors which influence the interpretation of sign [Morley and Cobbett, 1997].

The interpretation phase of the sign by occupants has been researched using interviews and surveys [Zhang *et al.*, 2017]. Benthorn and Frantzich [1999] invited 64 participants in Sweden to comprehend the advice of 6 safety signage. All the participants managed to identify 4 frequently appeared safety signage. Morley and Cobbett [1997] interviewed 1365 participants to study the comprehensibility of graphical exit signage used at airports and reported that occupant's skill to interpret the sign does not depend on language background. Cahill [1976] reported the interpretation problems of complex pictograms, such as describing actions or combining several different meanings. Salami [2007] identified signage as an aid to wayfinding, however, for people who cannot read or see this can stand as a barrier. The results from the above-mentioned studies demonstrate that the significance of graphical exit signage is recognised by the general public.

2.6 Summary

The aim of this thesis is to study and model wayfinding in a familiar and an unfamiliar building environment using signage. Hence, first, this chapter started with the detailed discussion on various definitions of wayfinding. Wayfinding is a spatial problem solving process [Arthur and Passini, 1992]. During wayfinding, occupants take decisions, execute decisions through their perception and past wayfinding experiences.

Later, a review on the wayfinding in the built environment along with principle theories and factors influencing wayfinding were covered. The human factors which can influence the wayfinding behaviour of an occupant include enclosure familiarity, communication, spatial orientation, cognitive map, route selection, culture, gender, age and special needs. The environmental factors which can impact the wayfinding behaviour include differentiation, visual access, layout complexity, signage and smoke.

Lastly, one of the important components of wayfinding, signage, and its impact on wayfinding was presented. There are three stages involved in the interaction between occupants and signage, namely, recognition, perception and taking action. The effect of the three stages may vary in different situations. For instance, during an emergency, even occupants are within the visible range of an emergency sign, it is not necessary that the occupants will perceive the sign for sure. In a normal situation, an occupant may not take an action according to the sign due to factors such as previous familiarity with the building.

In general, the probability that occupants will interpret the sign depends on cognitive characteristics such as their own interpretation of sign and their will to trust the information displayed, occupant's education level and the signage language information [Morley and Cobbett, 1997]. Lastly, taking action according to the information of the sign depends on occupant's characteristics such as the determination to take action, confidence on the decision taken, number of people following the signage route and present mental state.

Chapter 3 Evacuation Modelling

Chapter 2 discussed the essence of wayfinding in a built environment and the impact of signage system on wayfinding. This chapter examines how these concepts are implemented in existing evacuation modelling tools. In Section 3.1, an introduction to evacuation modelling is provided. Section 3.2 focusses on current techniques employed in evacuation modelling. This section also discusses the current techniques used by three distinct evacuation models, namely, PEDROUTE, buildingEXODUS and MASSEgress to explain the scope and essential attributes of evacuation models with an emphasis on occupant's wayfinding and occupant's interaction with signage.

3.1 Introduction

Evacuation is a process of moving people from the site with potentially harmful conditions to a relatively safe area during an emergency. An ideal evacuation system would prevent any injury or casualty [Tubbs and Meacham, 2007]. To establish an understanding of how people, act in an emergency, evacuation modelling is widely used as a practical method to improve safety design in buildings, forecast latent dangers under extreme conditions, help plan an emergency response and simulate emergency scenarios to study the root causes [Xie, 2011] [Winter, 2012].

The research on human movement and behaviour in an evacuation has been in existence for four decades [Gwynne *et al.*, 1999; Kuligowski *et al.,* 2010]. As today's building structures continue to evolve in terms of structural design and size, there is a consistent need to determine that a newly built structure meets the requirement for safe egress of all occupants. The methods for estimating building egress performance include full-scale evacuation [Gwynne *et al.*, 1999], compliance to prescriptive building code and regulations, simple hand calculations and using computer-based evacuation simulation tools [Galea *et al.*, 2011].

In a full-scale evacuation, an evacuation exercise is performed over a group of occupants in a structure. This approach may provide the opportunity to record the empirical data however, this approach possesses severe ethical, practical and financial issues. The ethical problems include the lack of realism in demonstrating an emergent evacuation scenario and the danger of subjecting the occupants to distress and physical injuries. The practical issues question the credibility of the evacuation trials which are run usually once. Hence, it provides the limited confidence that the trail correctly depicts the structure evacuation performance. Finally, to conduct an evacuation trial can be expensive and if it is required to rerun the trial, it could be more expensive.

A substitute to the evacuation trials is prescriptive building codes which accept or refuse a structure design on the basis of whether it complies with the codes [Gwynne *et al.,* 1999]. The building codes are based on general understanding and set of rules which rely on configurational considerations such as travel distance, exit widths and a number of exits. Thus, these building codes ignore environmental factors like the effect of heat and smoke on occupants and procedural factors like signage, occupant's prior familiarity with the structure and occupant's evacuation training. The compliance to prescriptive building codes indicates that structures are supposed to be safe. Therefore, the strict standards of building codes can assist in determining an optimal evacuation performance of a structure, but they are rigid and incapable to determine the impact of environmental and procedural factors on evacuation performance [Chooramun, 2011].

Safety engineers also use hand calculations to determine the evacuation performance prescribed in the Society of Fire Protection Engineers (SFPE) Handbook [Kuligowski *et al.,* 2010]. These calculations determine mass flow evacuation from a location in the structure. These calculations assume that occupant's initial location at the doorway of the egress area as the evacuation begins. Furthermore, these calculations also assume that the occupants are aware of a set of known rules such as "using nearest emergency exit". Hence, the behavioural features such as occupant's social interaction with other occupants, occupant's cognitive skills and the change of the environmental conditions due to the presence of fire/smoke are neglected.

Computer evacuation models are also used to assess the egress efficiency of a structure and occupant's behaviour during the egress. The computer-based evacuation models provide a virtual representation of real-world system based on the hypothesis and empirical data. These models reconstruct the development of the system according to the pre-defined rules and include not only the configurational factors but also consider the various environmental and procedural factors which can impact the evacuation performance.

Since the computer-based evacuation models overcome the shortfall of traditional approaches and provide the engineers an insight to access vital characteristics of egress, this method is favoured as compared to other methods. The computer based evacuation modelling aids the building engineer in deducing the evacuation performance of occupants and structure. This further helps in evaluating the safety level of occupants provided by the structure. Hence, the computer-based evacuation modelling approach helps in safety design of structures, predicts potential problems during an emergency, facilitates emergency response plan and also investigates the latent causes of disasters by simulations [Xie, 2011].

This study focuses on computer-based evacuation models. More specifically, the objective of this research is to improve the modelling of human wayfinding behaviour using signage in evacuation models. Most of the existing evacuation models provide an ideal platform to simulate the interaction between agents and signs and estimate how signage systems may facilitate an evacuation. However, most of the simulation models lack the capability to represent the interaction between agents and signs, especially a series of signs [Filippidis *et al.*, 2003], in normal circulation and emergency evacuation. The reason is most evacuation models focus on estimating the evacuation efficiency of a structure in a relatively ideal situation, where it is commonly assumed in modelling and simulation that agents are aware of the internal connectivity, the location of exits and their targets, ignoring agent's wayfinding process using external source of information, such as signage systems [MassMotion (2015), PathFinder (2013), FDS-Evac (Korhonen and Hostikka, 2008), STEPS (2010)].

3.2 Current techniques used in evacuation modelling

Evacuation modelling attempts to create a virtual representation of human behaviour during emergency situations within an enclosure. Evacuation modelling is practised over a range of enclosures like buildings, aviation and marine applications. This study focuses on studying evacuation modelling within built structures.

The different kinds of models can be represented by various modelling approaches. The modelling approaches consist of various methods for the depicting the built structure, agents and behaviour. The availability of various modelling approaches has led to the evolution of several evacuation/circulation models. These models can be classified according to the following factors [Gwynne, 2000]:

- Types of Evacuation Models.
- Representation of Agents in Evacuation Models.
- Representation of Geometry.
- Modelling Agent's Navigation Methods.
- Modelling Agent's Vision.

3.2.1 Types of evacuation models

There are three types of evacuation models which are used to simulate an evacuation scenario. These are Optimisation Models, Simulation Models and Risk Assessment Models.

Optimisation Models are formed on the notion that agents evacuate the structure in a simplified manner. Due to this optimistic assumption, these models do not assess various actions which could influence the overall performance such as delayed individual arrival. Furthermore, the choice of evacuation route adopted by occupants is optimal. Moreover, the purpose of optimisation models is to simulate scenarios where the agents are regarded as a homogenous group. Hence, these models do not represent an agent's individual character and behaviour. EVACNET [Kisko *et al.*, 1998], Takahashi's model [Takahashi *et al.*, 1989] are examples of optimisation models.

Simulation Models are those models which attempt to represent the behaviour and movement of the agents during an evacuation. Hence, these models are not only capable of achieving accurate evacuation result, but they also demonstrate the rational decisions and evacuation routes adopted by the agents. However, the behaviour and result precision in these models differs significantly compared to optimisation models due to their optimal notions. buildingEXODUS [Filippidis *et al.,* 2001, 2003, 2006, 2008; Xie *et al.,* 2007, Galea *et al.,* 2011], PEDROUTE (PEDROUTE V5 Manual), Legion [Kuligowski *et al.,* 2005, 2010], MASSEgress [Pan, 2006], PathFinder [Cappuccio, 2000], SIMULEX [Thompson, 1994] and FDS-EVAC [Hostikka *et al.*, 2007] are examples of this category.

Risk Assessment Models aim to recognise the dangers related to the evacuation which can affect the evacuation efficiency and attempt to quantify risk. This involves a repeated number of reruns of the model to determine the statistical variations corresponding to the changes applied to structure design or scenario conditions. The examples of risk assessment models are CRISP [Fraser-Mitchell, 1994] and WAYOUT [Shestopal and Grubits, 1994] [Chooramun, 2011].

3.2.2 Representation of agents

Gwynne *et al.,* [1999] and Kuligowski *et al.,* [2010] reported two ways of representing an agent in evacuation models namely, individual perspective and global.

In the individual perspective, the personal characteristics of each agent can be assigned by the user or generated by the model which are later used in the movement and decision making. This approach then allows the model to track the individual evacuation route and provides information about those agents, for instance, their location, age, gender and travelling speed. Evacuation models based on the individual perspective approach examine each agent with different personal attributes.

The examples of models established on the individual perspective approach include CRISP [Fraser-Mitchell 1994], buildingEXODUS [Galea *et al.*, 2011], LEGION [Berrou *et al.*, 2007], PathFinder [Cappuccio, 2000], MASSEgress [Pan, 2006] and FDS-EVAC [Hostikka *et al.*, 2007].

The global perspective approach does not treat the agents individually. Instead, agents are viewed as a homogenous group. In order to generate the results, close to the reality, the models based on the global perspective approach rely on the correlation between travel speed and density to determine evacuee movement [Ronchi and Nilsson, 2016]. This approach focusses on how the evacuation population move to a place of safety hence, ignoring the occupant interactions and assuming no variability in the population. However, it is important not to label global perspective as an inefficient approach. Although this approach fails to study the individual attributes in detail, it may be beneficial if the user is interested to find the congestion locations and the total evacuation time of structure. Models like EVACNET+ [Kisko and Francis, 1985], WAYOUT [Shestopal and Grubits, 1994] and Takahashi's model [Takahashi *et al.*, 1989] are based on the global perspective approach.

3.2.3 Representation of geometry

There are three fundamental approaches to represent a structure in evacuation models [Gwynne *et al.*, (1999), Ronchi and Nilsson, (2016)] namely coarse network, fine network and continuous.

Coarse Network

According to Ronchi and Nilsson [2016], the early evacuation models were introduced in the 1980s and the coarse network approach was the common method of defining the model's geometry. However, nowadays a few models are still using this approach [Gardiner, 2004].

In the coarse network approach [PEDROUTE (PEDROUTE V5 Manual), WAYOUT (Shestopal and Grubits, 1994), EVACNET4 (Kisko *et al.*, 1998), EXITT (Levin, 1989)], an enclosure is represented as network with nodes connected by arcs. Each node in the enclosure represents a compartment or a partition of the structure; e.g., a room or a corridor. Nodes and arcs can be assigned with characteristics [Ronchi and Nilsson, 2016]. For instance, nodes can accommodate a specific number of agents and arcs can prevent the agents' flow of movement entering a particular section.

While modelling the movement using a coarse network approach, an agent moves from one compartment to another; therefore, it is not possible to determine the exact location of an agent within a particular compartment. Given this, it lacks the capability to study the agent's trajectory, its interaction with both fellow agents and obstacles [Gwynne *et al.,* 1999].

Fine Network

The fine network approach is widely employed to represent agent movement combined with individual attributes in evacuation models [Gwynne *et al.,* (1999), Kuligowski *et al.,* (2010)]. The approach represents the entire enclosure as a fine network of nodes connected by arcs. This approach differs from the coarse network approach in that each node represents a small space that can normally be occupied by a single agent. The interaction of agents with building elements like obstacles, walls, columns etc., can be represented by blocked nodes which cannot be used by occupants [Ronchi and Nilsson, 2016] or by simply deleting the nodes from the geometry. This allows a more accurate representation of the geometry in the models.

In fine network models, the size, shape and interconnectivity of each node differ from model to model [Gwynne *et al.,* 1999]. For instance, EXODUS uses 0.5×0.5 m square nodes which are connected to 8 neighbouring nodes whereas SIMULEX [Thompson, 1994] uses 0.25 m × 0.25 m square nodes connected to 16 neighbouring nodes. Since the fine network models are capable of locating each occupant and tracing their trajectory, these models require more computational power to run a simulation. Nevertheless, the fine network surpasses the coarse network as it allows to represent sophisticated occupant behaviour and their interaction with building spaces which would affect their evacuation route [Kuligowski *et al.,* 2010].

Continuous models

In continuous models, the structural component is depicted by continuous space. The continuous models also typically allow viewing the agents individually [Ronchi and Nilsson, 2016]. Unlike the fine network approach where each node can accommodate one agent at a time step, in continuous models, agents share a continuous region and each agent possesses their unique location [Chooramun, 2011]. The continuous models use the coordinate system to trace the location of agents and have no restriction on agent's travel direction other than that prevented by obstacles or the presence of other agents.

The continuous models are capable of providing the closest depiction of real human movement [Ronchi and Nilsson, 2016]. This reality is depicted in three ways. Firstly, in real life, occupants move freely in continuous space rather than being locked to a grid. Secondly, occupants keep track of their movement and their fellow occupants to avoid any collision. And thirdly, the agents' body shape and size used in these models are the approximation of human body [Fruin, 1971]. To simulate the agents' movement smoothly, an occupant also keeps a particular minimum distance from fellow occupants' and structure spaces like walls, columns and obstacles to avoid overlapping.

A study by Chooramun *et al.*, [2010] discussed the concept of hybrid models which combines all three approaches to represent the geometry. Chooramun *et al.*, [2010], adopted the discretisation methodology which uses the best of all three approaches. In this study, a major portion of structure component is represented by fine node network and the continuous region is applied where greater accuracy is required. Lastly, the coarse node is used to represent in the section of geometry where locations of occupants are not required.

3.2.4 Modelling navigation methods and path planning algorithms

An important part of the evacuation/circulation modelling is the representation of the navigation strategies employed by the agents [Veeraswamy, 2011]. The agent navigation strategies can be represented through individual or global perspective [Kuligowski *et al.*, 2010].

An individual perspective is a scenario where an agent has specific or user defined knowledge of available exit paths. For instance, occupants are familiar with the entrance they use to enter the building and tend to use it during an evacuation [Sime1985, Shields and Boyce, 2000, Nilsson *et al.,* 2008 and Olander, 2015]). The global perspective assumes that the agents are completely familiar with the layout of the structure and know the locations of all the exits. Therefore, they will exit the structure through the shortest route to the nearest exit in an emergency. In brief, an exit route in an evacuation/circulation model can be calculated in two ways: first, using a user defined route and second, using the shortest route.

Most of the evacuation models require that the agents have prior knowledge of their target [SIMULEX (Thompson, 1994), buildingEXODUS (Galea *et al.,* 2011)]. In order to provide an agent with a means of navigating to their target, these models use map systems such as the potential map and the distance map to guide the agents in navigation.

The potential map provides distance information between any nodes within a geometry to its nearest exit. The assumption of using the potential map system is that the agents have full knowledge of all available exits. Therefore, the agents can select the nearest exit and always take the shortest route to evacuate. The computation of the potential value for each node initiates from each exit and recursively adds the physical distance to adjoining free nodes till all the nodes have been reached [Galea *et al.,* (2011), Xie (2011)]. This potential value can be changed to represent an exit being more attractive (small potential) or less attractive (large potential).

The distance map is similar to the potential map in terms of the algorithm used to construct the map. However, the difference is, each distance map is created for a particular exit. The use of distance map depicts the fact that the agents may have partial knowledge of the building layout, i.e. they are aware of one or several exits but not necessarily the nearest exit. The agents in the model may have different levels of familiarity; hence, the model simulates different familiarities by guiding the agents to follow different distance maps. In the past, the potential/distance map has been used in coarse network models [Kisko *et al.,* 1998], continuous models [Thompsons & Marchant, 1995] and fine node models [Galea *et al.,* 2011].

In both map-based approach, potential map and distance map, this method simulates an ideal situation which is prone to over-deterministic occupant exit route/door selection and over-optimal individual performance. In reality, people seldom act in this optimal and mechanical manner [Xie, 2011].

The potential and distance map approaches provide the agents with some spatial knowledge of the structural component. Both approaches are efficient in determining the evacuation performance of the structure, calculating the optimal evacuation time and identifying the areas of congestion, potential bottlenecks etc. Therefore, these approaches are more useful in assessing the evacuation efficiency given some degree of familiarity than to explore the agents wayfinding behaviour during an evacuation. The potential/distance map is based on the optimistic assumption that the agents are either familiar with the nearest exit or aware of at least one exit along with the routes towards their known exit; therefore, the agents choose the nearest exit and take the shortest route to evacuate. Hence, the potential map and distance map do not suit the situation where the agents are completely unfamiliar with an environment or their known exits become unavailable (e.g. due to the presence of fire hazards).

Given the above notion that the agents have full knowledge of the structure (or at least of the routes to the known exits), normally they do not need to perform any new wayfinding task during a simulation. In most evacuation/circulation models, agents' understanding of the routes are unchangeable. Therefore, the agents do not need the cognitive capability to perceive, understand and memorise the wayfinding information while they are navigating. Due to the lack of the capabilities to acquire information from the environment, the agents have limited responses to the changing conditions [Gwynne, 2000].

In reality the possibility of occupant being totally unfamiliar with a building cannot be ruled out completely. For instance, a passenger is travelling through an airport for the first time. Under this scenario, the individual would rely on their cognitive and communication skills to search for their desired target. In the context of evacuation/circulation models, Løvs [1998] discussed the navigation of agents with no previous knowledge of the exits or routes.

Løvs [1998] performed a mathematical study on agents using various wayfinding behaviours during an evacuation scenario. The included wayfinding behaviours ranged from simple random walks to complex shortest paths. In this study, it was demonstrated how agents who are unfamiliar with the structure use strategies to evacuate from a structure. Løvs created the Hampton Court maze in the EVACSIM model to demonstrate the agents' navigation (see Figure 3.1).

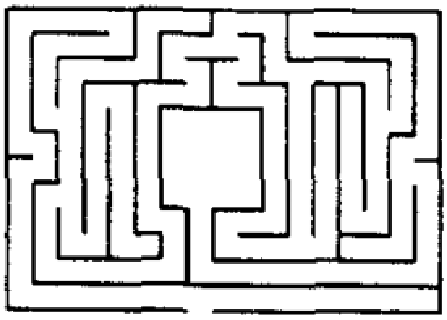


Figure 3.1: Hampton court maze [Løvs 1998].

In this study, a section of the building is called room and each room has one decision point. The occupant moves from one decision point to another decision point. A boundary connecting the two decision points represent the direct walkway path [Løvs, 1998]. The walkway network is a navigable route in the structure with a node located at each decision point. Figure 3.2 shows the walkway network of Hampton Court maze in Figure 3.1 where the nodes numbered from 1 to 16 represent the decision points. Node 1 is the source i.e., occupant's start node, node 16 is the final exit and all remaining nodes are transit nodes.

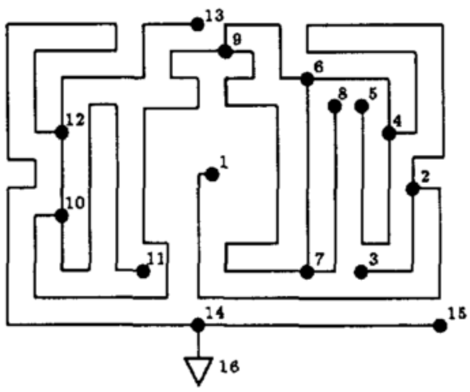


Figure 3.2: The walkway network with decision points [Løvs, 1998].

In order to perform the occupant's navigation, it was assumed that every occupant in this model has a main goal of leaving the structure. The occupant's response time was also set to 0; i.e., all occupants initiate their movement instantly, with a constant speed of 1.5 m/s. And lastly, occupants will execute their decision while movement.

The graph for the same structure was redrawn to show the possible final graph (see Figure 3.3). The walkways were eliminated by the links connecting the two decision points. In this model, a probability of an occupant k at node i moving to another node j when the whole system is in state X is defined as pk(i, j, X) [Veeraswamy, 2011]. Using this probability, Løvs [1998] introduced various models like a random choice, modified random choice, reduced turning probability, directional choice, shortest path etc,.

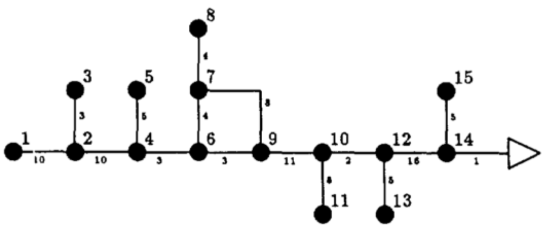


Figure 3.3: Building space represented in graph [Løvs, 1998].

In summary, in evacuation modelling most of the evacuation models require that the agents have previous familiarity of their destination [SIMULEX (Thompson, 1994), buildingEXODUS (Galea *et al.*, 2011)]. These models utilise map systems (potential map and distance map) to provide agents with a means of navigating towards their target. The potential map provides distance information between any nodes within a geometry to its nearest exit. The potential map depicts a scenario where the entire population have full knowledge of all available exits. In contrast, the distance map is constructed for a particular exit in the geometry. The use of distance map depicts the scenario that the agents may have partial knowledge of the building layout, i.e. they are aware of one or set of exits but not necessarily the nearest exit. However, there can be a scenario where an agent is unfamiliar with a building layout. Løvs [1998] discussed the navigation of agents with no previous knowledge of the exits or routes. He performed a mathematical study on agents to study various wayfinding behaviours during an evacuation scenario. These wayfinding behaviours ranged from simple random walks to complex shortest paths. In this study, it was demonstrated how agents who are unfamiliar with the structure use strategies to evacuate from a structure.

Path Planning Algorithms

Path planning of agents in an evacuation/circulation model involves planning a navigational path for agents from their respective start locations to their desired target while avoiding the obstacles.

The majority of the existing evacuation/circulation models use the shortest path algorithms. The shortest path algorithms are divided into two types namely, informed search and uninformed search. Both strategies dictate which path to select and which path to ignore during the navigation.

Uninformed Search

Uninformed search strategy (also called blind search) does not take target location into account hence this search is executed in all directions using a radial pattern until the target location is found [Lim *et al.,* 2015]. This method is usually employed when the location of final target is unknown. Hence, these algorithms are relatively slow than informed search algorithms. The examples of uninformed search are Breadth first search (BFS) and Depth first search (DFS).

Breadth first search is one of the fundamental algorithms for searching a graph. Let's suppose a graph $G = (V, E)$ where V is the set of vertices or nodes and E is the set of edges. For each vertex or node present in the graph, the breadth first search assigns two attributes namely distance and predecessor or parent [Cormen *et al.,* 2009]. The distance attribute provides the minimum number of edges in any path between the source node to another node. If there is no path between the two nodes, the distance attribute is set to infinity. The predecessor or parent vertex of a particular vertex represents shortest distance from the source vertex. If a node does not have a predecessor (for e.g., root node), the predecessor attribute is set to null.

In order to reach the destination node *d*, breadth first search initially assigns the null value to distance and predecessor attributes. A search to node *d* starts from source node *s* with the distance attribute set to 0. Then all the adjacent nodes of the source node *s* are visited and distance attribute for each adjacent node is set 1. The value for predecessor attribute is set to source node (*s*). This followed by traversing all the neighbouring nodes with distance 1 which have not been traversed before. Once these nodes are traversed the distance attribute is set to 2 and predecessor attribute is set to node from where last move was made. This process of searching nodes will last until all nodes accessible from the source node.

Depth first search (DFS) is another elementary graph search algorithm which traverses in "deeper" fashion [Cormen *et al.*, 2009]. Hence the deepest node of last known node *v* is explored first. If node *v* does not have child nodes, backtracking process initiates along the same branch which continuous until the top node of the branch [Tarjan, 1972]. A possible worst-case scenario for both search algorithms can be searching every node present in the graph. Hence, in worst case scenario the space and time analysis of breadth first search and depth first search is $O(V+E)$ where V is the number of vertices and E is the number of edges.

Informed Search

The informed search algorithms use the heuristic function to determine the location of the target at first [Lim *et al.*, 2015]. Unlike the uninformed search algorithms which perform searching in all direction, using the informed search algorithms the path finding direction is steered towards the target. A* algorithm is a typical example of informed search [Hart *et al.*, 1968].

The A* is a highly efficient algorithm which uses evaluation function to plan the low-cost path from start location to end location [Ferguson *et al.*, 2005]. This algorithm uses the evaluation function $f(n)=g(n)+h(n)$ where, g(n)=cost to reach a node n from the start node,

h(n)= cost to the goal from n

f(n)= total cost of path through n to goal

Initially the value of *g(n)* is set to infinity. The algorithm starts by updating the path cost to 0 and then this state is placed in a priority queue called *OPEN* list. Each state *s* in *OPEN* list is ordered according to the sum of its current path cost from the start and heuristic estimate of its path cost to the goal from n, *h(n)*. The state with the minimum sum is at the front of this OPEN queue. The heuristic *h(n)* generally underestimates the cost of the optimal path from n to the goal. The algorithm then dequeues the state s and updates the cost of all states to this state through a direct edge. If the cost of a neighbour state *s* changes, it is placed in OPEN list. The algorithm continues to dequeue the states off the queue until it dequeues the goal state [Ferguson *et al.*, 2005].

Robot path planning, and games are two major areas where A* algorithm is applied [Dechter and Pearl, (1985), Botea *et al.*, (2004)]. The other adaptations of A* algorithm is D* algorithm, D* lite algorithm [Koenig & Likhachev, 2002] and Lifelong planning A* algorithm.

The Dijkstra algorithm [Dijkstra, 1959] is another common algorithm used for optimal path finding in computer science. The Dijkstra algorithm is similar to the A* algorithm however the difference is Dijkstra algorithm search most promising states and does not use *h* heuristic [Ferguson *et al.*, 2005]. In certain cases, Dijkstra algorithm is favoured over the A* algorithm. For instance, Dijkstra algorithm is beneficial when agent has several targets and it is not known which target is the closest one [Veeraswamy, 2011].

3.2.5 Representing agent's vision

The modelling of agent navigation during an emergency evacuation or in circulation using the potential/distance map is primarily deterministic. Furthermore, the agent lacks the capability to perceive and process information necessary for conducting wayfinding. Therefore, there is a need for a new way to provide spatial awareness to the agent in order to simulate the adaptive response of agent to the changing environment and active wayfinding behaviour.

The visibility graph is a technique used in robotics for the navigation in a continuous 2-dimensional space [Chooramun, 2011]. In this technique, each vertex is regarded as a node and the line segment between the nodes are considered as links. A link is only created between the two vertices when there is a clear visibility with no obstacle in between. Similarly, a sub-goal method is another important technique for developing the navigation of agents [Chooramun, 2011]. Here in order to reach the destination, various intermediate visible sub-goals are defined which needs to be visited by the agents. This method has been used in various fields such as animation of virtual characters [Chooramun, 2011]. The navigation path from origin to target point contains sub-goals called as waypoints and lines connecting the waypoints are called path segments. Agents move from waypoint to waypoint using the path segments to reach their final target. Navigational Graph is another technique to represent the agent's visibility [Chooramun, 2011]. This technique is useful under the scenario when an agent target destination is not immediately visible from their starting location.

The navigational graph is an abstract representation of the visibility of the space, containing a network of waypoints and path segments [Chooramun, 2011]. Each waypoint is a two-dimensional coordinate which acts as a source to navigate the occupant towards their desired target [Chooramun, 2011]. The combination of all path segments in a navigational graph depicts a complete possible path an agent may take to reach the desired target (see Figure 3.4).

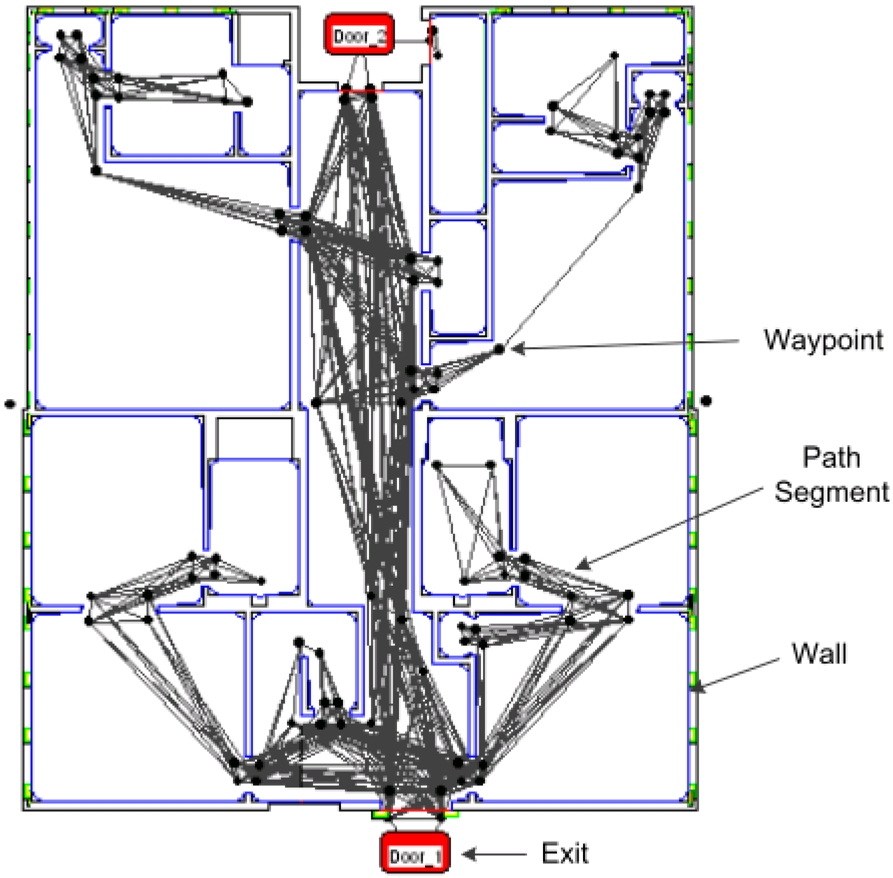


Figure 3.4: Navigational Graph of a structure [Chooramun, 2011].

The navigational graph is generated during the pre-processing of the simulation environment. The selection of the location of waypoints is a crucial step in navigation graph to determine the path planning of agents. This is due to the reason if waypoints are generated too close to each other, computationally expensive collision detection algorithms have to be implemented which may increase the simulation time [Chooramun, 2011].

In order to produce an efficient algorithm for agents' navigation in the navigational graph, the waypoints are generated only at places in the structure where internal angles are larger than 180̊. This resulted in fewer generated waypoints compared to visibility graph and therefore agents also perform fewer searches for waypoints [Chooramun, 2011].

The algorithm to generate a waypoint examines two consecutive edges and checks whether the internal angle is greater than or less than 180 degrees. If the internal angle is greater than 180 degrees, using vector arithmetic, the coordinates of the waypoint are calculated. Figure 3.5

shows two edges namely E1 and E2 [Chooramun, 2011]. V1 and V2 are vertices of E1 while V2 and V3 are vertices of E2. Considering E1 and E2 as vectors, the vector addition E1 (V2-V1) and E2 (V2-V3) results in a resultant vector R [Chooramun, 2011].

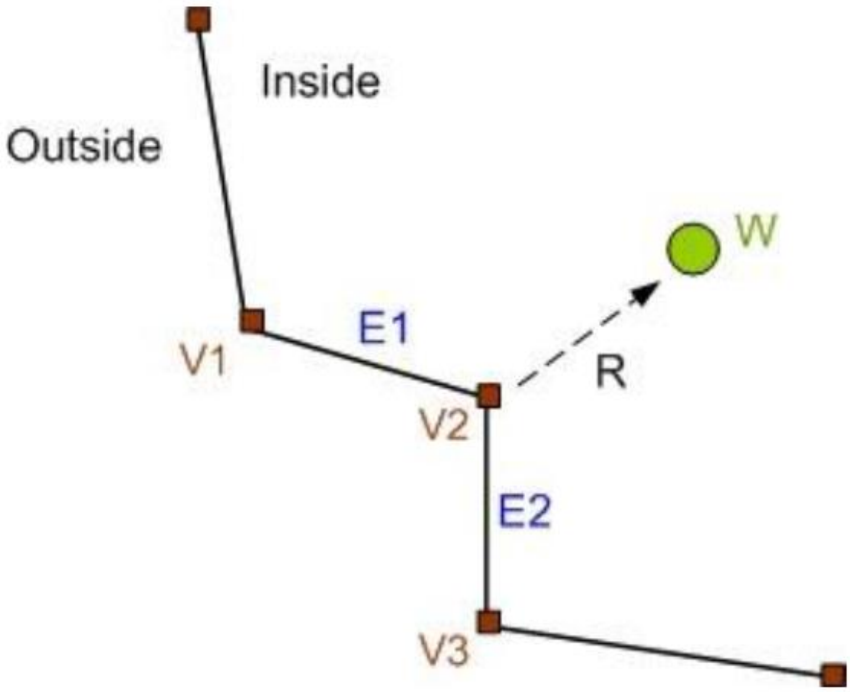


Figure 3.5: Calculation of the internal waypoint [Chooramun, 2011].

The newly generated waypoint's location would be situated on the resultant vector R and the coordinates of generated waypoint can be calculated using the following formulas [Chooramun, 2011]:

$$x = P2x + t * [(P2x - P1x)] + (P2x - P3x)]$$

$$y = P2y + t * [(P2y - P1y)] + (P2y - P3y)]$$

Chooramun [2011] study was based on the navigational graph and potential map approach. Each waypoint in the navigational graph is allocated a potential value using breadth-first search algorithm starting from the doors towards the connected neighbouring waypoints. The agents in this model use the potential values associated with the waypoints to decide their direction of travel in which the potential value declines. The approach of using waypoints provides the agents with a sense of direction and the potential value of each waypoint helps them to find the nearest exit available. It should be pointed out that the main objective of Chooramun's hybrid model was not wayfinding, but to provide an alternative way of path planning using the three existing approaches to represent the space (fine node model, continuous model and coarse model) so that the computational efficiency for simulating agents' movement and interaction can be maximised [Chooramun, 2011].

In the past, isovists or visibility graphs [Turner and Penn, 2002] have been used to represent the visible areas of an environment. An isovist (see Figure 3.6) is a visible region from a point in space. The polygon's boundary corners form the nodes of the graph and path segments of the polygon forms the edges of the graph [Veeraswamy, 2011]. However, this approach is computationally expensive, and disadvantages of this approach are first, selection of the location of the isovists and second, determining which edge need to be chosen [Veeraswamy, 2011].

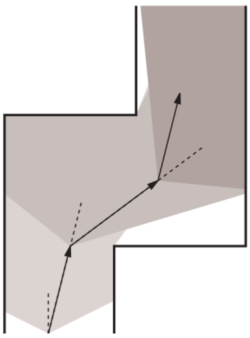


Figure 3.6: An Isovist polygon [Penn and Turner, 2002].

MASSEgress [Pan, 2006] is a sophisticated evacuation model in which each agent has a visual perception. An agent can 'see' the exit signs, exits, obstacles and other agents within the field. The visual field is a simple representation of the human visual field, defined by an arbitrary view angle and perception range. This model does succeed in setting an example where other models can follow to implement agent's vision but at the same time, this model provides no explanation on what basis agent's vision is implemented.

In summary, the main techniques to represent the agent's vision are visibility graphs [Chooramun, 2011], sub-goal method [Chooramun, 2011], navigational graphs [Chooramun, 2011] and agent's field of vision implemented by Pan [2009]. In visibility graphs, each vertex is regarded as a node and the line segment between the nodes are considered as links. A link is only created between the two vertices when there is a clear visibility with no obstacle in between. In the sub-goal method various in-between visible sub-goals are created which needs to be visited by the agents. The traversal path from origin to destination contains sub-goals called as waypoints and lines connecting the waypoints are called path segments. Agents move from waypoint to waypoint using the path segments to reach their final target. The navigational graph is an effective technique when an agent's destination is not directly visible from their starting location. Unlike visibility graphs where the path segments were connected to each and every visible node, navigational graph generates the waypoints where internal angles are larger than 180̊. This leads to fewer generated waypoints and therefore agents also perform fewer searches for waypoints. Pan [2009] implemented MASSEgress in which each agent has a visual sense. Each agent in MASSEgress can 'see' their surrounding space including exit signs, exits, obstacles and other agents within the field. The visual field is a simple representation of the human visual field, defined by an arbitrary view angle and perception range. However, this model provides no bases on what basis agent's vision is developed.

3.2.6 Modelling the agent interaction with signage system

Given the importance of signage systems in both circulation and emergency conditions, earlier there had been a concern that evacuation and pedestrian models neglected the representation the interaction between the agents and signage [Filippidis *et al.,* 2001]. In the last decade, various studies have been performed to study the interaction of the agents with signage systems under different circumstances [(Filippidis *et al.*, 2001, 2003, 2006, 2008; Xie *et al.*, 2007, Galea *et al.*, 2011), PEDROUTE (PEDROUTE V5 Manual), MASSEgress (Pan 2006) and Chu *et al.*, 2015]. Based on the results of these studies, a few signage models have been developed and included in the evacuation models.

According to the survey conducted by Kuligowski *et al.,* [2005] and Kuligowski et *al.*,[2010], the evacuation models which have a representation of signage system include ALLSAFE

[Heskestad and Meland (1998)], E-SCAPE [Reisser-Weston, 1996], PEDROUTE [PEDROUTE V5 Manual], buildingEXODUS [Galea *et al.,* 2011], MASSEgress [Pan, 2006], BGRAF [Ozel, 1985, 1987, 1988, 1991, 1993], Legion [Berrou *et al.,* (2007)], EvacSim [Poon, 1985; Poon & Beck, 1994], MOBEDIC (EGRESS) [Ketchell *et al.,* 1993] and SGEM [Lo and Fang, 2000]. The agents in these models are either forced to follow the signage or influenced by the signage depending on whether they fall within the pre-defined visibility catchment area of the sign and the probability in which they detect and comply with the sign [Xie, *et al.,* 2007].

The details of the signage model implementations have been found mainly for PEDROUTE, buildingEXODUS and MASSEgress by the author. Less information is available for the other models regarding the design of their signage model [Kuligowski *et al.,* 2005; Kuligowski *et al.,* 2010]. Xie [2011] summarised the function of signage in these models which are outlined in Table 3.1.

Table 3.1: The overview of the signage function in models.

Models	Role of signage in the model
ALLSAFE	Signage is used as a safety measure which can reduce the evacuation time.
E-SCAPE	Signage and distance to exit influences the occupant's route choice
BGRAF	Signage influences the wayfinding behaviour of occupants.
Legion	Unclear
EvacSim	Exit signs are employed to identify a particular exit.
MOBEDIC(EGRESS)	Signage is simulated as information points. Signage route has higher priority than other routes.
SGEM	The signage modelled is one of the factors that affect the occupant's route choices.

There are two possible approaches available to model signage in wayfinding [Filippidis *et al.,* 2006]. The first approach is based on sign "sees" the agent [buildingEXODUS (Galea *et al.,* 2011)]. Using this approach, the signage visibility from the location of the sign is calculated. Hence, the signage visibility is determined according to whether the agent is within the visible range of the sign. buildingEXODUS utilises this approach to represent the visibility of a sign. buildingEXODUS uses the concept of Visibility Catchment Area (VCA) which represents the physical extent to which the sign is visible to the agents in the structure. When the agent is in the VCA of a sign and facing the general direction of the sign, the agent can detect the sign.

The signage detection is based on empirical data suggesting that of the 38% of the occupants who detect a sign, 97% of these occupants use the information provided by the sign for wayfinding [Xie *et al.,* 2012]. In buildingEXODUS, each sign has a redirection node which holds the location of the next redirection node associated with another sign. Hence, the agent follows the direction of a sign by visiting the redirection node of the detected sign.

The alternative approach is based on the agent "sees" the sign [MASSEgress (Pan, 2006)]. Using this approach, the visibility of the sign is determined according to the location of the sign in context with the surrounding configuration and this is interpreted by the population during the simulation. MASSEgress is an example which utilises this approach. According to Galea *et al.,* [2011], both approaches produce similar results however, the latter is computationally expensive.

The next section discusses the techniques used by PEDROUTE, buildingEXODUS and MASSEgress along with a review of these three models to explain the scope and essential attributes of evacuation models with an emphasis on agent's wayfinding behaviour and agent's interaction with signage. The selection of these three models for reviewing is based on the fact that they can represent the impact of signage allowing agents to detect signs and use signage information to find a way out of the structure.

3.2.6.1 PEDROUTE

PEDROUTE is a pedestrian simulation software developed by Halcrow and London Underground Limited since 1987 [Buckmann & Leather, 1994; Barton & Leather, 1995; Bulman & Clifford, 1995; PEDROUTE V5 Manual].

PEDROUTE is a coarse network model consisting of blocks manually created by the model user. The blocks (rectangular polygon or non-rectangular polygon) can be used to represent various building components such as passage way, concourse, junction, lift, stairs, escalator, platforms and UTS gates.

The purpose of developing the PEDROUTE modelling tool was to simulate circulation scenarios in train stations. In PEDROUTE, the agents' target is assigned to them prior to the simulation. During circulation, the agents always move along the route from where they enter the station. PEDROUTE can also model the evacuation scenarios in the station. During an evacuation, PEDROUTE assigns the shortest route to the agents towards the available exit. Since PEDROUTE views the agents globally where they are modelled in groups, hence this model does not track the locations and travel paths of individual agents.

PEDROUTE allows a model user to add signage in the model. Using the signage, the model user can manually control a few agents or the entire population towards a destination. In this model, it is assumed that once agent "see" the sign, agent start following the route indicated by the sign. The compliance of signage is governed by a global compliance probability called SPRO which is set to 100% by the model developers. This is a limitation of this model.

Since the agents always move along the shortest route available, the underlying assumption in PEDROUTE is that the agents are aware of the structure. This is another limitation as this model does not simulate the agents with no knowledge or partial knowledge of the building layout.

3.2.6.2 buildingEXODUS

The EXODUS model has been continuously in development over twenty-five years by the Fire Safety Engineering Group (FSEG) at the University of Greenwich, the UK. EXODUS is a suite of software tools (airEXODUS, buildingEXODUS, maritimeEXODUS and railEXODUS) developed to model the emergency evacuation and normal circulation of people within complex-built environments [Galea *et al.*, 2011]. The variant of the software employed to model the egress from the buildings or closed enclosures is buildingEXODUS.

buildingEXODUS is a fine network model which consists of five core submodels (see Figure 3.7).

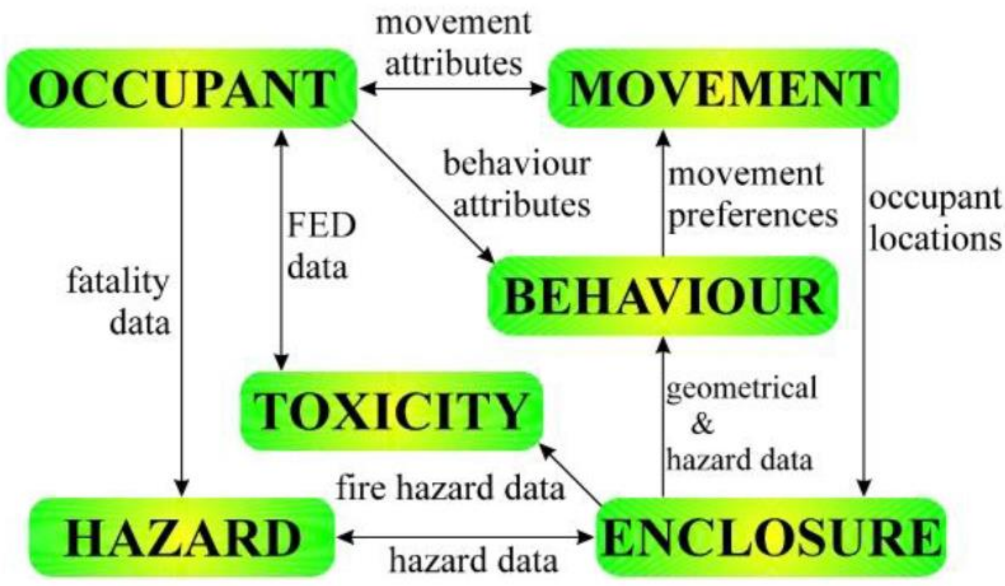


Figure 3.7: Five sub-models in buildingEXODUS [Galea *et al.*, 2011].

- **Occupant** sub-model provides the identity of an occupant. The population may consist of occupants with different attributes, such as gender, age, walking speed and level of familiarity with the structure etc.

- **Behaviour** sub-model model occupants' behavioural responses to the present condition using their individual attributes.

- **Movement** sub-model manages the navigation of occupants in the structure from their present location until they reach their target location.

- **Hazard** sub-model controls the distribution of fire hazards such as heat, smoke during the simulation. It also manages the physical tasks like door opening, debris and bodies.

- **Toxicity** sub model determines the impact of toxic products emitted via the hazard sub-model on occupants.

buildingEXODUS is employed to model the evacuation and circulation scenarios within the built environment. The buildingEXODUS software takes into consideration people-people, people-fire and people-structure interactions [Galea *et al.,* 2011] and uses rule based concepts to model agents' responses to the situation.

The human factors which affect the wayfinding behaviour identified in Chapter 2 (Section 2.3.1) can be represented in buildingEXODUS. The human factors related to this research include spatial orientation and enclosure familiarity. The factor which currently cannot be modelled is cognitive mapping.

The environmental factors which affect the wayfinding behaviour were also identified in Chapter 2 (Section 2.3.2) can be represented in buildingEXODUS. The environmental factors related to this research such as differentiation, visual access, complex structures and signage can be modelled in buildingEXODUS.

The Concept of Visibility Catchment Area (VCA)

In buildingEXODUS, a user can add signs into a built structure to simulate the interaction between agents and signage. A user can place an individual sign or a series of signs and check the locations from where each sign is visible to the agents. To represent the visibility of the signs within the model, Filippidis *et al.,* [2001, 2003, 2006, 2008] introduced the concept of Visibility Catchment Area (VCA) which is defined as the region from where an agent can discern the information provided by the sign (see Figure 3.8). That means, if the agent is within the extent of VCA of the sign and standing in the general direction relative to the sign without any physical obstruction in between, the agent can discern the sign.

Geometrically, the VCA of a sign is assumed to be represented as a visibility polygon spreading outwards from the point on the sign [Filippidis *et al.,* 2006]. The visibility polygon concept provides an easy process to establish the visibility of a sign in a structure. If an obstruction is placed between the occupant and sign, a shadow region will develop which prevents the occupant to see the sign (see Figure 3.8).

The extent of VCA of a sign depends on the location and height of the sign and obstruction Filippidis *et al.*, [2001, 2003, 2006, 2008]. buildingEXODUS determines the VCA of a sign using the line of sight algorithm which detects the free nodes that has visibility access to the particular sign. The algorithm uses the mid-point of the lower edge of the sign and a point in space equal to the height of the observer (see Figure 3.8). The reason for using the center of lower edge is an assumption that, if this point can be seen it is likely that the entire sign will be seen, at least for small signs. For large signs, it is possible that the center point of the base if visible and part of the top of the sign may be obscured [Filippidis *et al.*, 2006].

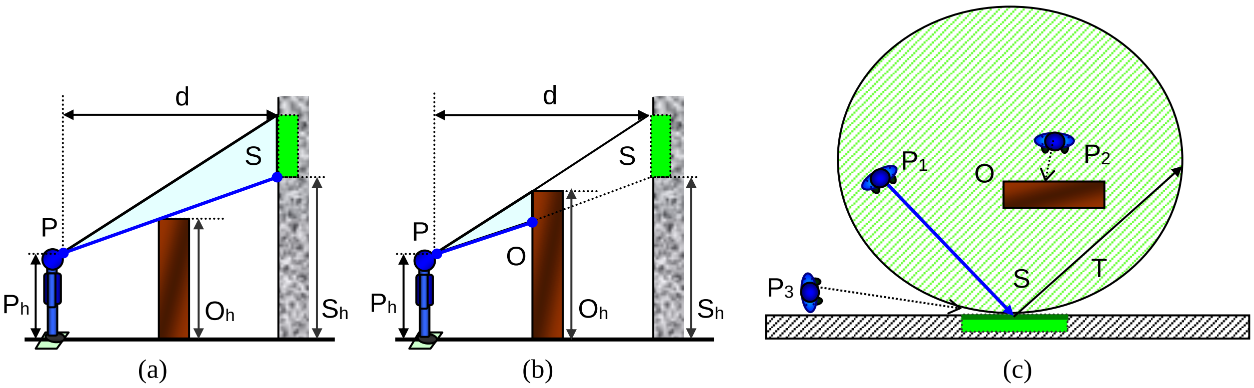


Figure 3.8: Exit sign visibility behind an obstacle [Filippidis *et al.*, 2001, 2003, 2006, 2008].

Another factor which has an impact on the shape and size of the VCA is the angular separation of the sign [Filippidis *et al.*, 2006]. This angular separation depends on the size of the sign, the distance between occupant from the centre of the sign and the observation angle. The observation angle can be defined as the angle which is subtended by the occupant's travel direction and location of the sign. If an occupant views the sign sideways making an observation angle of 90°, the angular separations is equal to 0 making the sign invisible to the occupant. On viewing the sign straight making 0° observation angle proves the maximum visibility of the sign. Evidently, there will be a minimum angular separation beyond which, to read the sign will not be possible. There will also be a maximum viewing angle after which occupant will be unable to read the sign [Filippidis *et al.*, 2006]. In summary, from the same viewing distance as the occupant's viewing angle increases, the angular separation decreases till maximum observation angle point after that resolving the sign is difficult or impossible.

The concept of VCA was later improved by Xie *et al.*, [2005] through theoretical analysis and experimentations to prove the relationship between the angle of observation, sign size and maximum viewing distance. In this study, it was proved that the maximum viewing distance depends on the observation angle and as the observation angle increases, the maximum viewing distance decreases. It was also reported that sign size is directly proportional to both maximum viewing distance. It means as the sign size increases, the maximum viewing distance also increases.

When Filippidis *et al.*, [2001] introduced the VCA model, it was assumed that the agent will see the sign and use the information relayed by the sign provided agent lies within the VCA. Thus, due to the lack of data to explain how occupants detect, comprehend and comply with the information provided by the sign, this issue was never addressed properly. Xie *et al.*, [2012] conducted evacuation trails to assess the probability of occupants seeing a sign without any physical obstruction. The signs were installed at the appropriate locations according to the signage standards. Xie *et al.*, [2012] reported that 38% of the participants detected the sign and subsequently 97% of them used the information provided by the sign for wayfinding. Furthermore, it was also argued that the current emergency signage system is less successful in assisting occupants for wayfinding than traditionally expected.

In buildingEXODUS, a user can place a series of signs along the escape routes leading to different exits. Filippidis *et al.*, [2003, 2006, 2008] termed the series of signs as chain signage system and represented the behaviour of agents following chain of signs in the buildingEXODUS software. Filippidis *et al.*, [2006, 2008] classified the signage system to discern the level of redirection deduced by an individual sign. The chain signage system was an attempt to represent the interaction of occupants with a chain of signs in a complex structure. In chain signage, the signs were classified into *zero*, *first* and *higher* order signs (see Figure 3.9). A *zero* order sign indicates to signs that are installed directly above the exit. A *first* order sign denotes to sign that point to zero order signs. Lastly, *higher* order signs are signs that lead the occupant to another sign. Higher order signs lead the occupant to an area where another sign of the chain signage system is present and nearer to the target exit. To create chain signage system in buildingEXODUS, a model user manually connects the higher order signs to first order signs.

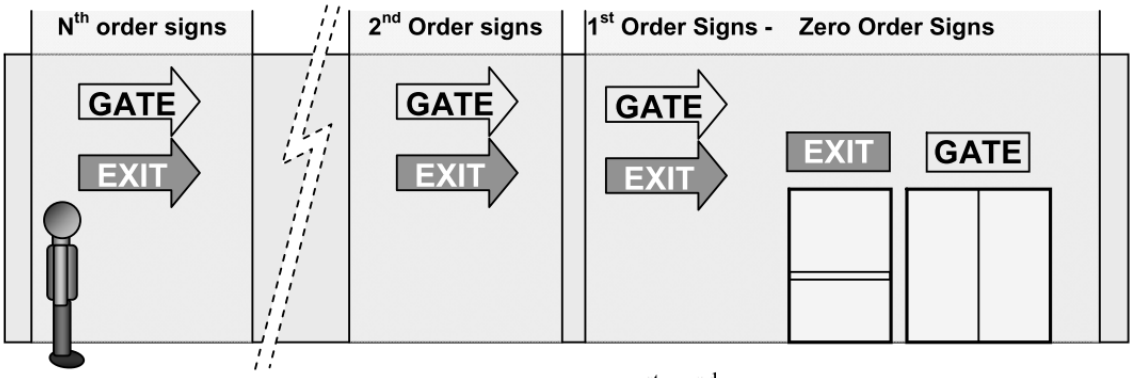


Figure 3.9: Chain signage system containing zero, first and higher order signs [Filippidis *et al.*, 2006, 2008].

An example of the chained signage is illustrated in Figure 3.10 [Filippidis *et al.*, 2008], where an agent P tries to leave the building, without knowing the exit location. This agent is relying on the information provided by the chained signage. Assuming that the agent detects and comprehends the signs, the agent will move from the vicinity of sign A to the other signs B, C, D, E, until arriving at the zero-order sign F, where the final exit is located.

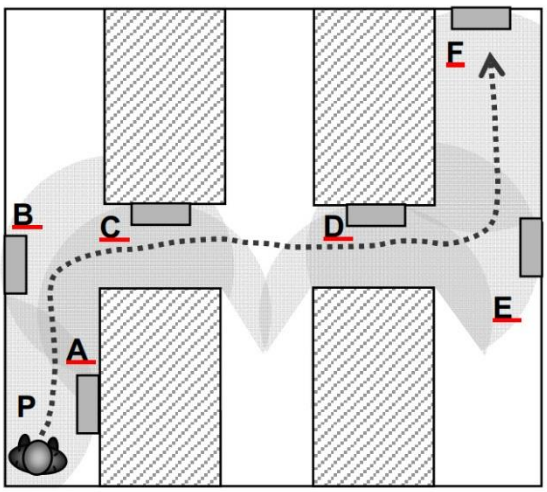


Figure 3.10: Chained signage network guiding occupant P from start location to reach the final exit F [Filippidis *et al.*, 2008].

The chain signage model developed by Filippidis *et al.*, [2008] is implemented within buildingEXODUS. To simulate the higher order signs, Filippidis *et al.*, [2008] used the concept of redirection node. A redirection node is a node which provides the location of another redirection node associated with next sign in the signage chain. For instance, in Figure 3.11, when an agent enters the VCA of the sign and detects the sign, the redirection node conveys the agent the location of the redirection node of next sign in the signage chain. buildingEXODUS then sets the agent's target to visit the redirection node of the next sign.

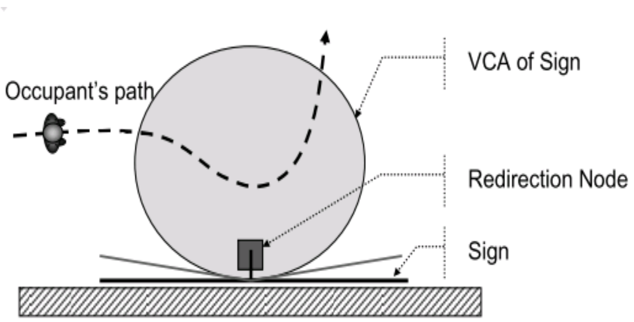


Figure 3.11: A sign and associated redirection node [Filippidis *et al.*, 2008].

When an agent is following a signage chain along the escape route, it may be possible that the agent may miss one or more signs. In buildingEXODUS, if an agent fails to detect the next sign in the signage chain, four behaviours may be executed. These are searching behaviour, backtracking behaviour, lost behaviour and fail-safe behaviour [Filippidis *et al.,* 2008]. These behaviours depend on the Expected Distance between Signs (EDBS) which represents the distance within which the next sign is expected to be seen by the agent. In buildingEXODUS, the default value of the EDBS is proposed to be 30m.

- **Searching Behaviour:** This behaviour is activated once the agent has travelled 2 times of EDBS value and failed to find the next sign. During this behaviour, the agent continues to move in the general direction of travel according to the information received from the last two observed signs in the hope to find another sign down in that direction.

- **Backtracking Behaviour:** When the agent is in *searching* mode and has travelled twice of the EDBS from the last seen sign and failed to detect the next sign, then *backtracking* is activated. In *backtracking,* agent will head to the last known sign. This behaviour symbolises the verification stage of the agent. The agent moves back to their last location and tries to find the information from the signage.

- **Lost Behaviour:** This behaviour will be triggered if the agent has travelled 3.5 times of the EDBS or has returned to their start location. At this point, the agent attempts to communicate with other agents to acquire knowledge of the next sign or exit.

- **Fail-Safe Behaviours:** If the agent has travelled four times of the EDBS then the agent will switch to *Fail-Safe* behaviour. Under this behaviour, the agent will give up the search for their target and leave the structure by the nearest exit.

Using redirection node allows the model user to simulate the agents' wayfinding behaviour using a series of signs. However, the redirection node is also a limitation of the buildingEXODUS signage model. As redirection node provides information about the redirection node of next sign, the agent is implicitly aware of the location of the next sign. Hence, the agent "hops" from one redirection node to another redirection node until they find an exit. The agents in buildingEXODUS lack the understanding of the space connectivity due to redirection node.

For instance, in Figure 3.12, when the agent enters the VCA of sign 1 and detects the sign, the redirection node associated with sign 1 provides the location of the redirection node associated with sign 2. Similarly, when the agent detects sign 2, the redirection node of sign 2 provides the location of the redirection node associated with sign 3. If the agent also detects sign 3 when visiting the redirection node of sign 3, the agent gets the location of the redirection node of sign 4. This process continues until the agent finds an exit.

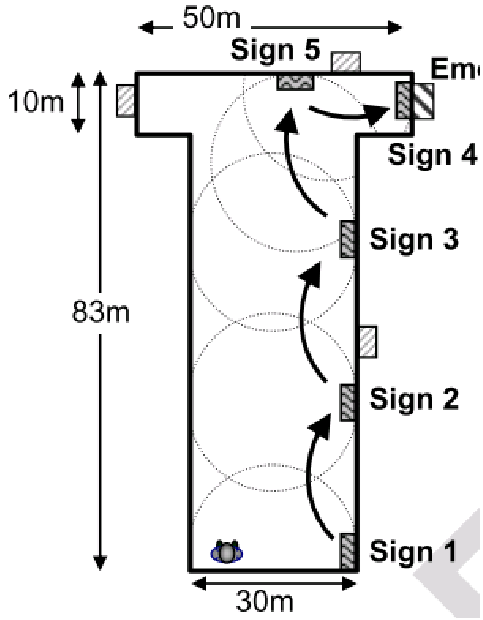


Figure 3.12: Layout of a demonstration geometry [Filippidis *et al.*, 2008].

Due to the redirection node, agents follow the signage in buildingEXODUS deterministically. When the agent detects a sign, they are implicitly provided with a pre-defined target, a redirection node, to visit. Hence, an agent does not follow the direction of a sign, in fact, the agent moves from one redirection node to another redirection node. In real world, if an occupant in a building sees a sign that indicates the direction to their desired destination, the occupant would follow the direction of the sign. During the movement, if the occupant finds another sign pointing to their desired destination, they may start following the next sign. Therefore, the wayfinding behaviour of the agents while following a chain of signs in buildingEXODUS is different from the real-world behaviour of using a chain of signs to reach the desired destination.

The approach introduced above [Filippidis *et al.*, (2003, 2006, 2008)] for modelling the interaction with a series of signs is a compromise for the lack of agent's understanding of space connectivity and a sense of direction. In addition, there is a potential for the agents to be trapped in an unnecessary loop during their search for signs following this modelling approach as the agents have no memory of route experiences. Due to the same limitation, the agents must be assigned an initial target to go as they do not possess the capability of wayfinding in an unfamiliar environment.

In real world, during wayfinding in a built environment, occupants hold a cognitive map or mental image of structure in their mind which allows them to recognise and differentiate building components (such as used route and unused route, familiar space and unfamiliar space) [Tolman (1948), Downs and Stea (1973), Passini (1984), Arthur and Passini, (1992)]. This mental image can be updated when new information is perceived or expended when they explore unfamiliar spaces. Based on this metal image they can make an appropriate route choice accordingly, such as choosing their familiar route, searching for an alternative route or even backtracking if necessary.

3.2.6.3 MASSEgress

MASSEgress [Pan, 2006] (Multi-Agent Simulation System for Egress Analysis) is another major evacuation model which is capable of representing the interaction between agents and signage. In MASSEgress each agent is equipped with a Perception System, Behaviour System and Motor System. Unlike the agents in most other evacuation models whose movement relies on pre-computed information like the potential map or distance map, in MASSEgress the agents navigate using their perception system. The built environment of the structure is depicted through the continuous region and built structure components like obstructions, doors, assembly points and signage can be generated using the CAD tools [Pan, 2006].

Unlike buildingEXODUS in which the sign 'sees' the agents (i.e. the agents enter the VCA of the sign to be able to see the sign), in MASSEgress the agents are able to perceive the environment through their own vision. The vision of agents has been adopted using the concept of View Volume which is a visual cone determined by a perception range and a view angle [Pan, 2006]. A sign, an agent or an obstacle is visible to the agent if it falls within the view volume of the agent and is not obstructed by any obstacle (see Figure 3.13). Since the agents have their own vision which needs to be updated frequently to see the environment, this method is computationally expensive as compared with buildingEXODUS approach. Moreover, important detail like the theoretical background of creating visual cone is unclear from the discussion [Xie 2011]. Furthermore, in MASSEgress an object (e.g. sign, door, etc.) is visible to the agent if it falls within the view volume, i.e. it implicitly states that the signage detection and compliance probabilities have been set to 100%.

Like buildingEXODUS, an agent in MASSEgress also lacks the memory to remember their past wayfinding experience. In MASSEgress, if the agents lose sight of their goal point or target exit, the agents walk randomly until a new goal is detected.

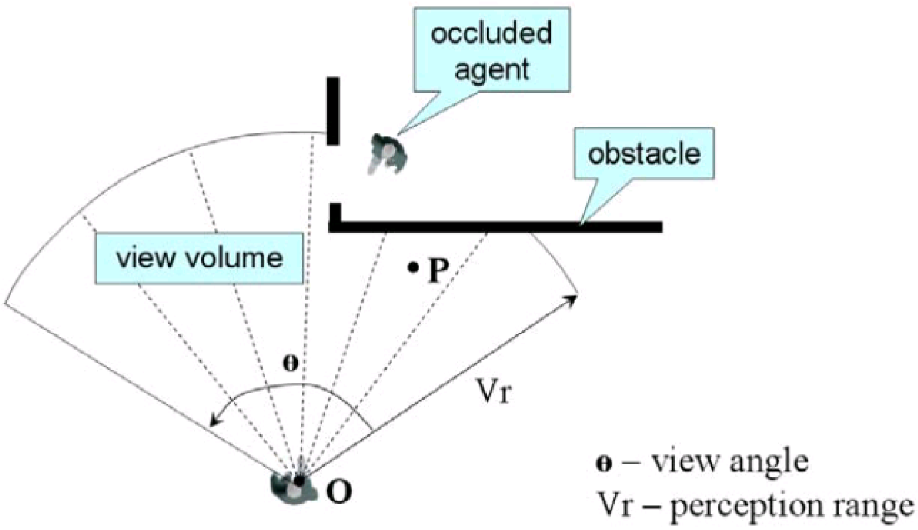


Figure 3.13: The visual cone of an agent in MASSEgress [Pan, 2006].

The agent's visual cone is formed by computationally expensive algorithms which executes at each time step of the simulation. However, to compensate the efficiency of MASSEgress, Pan [2006] used a hybrid approach by combining point test algorithm and a ray tracing algorithm. The point test algorithm is used to determine the visibility of spatial information like exits, assembly points, which are fewer in number. For example, in Figure 3.13, an agent "O" with a perception range of V_r subtending a view angle Θ can "see" the point P in the space.

The ray tracing algorithm is used to determine the visibility of static objects like walls and obstacles so that the agents can prevent collision while wayfinding. The algorithm casts three rays at each step along the left, right and centre of the agent's visual cone. If any of these rays (left, right and centre) intersects the border of the obstruction, the occupant will detect a potential collision. To avoid the collision, the occupant steers away from the obstacle.

To avoid collision between the agents, an efficient grid method has been employed with a time complexity of O(N). Prior to simulation, an underlying grid is created which registers each agent to a cell. During the simulation, whenever an agent in the model attempts to move, it checks the neighbouring cell. If the neighbouring cell is available, the agent is deregistered from the old cell and then registered to the new neighbouring cell. However, if the neighbouring cell is not available to move, a conflicting situation arises which will block the movement of the agent. Hence, instead of iterating through all pairs of agents for collision detection, the tests are only applied to neighbouring cells [Pan, 2006]. This saves considerable simulation time and computational complexity.

3.3 Summary

In this chapter, a literature review on evacuation modelling is performed mainly examining the techniques related to represent agent wayfinding behaviour and the interaction with signage. The review performed highlighted the limitations in the existing approaches for modelling agent wayfinding using signage system. The review also pointed out the lack of features that are necessary to improve the representation of the interaction with signage. These findings are significant with respect to the development of a new signage-based navigation model presented in Chapter 4.

In Section 3.2, the current techniques used in evacuation modelling were discussed. The evacuation modelling constructs a virtual representation of human behaviour during the emergency situations within an enclosure. This study focusses on studying evacuation modelling within built structures. There are different modelling approaches to represent different kinds of models which eventually led to the development of several evacuation/circulation models. Approaches which were discussed include types of evacuation models (Section 3.2.1), representation of agents in evacuation models (Section 3.2.2), representation of geometry (Section 3.2.3), modelling agent's navigation methods and path planning algorithms (Section 3.2.4) and representing agent's vision (Section 3.2.5). It was found that evacuation/circulation models mainly focus on estimating the egress time and exits usage; while little has been addressed regarding the representation of the interaction of signage and agents.

In Section 3.2.6 several evacuation models that are capable of representing the interaction between agents and signage were introduced. Of them three models, PEDROUTE, buildingEXODUS and MASSEgress were analysed in detail. The limitations which exist within these models in representing the interaction between agents and signage were identified. First, the agents lack the sense of the space connectivity and direction from the signs. Second, the agents lack memory of the past navigational experience. Due to these limitations, agents' movement, while the following signage, appears deterministic.

Given these limitations within the current modelling approach and the lack of features identified, a new signage-based navigation model is proposed and implemented to address the research questions raised in Chapter 1. The new model integrates navigation graph and signage visibility to give the agents a sense of space connectivity and direction so that the agents can perceive the signage direction and follow this direction along the escape route. The model also introduces agent's memory to record their wayfinding experience.

Chapter 4 Design and Development of the New Signage-based Navigation Model

4.1 Introduction

A new signage-based navigation model is designed and developed in order to address the research questions raised in Chapter 1 (Section 1.2). The new model is implemented and tested using the buildingEXODUS simulation software (version V7.0.0.2561) as the test platform as it is readily available to the author. In this chapter, a detailed description of the model design is given. How the new model can be implemented in any other evacuation models is also discussed at the end.

4.2 Limitations in existing modelling approaches

In Chapter 2, a literature review was conducted to examine occupant wayfinding behaviours in a built environment and the role of the signage system during the wayfinding process. In Chapter 3, how these wayfinding behaviours are represented in evacuation/circulation modelling are discussed. Both chapters helped to identify the knowledge gaps, the limitations in the existing modelling approaches and the possible direction of improvement. Based on these findings, a new signage-based navigation model is designed and developed. Before presenting the new model, it is worth highlighting the knowledge gaps and limitations in the existing modelling approaches again.

Signage systems are an important part of wayfinding design in a built environment. They are particularly important during an emergency evacuation as they provide crucial directional information along the escape routes planned for the structure. However, most of the simulation models lack the representation of the interaction between the agents and signs. This is because these models focus on estimating the evacuation efficiency of a structure in a relatively ideal situation where the agents can use pre-computed map systems such as the potential map and the distance map to navigate towards their desired target. The underlying assumption of using potential/distance map approach is the agent have full or partial familiarity of the exits. Hence, the agents ignore the wayfinding process using an external source of information, such as signage systems.

A few evacuation simulation models [buildingEXODUS (Filippidis *et al.,* 2001, 2003, 2006, 2008; Xie *et al.,* 2007, Galea *et al.,* 2011), PEDROUTE (PEDROUTE V5 Manual), MASSEgress (Pan, 2006), ALLSAFE, E-SCAPE, BGRAF, Legion, EvacSim, MOBEDIC(EGRESS) and SGEM [Kuligowski *et al.,* 2005; Kuligowski *et al.,*, 2010; Xie, 2011] have the capability of representing the interaction between the agents and signage. They can simulate the agent's behaviour of finding a previously unknown escape direction through detecting one or more signs and following the signage. However, in all of these models, the agents lack the sense of direction and the connectivity of space. Due to lack of an individual memory, the agents also do not store and use their past navigation experiences in wayfinding. Therefore, these models have limited capability to use the information in a successive wayfinding process along the planned escape routes that are normally present in the structure to a final exit point. For instance, in buildingEXODUS, a model user has to manually connect the signs to form a chain to create a signage system. When the agents start following a sign, they are implicitly directed to the next sign along the signage chain. Besides, due to the lack of the capability to store their past wayfinding experience, the agents are not able to use their past wayfinding experience to make informed decisions in navigation. For instance, if the agent following a signage direction fails to detect the next sign along the signage chain, the agent would execute arbitrary searching and backtracking behaviour [Filippidis *et al.,* 2006, 2008] or random walk [Pan, 2006]. These behaviours sometimes can lead to unnecessary and unrealistic movement, such as being trapped in a loop.

In summary, the major limitations of the existing modelling approaches are:

- **Optimal navigation path based on exit knowledge:** It is normally required that the agents have some form of knowledge of the location of exits and their targets. The model then works out an optimal path using the shortest route approach for the agents. Hence, the wayfinding process using an external source of information, such as signage systems is largely ignored. As a result, the simulation results produced reflect an ‘arranged’ evacuation scenario rather than that based on human wayfinding in a real emergency.

- **No sense of direction and internal connectivity of space:** The agents lack a sense of direction and space connectivity; therefore, they normally cannot follow a direction but heading for an assigned target.

- **Memory:** The agents do not store their navigation experience; therefore, they could make an unnecessary and unrealistic movement (such as being trapped in a loop or travelling repeatedly along the same route) if they have to retrace or search.

4.2.1 How the limitations are addressed

The new signage-based navigation model can simulate three different kinds of navigation strategies. The first two navigation strategies are scenarios which can be modelled by current evacuation models such as, simulating the agent’s behaviour with the full or partial familiarity of the structure and agent following a sign or series of signs in the structure. In addition, the new model can also simulate the agent’s wayfinding behaviour with no previous familiarity with the structure.

4.2.1.1 Introducing a sense of direction and space connectivity through navigation graph

One of the objectives of designing the new signage-based navigation model is to provide a sense of direction to an agent without significantly increasing the demand for computational power. MASSEgress [Pan, 2006] is an exception which actually simulates the agent sense of vision. In this model, each agent has an individual field of vision which is simulated by point test algorithm, ray tracing algorithm and grid method. The point test algorithm allows the agent to “see” an object such as exit, sign etc. by checking whether it is located within the visible distance. The ray tracing algorithm uses three rays (left, right and middle) to detect obstacles or another agent. And lastly, the grid method, which allows an agent to avoid collisions.

Although the time complexity of each algorithm for N agents is still O(N), the model performs a much more complex calculation to determine the travel direction for each agent at each time step than buildingEXODUS.

On comparing the three methods (point test algorithm, ray tracing and grid method) of MASSEgress to buildingEXODUS, the latter performs only grid method to avoid collisions. Since MASSEgress is executing two additional tasks at each time step, it makes the MASSEgress more computationally expensive than buildingEXODUS. However, the two additional tasks also allow MASSEgress to achieve natural perception and movement of agents.

In the new signage-based navigation model, an agent is introduced with a sense of direction and space connectivity through the navigational graph. The idea of the navigational graph was adopted by Chooramun [2011] who used this technique as a means to navigate the agents in the simulated environment within the continuous space.

A navigational graph is a connected network of waypoints (see Figure 4.1). Each waypoint is a two-dimensional coordinate, a reference for guiding the agent's movement. The waypoints are connected through path segments if they are visible to each other. An agent moves from one waypoint to another using the path segments between them. A collection of all waypoints and path segments creates the path which an agent can take to reach their target.

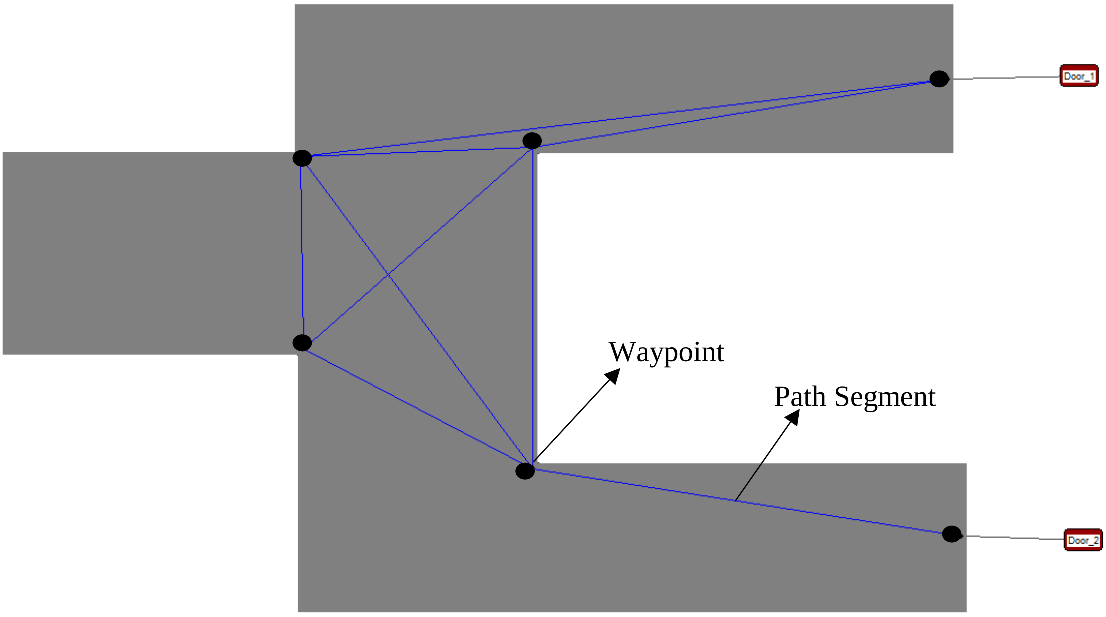


Figure 4.1: A navigational graph in buildingEXODUS.

In a navigational graph, each waypoint inherits the potential value and distance values from the overlapped node. The waypoints which are connected to other waypoints are visible to each other. Using the navigational graph, the agents are allowed to retrieve information from the visible waypoints. The agents have the same level of information as in the current modelling approaching using the nodal network. In the new signage-based navigational model, an agent has a sense of direction and connectivity of structure through the navigational graph.

The navigational graph of a simulation structure is created in two steps in buildingEXODUS (as the test platform). Firstly, the boundary of the structure is drawn manually using the standard polygon function provided by buildingEXODUS. The waypoints are then automatically generated once the polygon is converted into a navigational region. The selection of the location of waypoints is a crucial step in the navigational graph to determine the path planning of agents. This is due to the reason if waypoints are generated too close to each other, computationally expensive collision detection algorithms have to be implemented which may increase the simulation time.

To produce a computationally efficient algorithm for the agents' navigation, the waypoints are generated only at locations in the structure where internal angles are concave [Chooramun, 2011]. This results in fewer generated waypoints and therefore, agents also perform fewer searches for waypoints. Therefore, the approach of using the navigational graph is simple and effective because it is neither computationally expensive nor memory expensive.

The new signage-based navigational model has an additional, however not significant, computational power requirement compared to buildingEXODUS. This is due to the introduction of memory in the new model. When an agent visits a waypoint, they store the waypoint in their memory which increases the size of the memory. It should be noted that agent's searching for waypoint does not execute at each time step. Searching behaviour executes when an agent reaches their current target waypoint and have to decide next target waypoint to select. Therefore, the requirement for additional computational power does not increase significantly compared to the buildingEXODUS software.

The agents in the new model navigate using the navigational graph waypoints used by the agents as the reference points for navigation are generated at only concave corners within a structure. Since the number of waypoints is much smaller than the number of nodes within a nodal network representation of the structure, it required less frequent execution of searching algorithm compared with the navigation approach based on the nodal network. However, the use of waypoints can cause false congestion (see Figure 4.2). This is because the agents attempt to move to the reference point from their respective locations and then decide which way to go next. They need to be within a certain decision distance to the reference point before searching for the next reference point. In the current implementation of the model, the decision distance is set to 1m [Chooramun, 2011]. At locations where there are multiple agents, they may compete for the small space around the target waypoint as the reference point for navigation, hence, causing a false congestion.

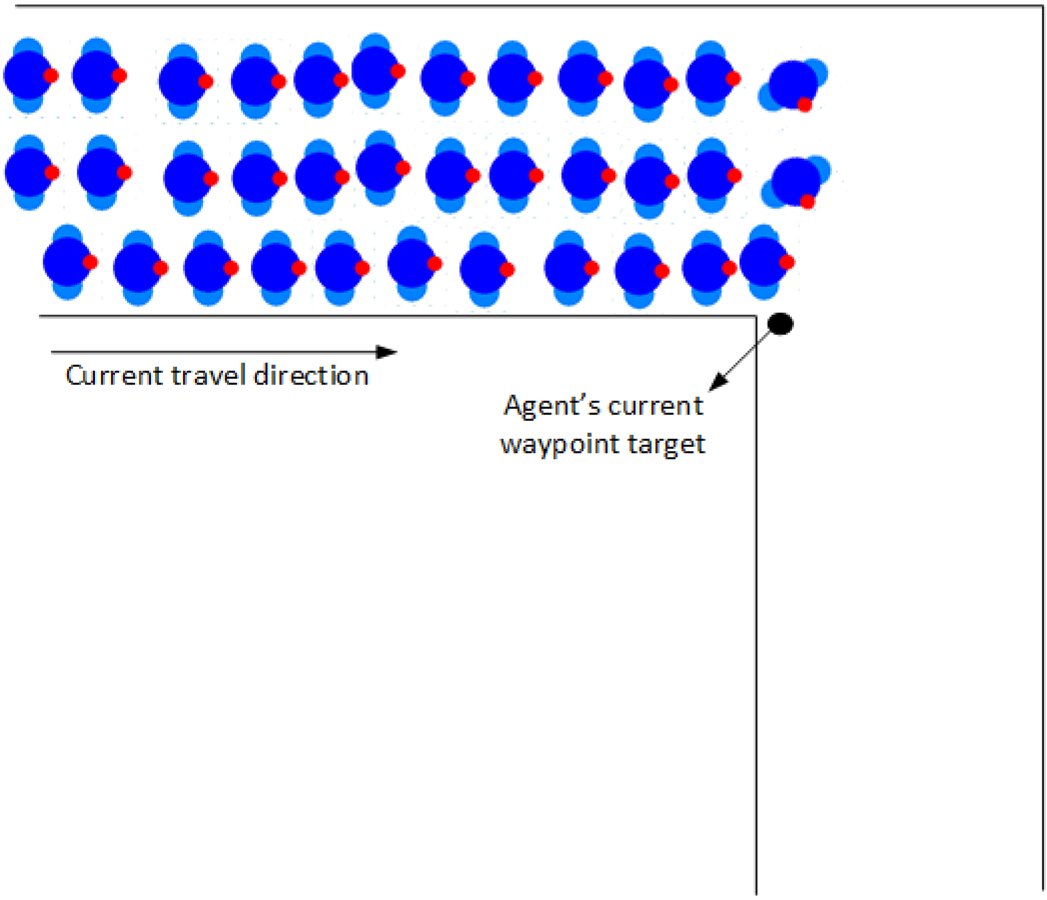


Figure 4.2: Congestion due to a small threshold value.

To address the issue of false congestion, the new signage-based navigation model requires modifications in the implementation. A possible solution is to introduce variable decision distance. For instance, an agent may have a decision distance of 1m whereas another agent's decision distance may be 1.5 m. This modification would relief the competition for the small area around the target waypoint. This is considered as future work.

The generated waypoints in a structure can also lead to non-optimal walking paths. For instance, Figure 4.3 shows an agent in an unfamiliar structure with two internal rooms. And, Figure 4.4 shows the navigational graph of this structure.

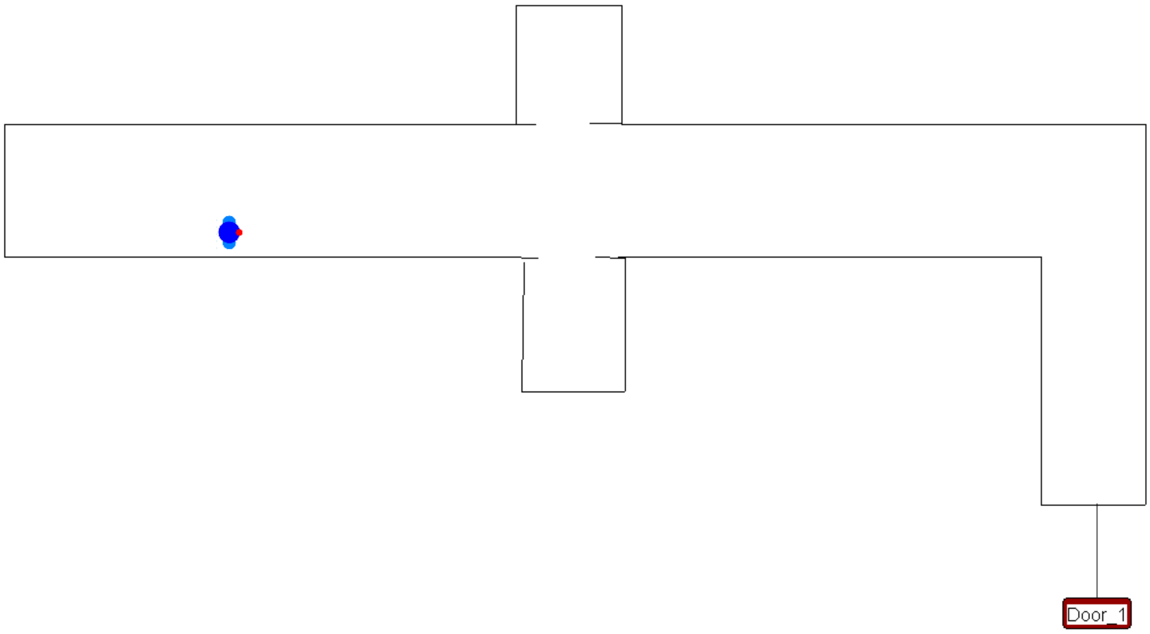


Figure 4.3: Agent's starting location to demonstrate non-optimal walking paths.

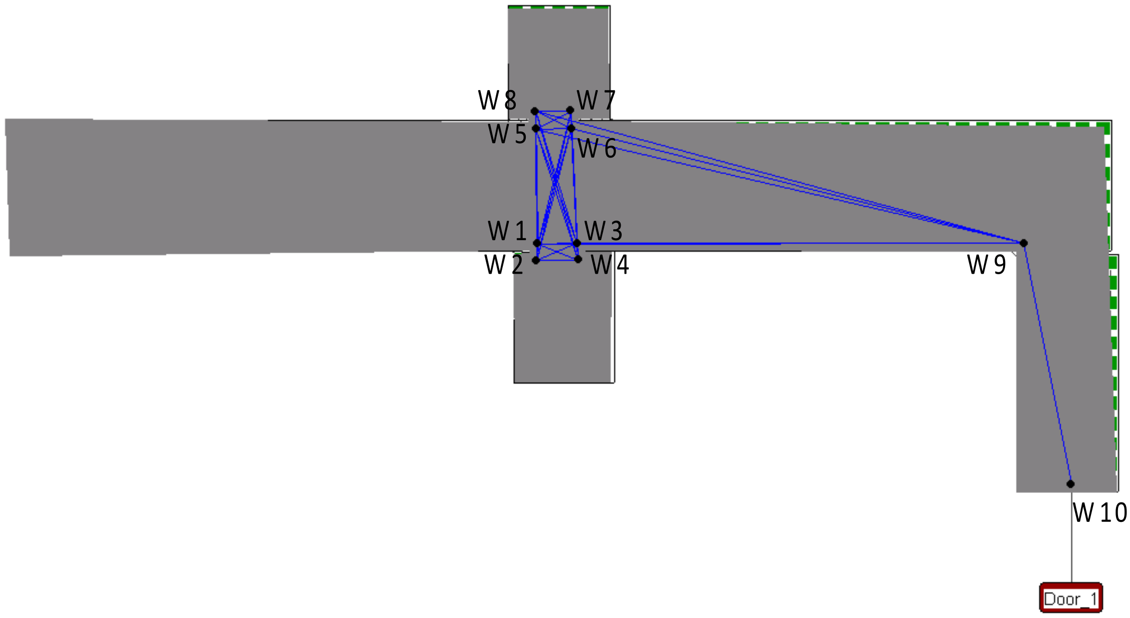


Figure 4.4: The generated navigational graph.

At the beginning of the simulation, the agent spots the nearest unvisited visible waypoint W1 visible from his start location (see Figure 4.4). From waypoint W1 the agent would the other nearest unvisited visible waypoints W2, W4 and W3. From waypoint W3, the agent would move to waypoint W6, W7, W8, and W5 then to W9 and W10.

Each internal room in this structure contains four waypoints and these rooms do not have another door opening. It can be noticed from the agent's movement that they visit all four waypoints containing each room. This is a non-optimal travel path.

In the future implementation of the new signage-based navigation model, an agent will be capable of understanding spatial elements of the structure. Hence, they would be able to differentiate between the open space and a room. If an agent visits the waypoints of a room with no another door opening, rather than visiting all their waypoints, the agent may visit either one of the waypoints. Furthermore, an alternative to preventing non-optimal travel paths would be rationalising the location of waypoints in the structure. At the location where waypoints are located close to each other such as an internal room, those waypoints could be combined into one waypoint.

The waypoints in a navigational graph are generated at only concave corners which results in fewer waypoints and eventually fewer execution of the searching algorithm. However, in the future implementation of the model, the locations of waypoints can be further rationalised to reduce the computation time and the agent's movement in two ways: first, introducing a threshold distance and merging any visible waypoints within this distance as one waypoint, and, second, providing the waypoint a type depending on the location of the waypoint (normal type or internal door type). To address the issue of rationalisation of waypoints location, the new signage-based navigation model requires further amendments in the implementation.

First**,** a possible solution is to introduce an arbitrary threshold distance value (e.g. 5 m). If the distance between any two waypoints visible two each other is less than 5 m, this would mean that the two waypoints are closely located to each other. In that case, these two waypoints will be replaced with a single waypoint which will have the average potential/distance value of the particular two waypoints.

For instance, in Figure 4.5, an agent has no previous familiarity with the exit and the agent's starting location is waypoint W3. The agent's searching behaviour initiates through finding the nearest unvisited visible waypoint from the agent's current location. From waypoint W3, the agent finds waypoint W1 as the nearest unvisited visible waypoint. Before moving to waypoint W1, the agent will check whether the distance between waypoint W3 and waypoint W1 is less than 5 m. Since the distance between these waypoints is more than 5 m, this would mean waypoint W3 is not located near to waypoint W1. Hence, the agent will continue using waypoint W1. In the similar fashion the agent further used waypoint W2 as a nearest unvisited waypoint. At W2, there are no more unvisited waypoints nearby nor an exit. Therefore, the agent has to backtrack to the most recent visited waypoint W3 within a visible range which has unvisited waypoints connected to it, i.e. there is still unvisited space from W3 (waypoint W4, W7 and W8).

Back to waypoint W3, the agent's continues searching for a nearest unvisited waypoint in a different direction. Waypoint W4 is the nearest unvisited waypoint from waypoint W3. At waypoint W4, the next nearest waypoint is W7. However, the distance between waypoint W4 and waypoint W7 is less than 5 m. Hence, according to the proposed amendment, these two waypoints will be replaced by single waypoint called *G1* (see Figure 4.5). The *G1* waypoint location will be based on the average distance/potential value of waypoint W4 and waypoint W7. From *G1*, the agent will then move to the nearest unvisited waypoint W5. Waypoint W6 is the next nearest unvisited visible waypoint. But the distance between waypoint W5 and waypoint W6 is less than 5 m. Thus, waypoint W5 and waypoint W6 will also be replaced by a single waypoint called *G2* which will be located at the average distance/potential value of waypoint W5 and W6.

At *G2*, there are no more unvisited waypoints nearby nor an exit. Therefore, the agent will backtrack to the most recent visited waypoint *G1* which has further unvisited waypoint connected (waypoint W8). From *G1* waypoint, the agent will use waypoint W8 and W9 to leave the structure through Door 1. This modification would reduce the number of waypoints and path segments in the navigation graph (see Figure 4.5 and Figure 4.6). This is considered as future work.

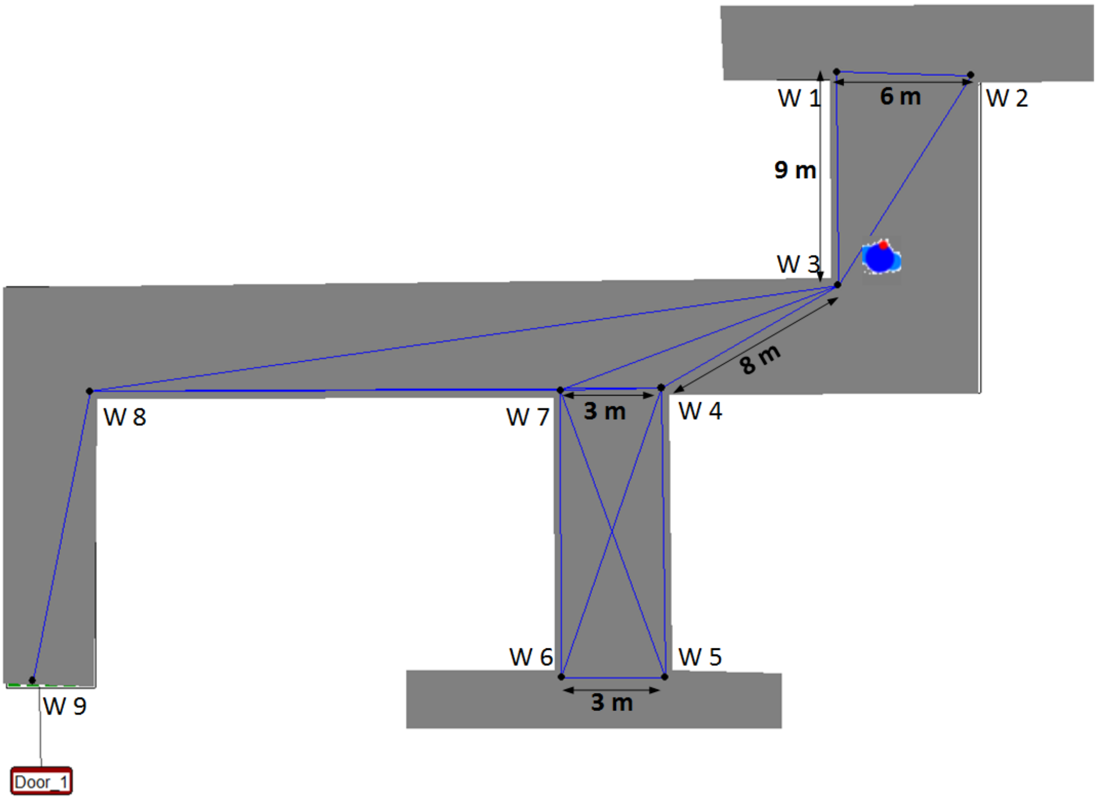


Figure 4.5: Current representation of waypoints in a navigational graph.

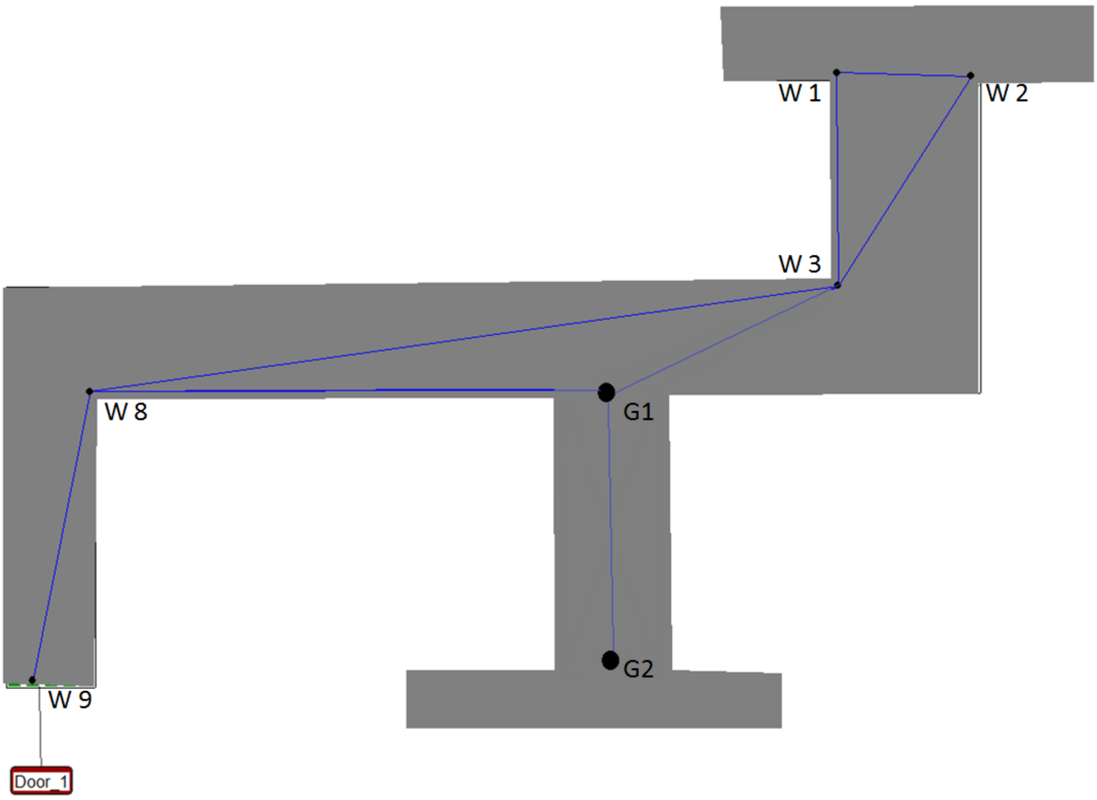


Figure 4.6: Proposed rationalisation of waypoints in a navigational graph.

Second, another possible solution to rationalise the navigational graph is to provide each waypoint a type depending on the location of the waypoint. In the future implementation of the new model, the model user will be able to assign a type to the waypoints. The type of each waypoint located in the internal door can be set as internal door type and other waypoints can be set as normal waypoint. This allows an agent to differentiate between an internal door waypoint and a normal waypoint.

For instance, Figure 4.7 depicts a structure with ten rooms (R1-R10) and two corridors (C1 and C2). Each room has an internal door consisting of four waypoints located close to each other (circled in red). If an agent is located in room R1, the current searching behaviour will allow the agent to use the nearest unvisited waypoint to perform the searching (W1→W2→W3→W4). After visiting waypoint W4, the agent will visit the waypoint W7 (room R2 internal door waypoint). This searching process will continue until the agent finds an exit/sign. The agent's searching behaviour of visiting all the internal doors waypoints leads to unrealistic and unnecessary movement behaviour. To address this issue, in future implementation of the new model, all internal door waypoints can be replaced as one waypoint. This will reduce the number of waypoints and path segments in the navigational graph significantly. The improved navigational graph is depicted in Figure 4.8 in which each internal door has one waypoint.

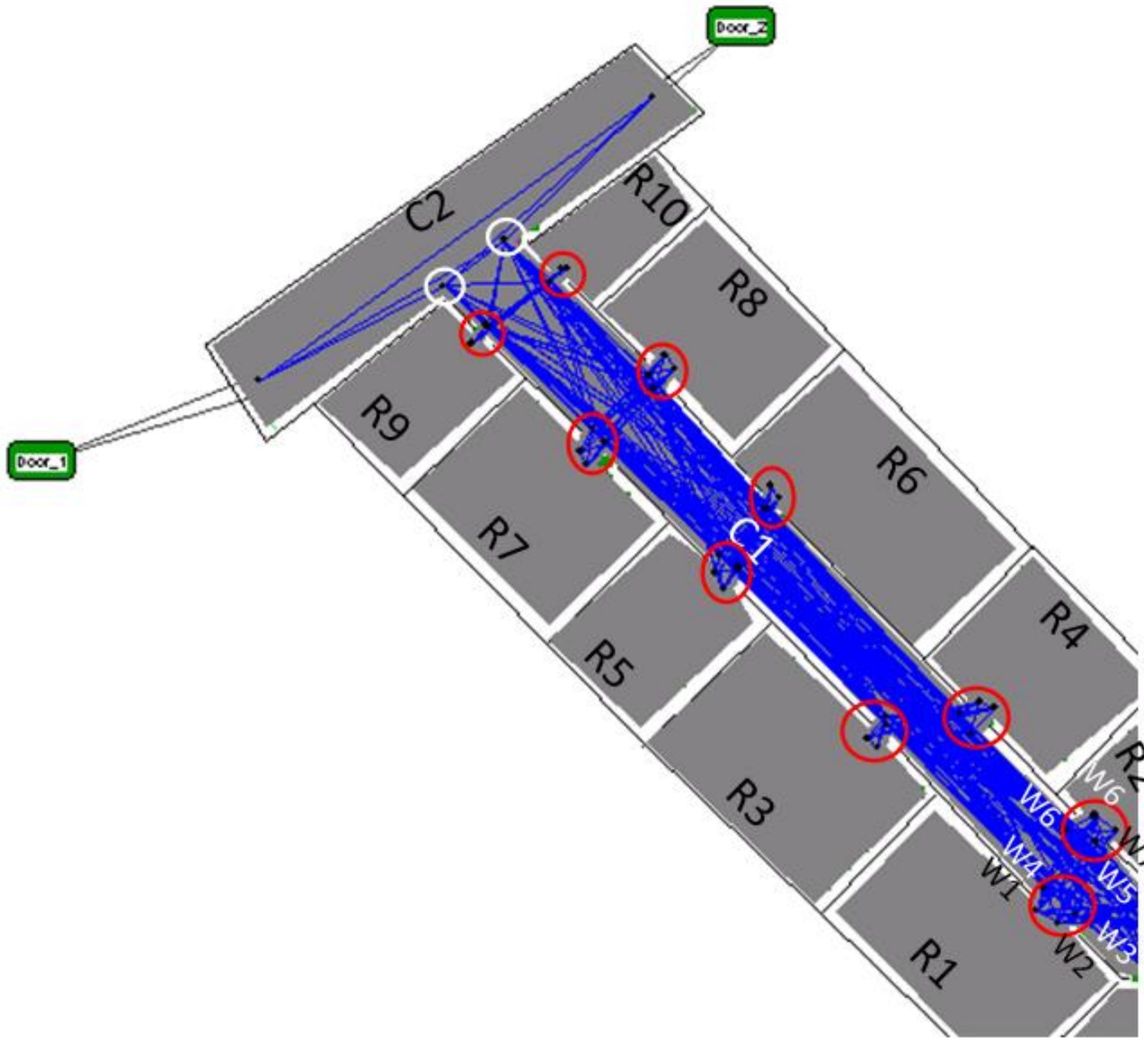


Figure 4.7: Alternative approach for rationalising the navigational graph.

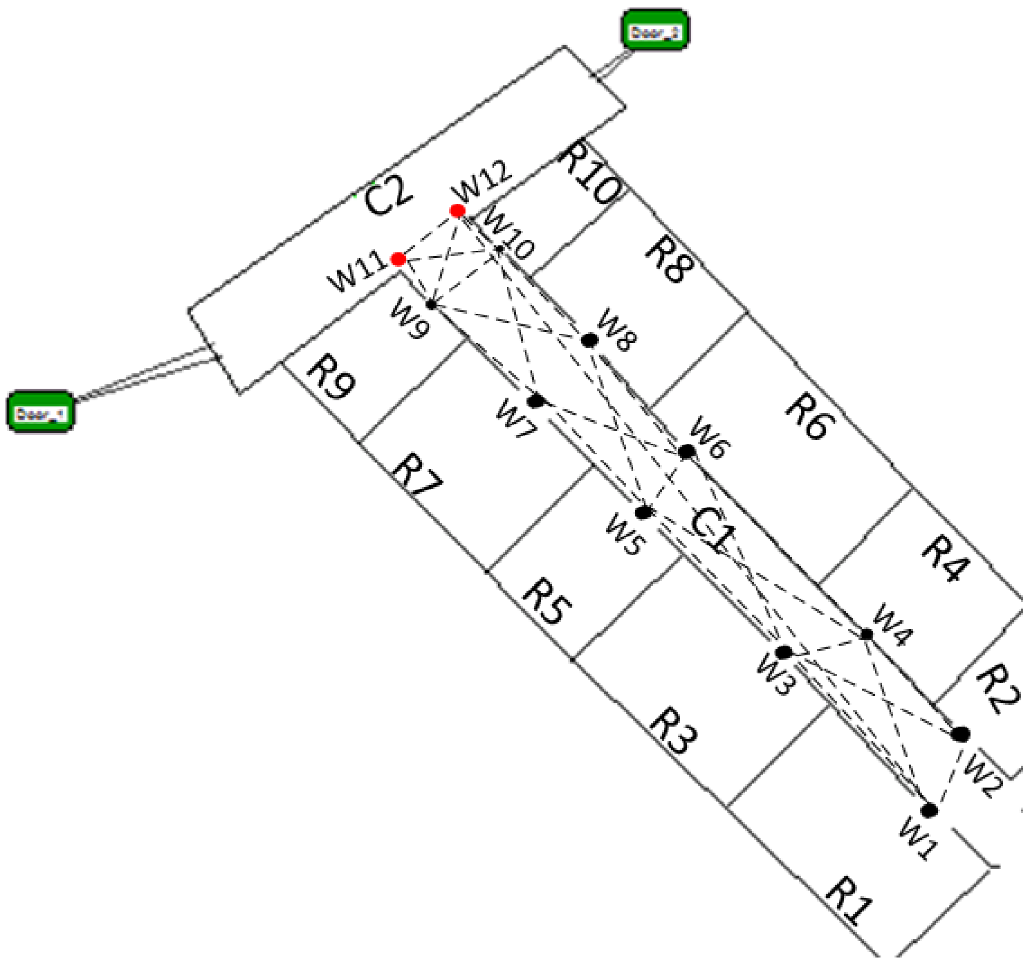


Figure 4.8: Proposed rationalisation of waypoints in a navigational graph by merging and assigning type.

In this approach, additional behavioural rules can be applied to prevent the agent's unnecessary searching behaviour of visiting each internal door waypoint. Before moving to the nearest unvisited waypoint, the improved searching algorithm will allow the agent to check the waypoint type. If the waypoint type is an internal door, the agent will ignore the internal door waypoint and use the normal waypoint for their navigation. For instance, in Figure 4.8, prior to movement, the agent will check the waypoint type and ignore visiting the internal door waypoints (waypoint W1-W10) and will use the normal waypoint W11/W12 for the navigation.

Providing a type to a waypoint can resolve the agent's unnecessary movement of visiting each internal door waypoint. However, proper care and testing would require to ensure the correctness of the proposed amendment in the searching algorithm. For instance, an internal door may be connected to an exit. In this scenario, if an agent ignores using the internal door waypoint, he may eventually miss the exit. Hence, while assigning the type of a waypoint, it must be ensured by the model user that internal door is not connected to an exit. If the internal door is connected to an exit, the model user should assign the waypoint type as normal waypoint.

Another possible issue can be the distance between the internal door waypoints of two internal doors. For instance, in Figure 4.9 internal room R1 and R2 have internal door waypoint W1 and W2 respectively. The distance between W1 and W2 is 2 m. Since the distance is less than the arbitrary threshold distance of 5 m, according to the first proposed method to rationalise the location of waypoints, waypoint W1 and W2 should be replaced by a new waypoint. The newly created waypoint will be located at the average distance/potential value of two internal door waypoints. This modification over the internal door waypoints can disturb the navigational graph and the possible route choices of the agent. Hence, to address this possible problem, an exception to internal door waypoints should be included while testing the threshold distance value of 5 m between waypoints. According to this exception, in any given scenario, two internal door waypoints of different internal doors will not be replaced by one waypoint.

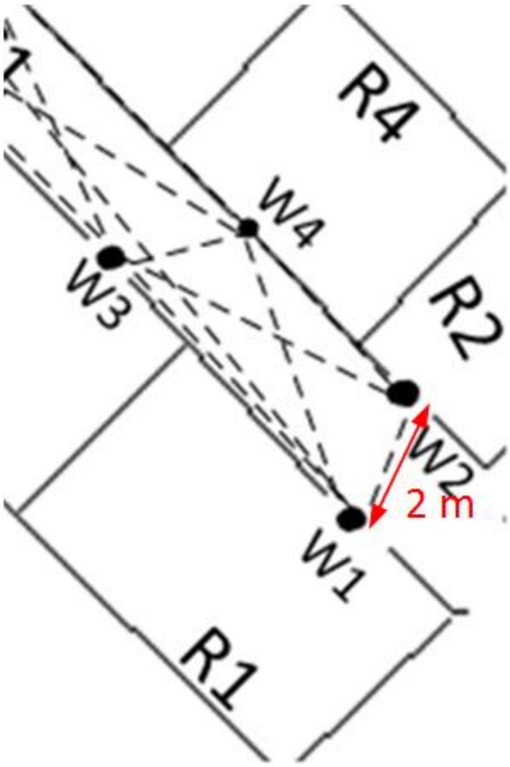


Figure 4.9: A possible issue while rationalising the location of waypoints.

4.2.1.2 Introducing agent's memory to create an individual navigational experience

In the new signage-based navigation model, each agent is equipped with an individual memory to store their individual navigation experience. During wayfinding, if an agent visits a waypoint or detect a sign, the agent will record the waypoint or the sign along with the time of the event. The memory provides an understanding of visited and unvisited space in the structure, which help prevent the agent from performing unrealistic milling behaviour (see Section 3.2.6.2)and random walk behaviour (see Section 3.2.6.3).

Using their memory, an agent can also avoid reusing signage information that fails to help them in wayfinding. For instance, if the agent used a sign without finding a viable escape route or exit, the agent may decide not to follow the sign if he detects the sign again.

The memory of an agent can play an important role in the modelling of ingress, circulation and evacuation scenarios. Ingress can be defined as a process where an occupant enters a building with a task and no previous familiarity with the structure [Gwynne and Kuligowski, 2009]. For example, an occupant visiting an airport for the first time with no knowledge of check-in desk, flight gate number etc. Hence, to board the flight, an occupant looks for information such as signage from surrounding space and continues the process until they reach their desired destination. In this manner, the ingress initiates. Circulation is similar to the ingress. However, the difference between them is during the circulation process, an occupant is inside the building and may also have some limited familiarity with the structure [Gwynne and Kuligowski, 2009].

In evacuation modelling, different level of familiarity can be modelled using the memory. The agent's memory can simulate how they learn the environment during wayfinding. The role of the agent's memory has not been studied yet in the current evacuation/pedestrian models. Hence, the existing models also lack the capability to simulate the scenarios which transitions between ingress, circulate and evacuation as the existing models focus on either circulation or evacuation process and ignoring the ingress process.

In this study, memory is a key part of the new signage-based navigation model. Hence, the new model, in addition to circulation and evacuation scenarios, can also model ingress scenarios. If an agent detects a sign, the agent starts following the direction of the sign (Section 4.5.2). During an ingress scenario, an agent searches the surrounding space to find information (Section 4.5.3). The agent's memory allows the agent to store the visited places and helps to retrace their path if they are disoriented while wayfinding.

4.3 Overview of the new signage-based navigation model

Based on the analysis of the limitations identified in the existing modelling approaches and discussion of the proposed methods to improve the representation of the interaction between agents and signage system (especially chain signage) in evacuation modelling(see Section 4.2), a new signage-based navigation model which integrates signage (with direction), navigational graph, individual memory and search algorithm into the simulation of agent wayfinding during an evacuation is developed and presented in this section. The new model is mainly composed of three modules: the memory module, the navigation module and the movement module (see Figure 4.10).

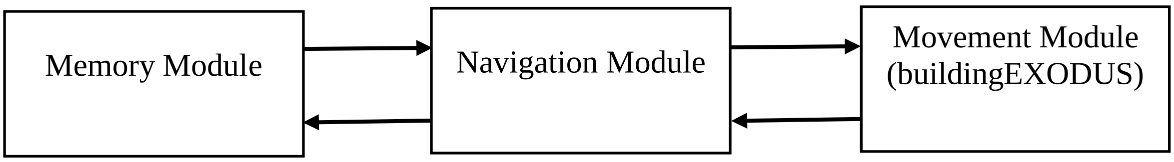


Figure 4.10: The structure of the new signage-based navigation model.

The memory module is responsible for storing agent's visited waypoints and perceived signs which form agent's wayfinding experience. The navigation module provides the agent a capability to decide what action to perform under three distinct navigation scenarios. These scenarios are:

- **Navigation Strategy 1 (NS1): Agent's full or partial familiarity with the exits:** In this scenario, the agents' wayfinding behaviour when they have full or partial familiarity with the exits/exit is simulated (Section 4.5.1).

- **Navigation Strategy 2 (NS2): Following Signs along the route:** In this scenario, the agents with or without previous knowledge of the layout of the structure can find an exit using the signs configured as a signage chain along the intended escape route (Section 4.5.2).

- **Navigation Strategy 3 (NS3): Agent without familiarity with building layout or with invalid exit knowledge:** In this scenario, the agents with no previous familiarity with the structure can find an exit without using signage (Section 4.5.3).

The movement module mainly utilises the occupant movement simulation mechanism in the test platform, i.e. buildingEXODUS, to control agent's movement towards the targets determined by the navigation module. The version of the buildingEXODUS software used in this thesis is V7.0.0.2561.

To run a simulation using the new model, the model user requires to execute the following steps (see Figure 4.11).

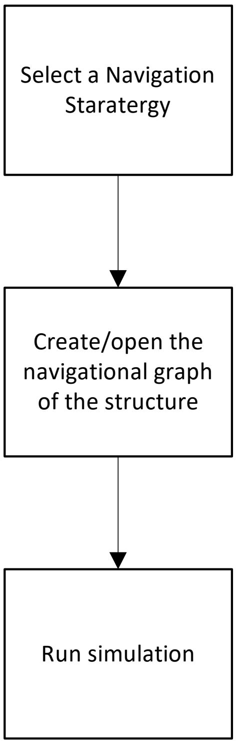


Figure 4.11: Steps required to run a simulation using the new model.

- **Selecting a navigation strategy**. If the user wants to study the structural efficiency, the use Navigation Strategy 1 would be beneficial. If the user likes to study the influence of the signage system on the agents' wayfinding behaviour, the Navigation Strategy 2 would be useful. Similarly, if the focus of the scenario is to simulate the movement of the agents with no previous familiarity with the structure, then the Navigation Strategy 3 would be required.

- **Create the navigational graph of the structure**. The navigational graph is drawn manually using the standard polygon function provided by buildingEXODUS. The waypoints are then automatically generated once the polygon is converted into a navigational region. A user can save the navigational graph for future use.

- **Run simulation**

4.4 The memory module

In order to pursue cognitive behaviour, an agent needs to have a memory of their past visited places. Using the memory, the agent can avoid revisiting the places which did not lead them towards their target previously. In addition, the memory also helps to avoid unnecessary backtracking behaviour [Galea *et al.,* 2011] and random walk behaviour [Pan, 2006]. Therefore, in the new model, agent's memory is introduced.

In the new model, each agent is equipped with individual memory which stores visited waypoints and detected signs in a list. The memory also stores the time stamps of visited waypoints and detected signs. If an agent encounters a sign or a waypoint, the memory module will check whether the particular sign or waypoint has been stored (see Figure 4.12). If the agent is using a particular sign or visiting a waypoint for the first time, the sign or the waypoint will be stored in the memory along with the time of the event (i.e. perceiving the sign or visiting the waypoint). However, the particular sign or waypoint will not be stored again in the memory if the agent or visited has used it in past. However, only the time of the event will be updated.

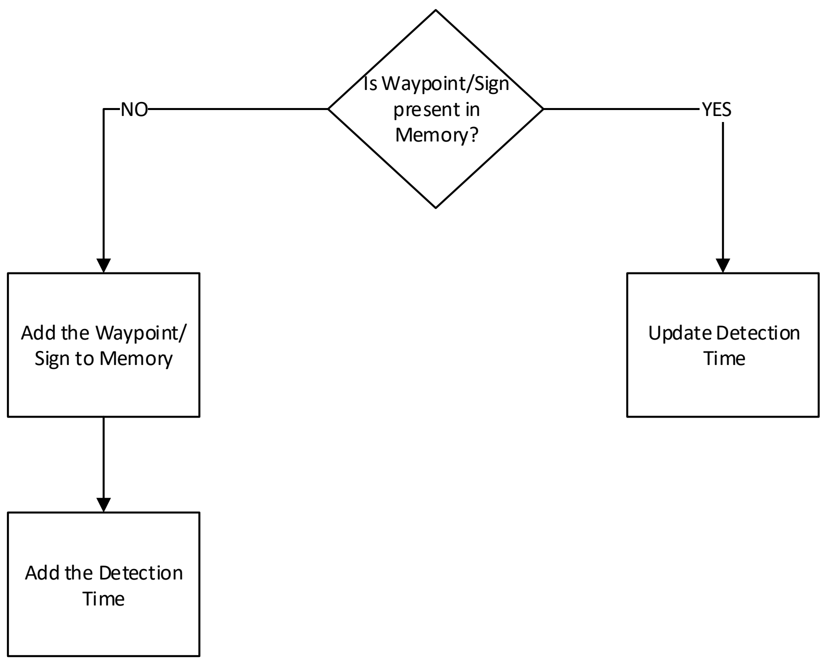


Figure 4.12: An agent's memory.

4.5 The navigation module

The navigation module is responsible for navigating through the space using the activated navigation strategy and individual navigation experience to identify the path composed of intermediate targets towards the final exit or target. This module simulates the agent's wayfinding behaviour and movement using three different navigation strategies. These are:

- **Navigation Strategy 1 (NS1): Agent's full or partial familiarity with the exits**

  When an agent has full familiarity with the exits, the agent uses the nearest exit to leave the structure from their current location. The agent follows the route formed of visible waypoints with the minimum potential until reaching an exit or seeing a sign (agent switch to Navigation Strategy 2).

  Similarly, when an agent has either a target exit assigned or partial familiarity with one or more exits, the agent selects a waypoint with the minimum distance to the target exit until reaching the exit or seeing a sign (agent switch to Navigation Strategy 2).

- **Navigation Strategy 2 (NS2): Following signs along the route**

  If the agent detects a sign, the agent starts following the direction of the sign by selecting a waypoint located at the minimum angle in the direction of the sign.

- **Navigation Strategy 3 (NS3): Agent without familiarity with building layout or with invalid exit knowledge**

  The agent explores the surrounding space using the Breadth First Search algorithm. The agent visits the nearest unvisited visible waypoint until reaching an exit or seeing a sign (agent switch to Navigation Strategy 2).

In the new model, the agent can adapt to the situation and switch to the other navigation strategies (see Figure 4.13). For instance, given the agent has full or partial familiarity with the structure (Navigation Strategy 1), if the agent detects a sign, the agent's navigation will switch to Navigation Strategy 2. If the agent could not find next sign or an exit following the detected sign direction, the agent will switch back to the original navigation strategy. Similarly, if the agent is not familiar with the structure (Navigation Strategy 3), when detecting a sign, the agent will start using the Navigation Strategy 2 to follow the sign direction. It should be noted that Navigation Strategy 1 and Navigation Strategy 3 are contrary in nature as the former represents the agent's full or partial familiarity with the exits and latter represents no previous knowledge with the exits. Hence, an agent will not switch between these two navigation strategies.

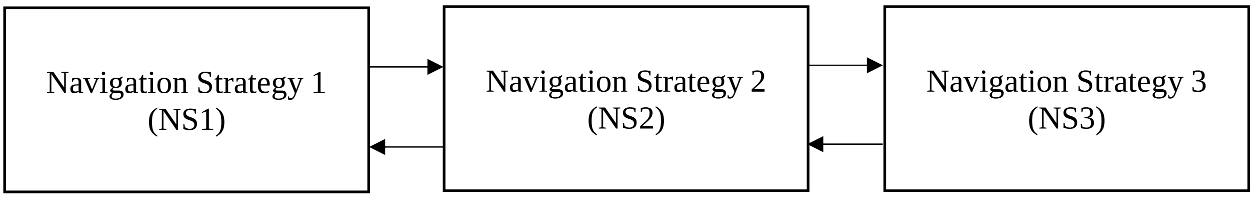


Figure 4.13: Switching between different navigation strategies.

The following sections explain each navigation strategy with the underlying algorithms implemented.

4.5.1 Navigation Strategy 1 (NS1): Agent's full or partial familiarity with the exits

In the new signage-based navigation model, the agent moves along the route consisting of visible waypoints from their locations. The visible waypoints from agent's location are found using the intersection between the two lines algorithm. Using NS1, the agent selects the visible waypoint with minimum potential value or minimum distance value towards his target until either he reaches an exit/target or he detects a sign. If the agent detects a sign, the agent's navigation control is transferred to NS2 (Section 4.5.2). Figure 4.14 depicts the working of this module.

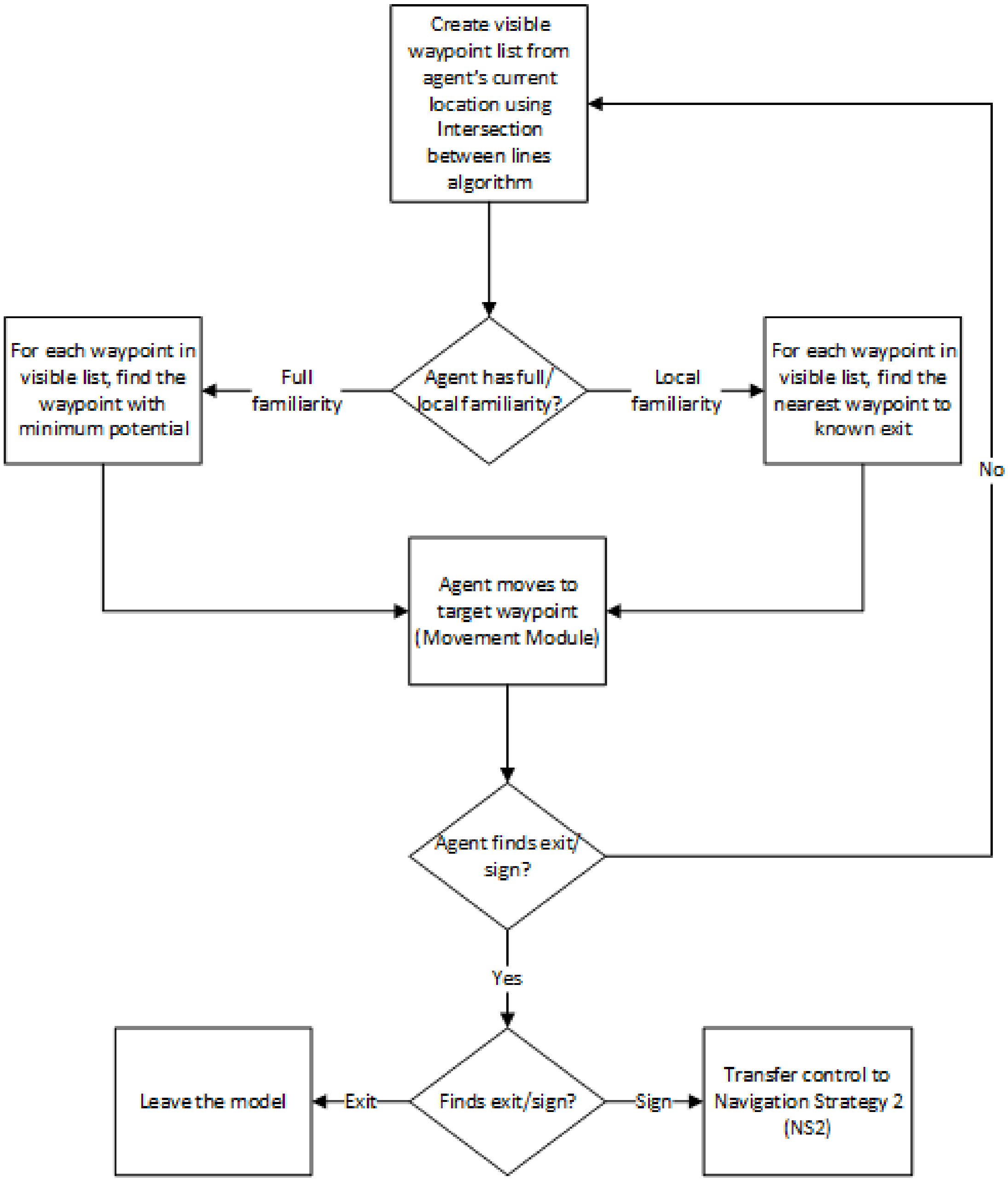


Figure 4.14: Working of Navigation Strategy 1.

Identify visibile waypoints

To begin the navigation, first, a list of visible waypoints from the agent's current location is created using the detection of intersection between two lines algorithm. In this thesis, it is assumed that the entire population have no visual impairment, their vision is not distracted or blocked by other agents and lastly, the agents are not habituated to the existence of the sign. The detection of intersection between two lines algorithm requires the agent's current coordinates and waypoint coordinates to generate a line. The algorithm tests whether this line intersects with any boundary line of the geometry. If an intersection is found, this would mean there is an obstacle between the agent and the waypoint. If no intersection is found, this would mean that this particular waypoint is visible from the agent's current location and will be added to the visible waypoints list.

4.5.1.1 Modelling agent's full familiarity

To further explain the working of this algorithm, Figure 4.15 depicts a structure containing a number of waypoints, an exit and an agent. From the agent's current location, waypoint W1 and W2 are visible. The algorithm uses the agent's current location coordinates and each waypoint coordinates to generate a line. If no intersection found between the generated line and any boundary line, this would indicate that the agent can see the particular waypoints (W1 and W2). In this case, W1 and W2 will be added to the visible waypoint list.

If the generated lines intersect with the boundaries, this would mean that there is an obstruction between them. Therefore, W3, W4 and W5 will not be added to the visible waypoint list.

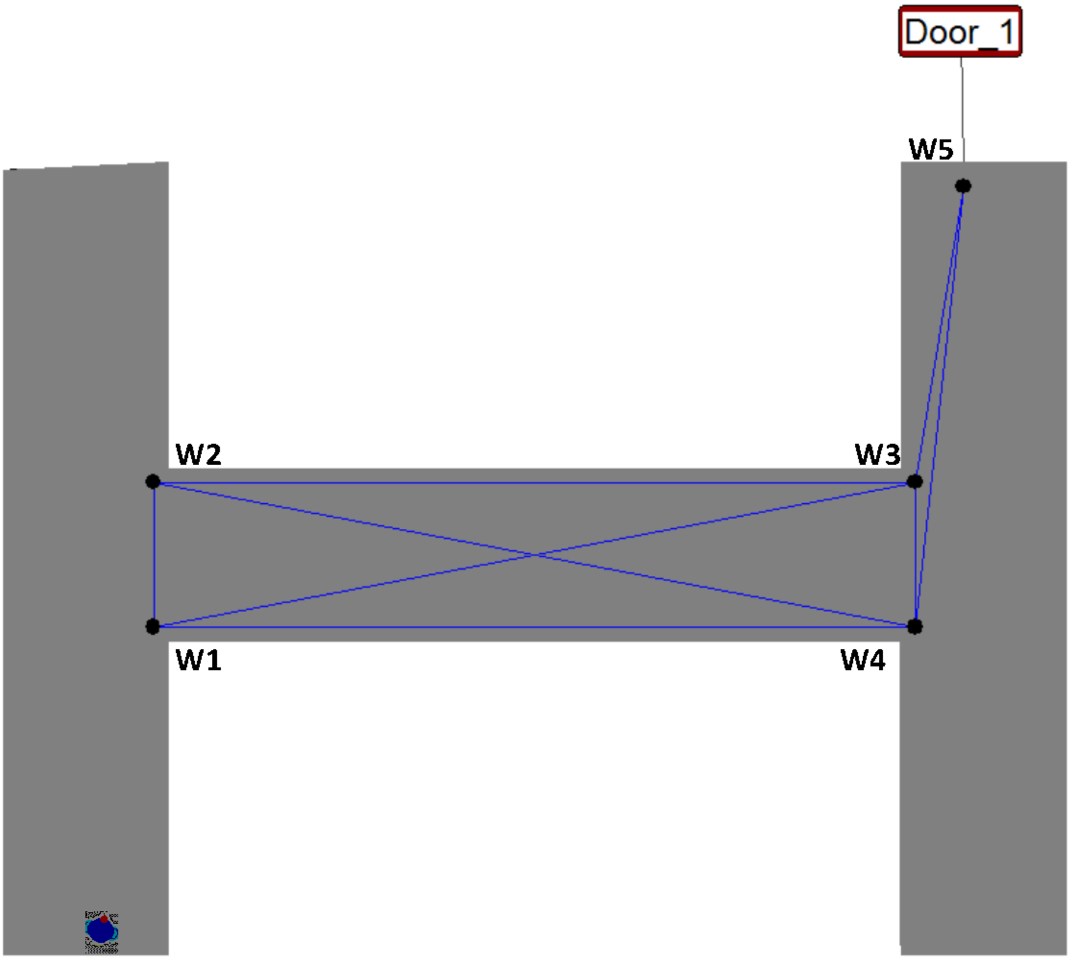


Figure 4.15: Visible waypoints W1 and W2 from the agent's location.

After creating the visible waypoint list, the distance between the agent and each visible waypoint is calculated (*distanceValue*) in addition to the potential value of visible waypoint to exit (*potentialValue*). This addition value would signify the agent's cost of travelling. The waypoint with a minimum sum of *distanceValue* and *potentialValue* i.e., the travelling cost is selected as the agent's target.

For instance, in Figure 4.16, from the agent's current location waypoint W1 and W2 are visible. To select the agent's target waypoint, first, the distance between the agent and each visible waypoint is retrieved. The distance between the agent and W1 is 4m whereas the distance between the agent and W2 is 10m. Similarly, the potential value of W1 to Door 1 is 5m and potential value of W2 to Door 1 is 3m. If the agent uses W1, then the total cost of travelling will be 9m (4m+5m). If the agent utilises W2, the total cost would be 13m (10m+3m). According to the Navigation Strategy 1 algorithm, the waypoint with minimum travelling cost will be selected as agent's target. Therefore, W1 will be set as agent's target.

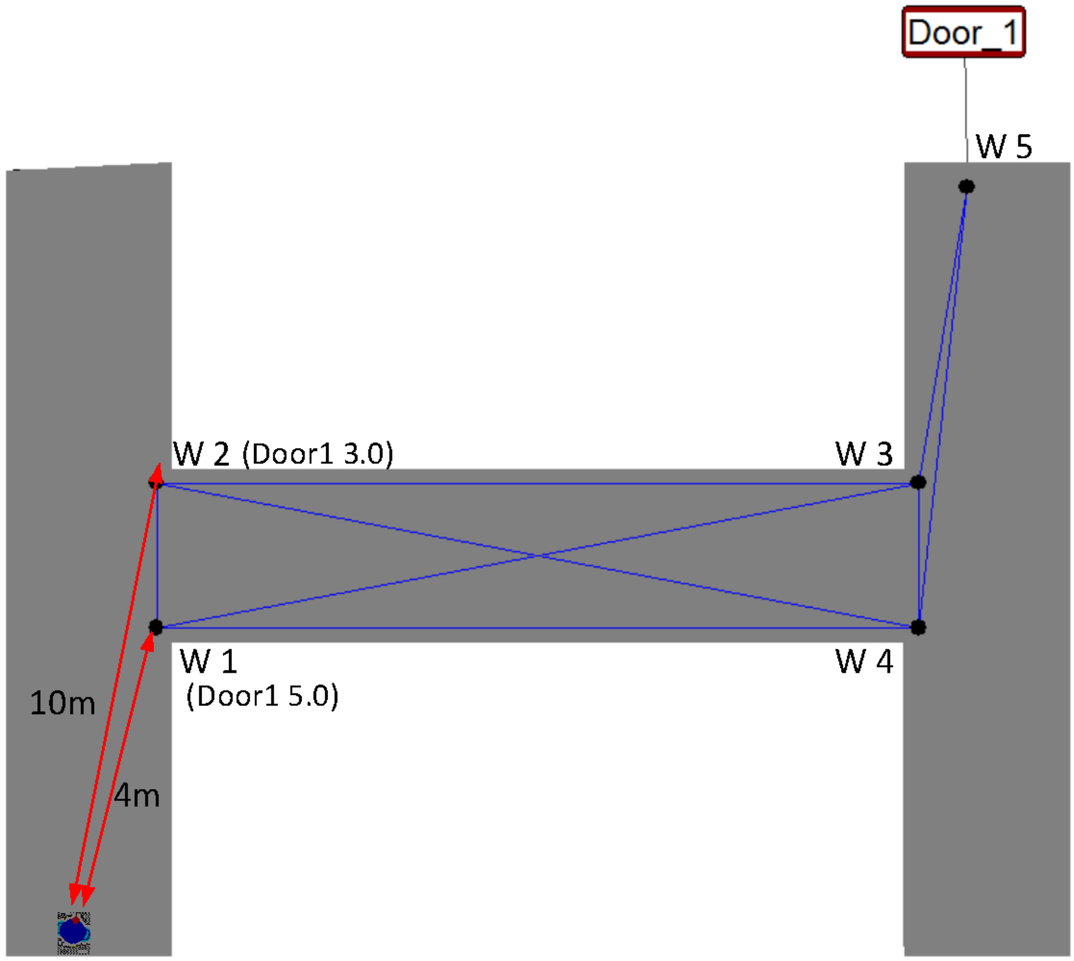


Figure 4.16: Calculating agent's travel cost when the agent has full familiarity.

Then, buildingEXODUS, responsible for moving the agent from their current location to selected waypoint, will move the agent. At this point, three possible actions can occur.

First, if the agent finds an exit, the agent will use it and leave the model. Second, if the agent sees a sign, the agent will start following the sign using the Navigation Strategy 2 (Section 4.5.2). And, third, if the agent does not find any exit or sign, the agent will continue using the potential map. Therefore, when the agent moves to target waypoint (W1), the process of creating visible waypoints start again consisting of W2, W3 and W4. To find the agent's next target waypoint, a visible waypoint with a minimum cost of travelling is then set as the agent's next target. buildingEXODUS then moves the agent from their current location to the newly selected target waypoint. This process continues till the agent reaches the exit.

4.5.1.2 Modelling agent's partial familiarity

If an agent is familiar with an exit in the structure, the agent would prefer to use the already known exit. Hence, after creating the visible waypoint list, agent's cost of travelling is the sum of the distance between the agent and each visible waypoint (*distanceValue*) and the distance value of each waypoint to the known exit (*distanceExitValue*). The waypoint with minimum travelling cost is selected as the agent's target. For instance, in Figure 4.17, an agent is aware of Door 2, from agent's starting location waypoint W1 and W2 are visible. To select the agent's target waypoint, first, the distance between the agent and each visible waypoint is retrieved. The distance between agent and W1 is 4m whereas the distance between the agent and W2 is 10m. Similarly, the distance between W1 to Door 2 is 15m and the distance between W2 and Door 2 is 18m.

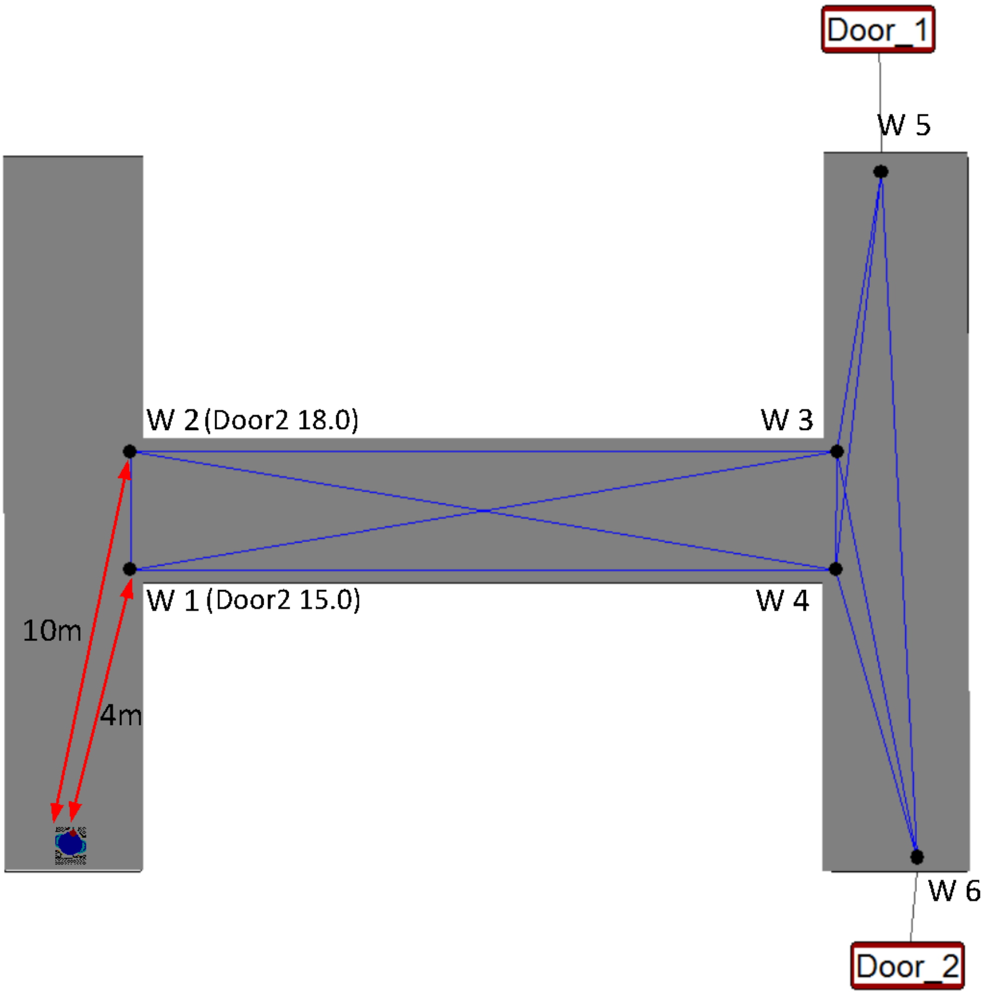


Figure 4.17: Calculating agent's travel cost when the agent has partial familiarity.

If the agent uses W1, then the total cost of travelling towards Door 2 will be 19m. If the agent utilises W2, the total travelling cost would be 28m. The waypoint with the minimum travelling cost will be selected as the agent's target. Therefore, in this case, W1 will be set as the agent's target.

After finding the agent's next target, buildingEXODUS then moves the agent from their current location to selected waypoint. Similar to the previous case where the agent has full familiarity with the exits, at this stage, three possible scenarios can occur.

First, if an agent finds an exit, the agent will use the exit and leave the model. Second, if the agent detects a sign, the agent will start following the sign using the Navigation Strategy 2 (Section 4.5.2). And, third, if the agent does not find any exit or sign, the agent will continue using the Navigation Strategy 1. Therefore, in Figure 4.13, when the agent moves to target waypoint (W1), the process of creating visible waypoints start again consisting of W2, W3 and W4. To find the agent's next target waypoint, a visible waypoint with a minimum cost of travelling is then set as the agent's next target. buildingEXODUS then moves the agent from their current location to the newly selected target waypoint. This process continues till the agent reaches the exit or detects a sign.

4.5.2 Navigation Strategy 2 (NS2): Following Signs along the escape route

An agent may have full, partial or no knowledge of the exits. Irrespective of the agent's original navigation strategy based on their level of familiarity with the structure, if an agent detects a sign during their navigation, the agent will switch to Navigation Strategy 2 for wayfinding.

The agent's navigation using the signage has two stages, Signage Perception (Section 4.5.2.1) and Following a Sign (Section 4.5.2.2). These two stages are explained in the following sections providing their in-depth description.

4.5.2.1 Signage perception

Perception is the ability to perceive or recognise something. In order to make correct decisions while wayfinding, it is crucial for an agent to successfully recognise a spatial object like a sign, a door, obstacles etc. As the name suggests, signage perception allows the agent to perceive a sign provided that the agent is able to physically see the sign.

As previously discussed in Chapter 3, Section 3.2.6.2, in buildingEXODUS to represent the physical visibility of sign, the concept of Visibility Catchment Area (VCA) is used which is defined as the region from where it is physically possible to perceive the sign [Filippidis *et al.*, (2001, 2003, 2006, 2008); Xie, (2011); Galea *et al.*, (2011); Xie *et al.*, (2012)]. In the original VCA model, due to the lack of data to represent actual signage visibility probability, a simple approach was adopted, and it was assumed that if an agent is in the VCA regardless of their orientation to the sign, agent will detect and follow the sign [Filippidis *et al.,* 2001, 2003, 2006]. At later stages, a revision made to the VCA model that to actually see the sign, the agent must be facing the general direction of the sign [Filippidis *et al.,* 2006]. This was achieved by calculating the relative orientation between the sign and the agent's travel direction.

In buildingEXODUS, the relative orientation between the sign and the agent's travel direction is calculated when the agent is in the VCA of the sign. Then, the angle between the agent's travel direction and the sign location is measured through a hypothetical signage visibility probability. Since there is no data collected for this measurement, a hypothetical relationship between the visibility probability and the observation angle was proposed. According to this relationship, the smaller the angle between the agent's travel direction and the sign location, the higher the probability to discern the sign will be. That means the visibility probability is maximum at 0^{o} when the agent is looking at the sign straight on, which provides the maximum possibility to detect the sign. Furthermore, the visibility probability is smaller at 90^{o} when the agent is viewing the sign side on and reduce to 0 at 180^{o} the agent is looking away from the sign.

The current implementation does not implement a dependant probability of the agent seeing the sign based on their relative orientation. However, the relative orientation between the agent and sign is implemented in buildingEXODUS, hence this particular feature can also be implemented in the new signage-based navigation model. As previously explained the visibility of a sign in Chapter 2 (Section 2.5.1) Filippidis *et al.*, [2006] proposed the hypothetical visibility probability according to the agent's travel direction and observation angle [Figure 4.18a]. Figure 4.18b depicts how a space around an occupant can be divided into angular zones where each angular zone has an associated observation probability.

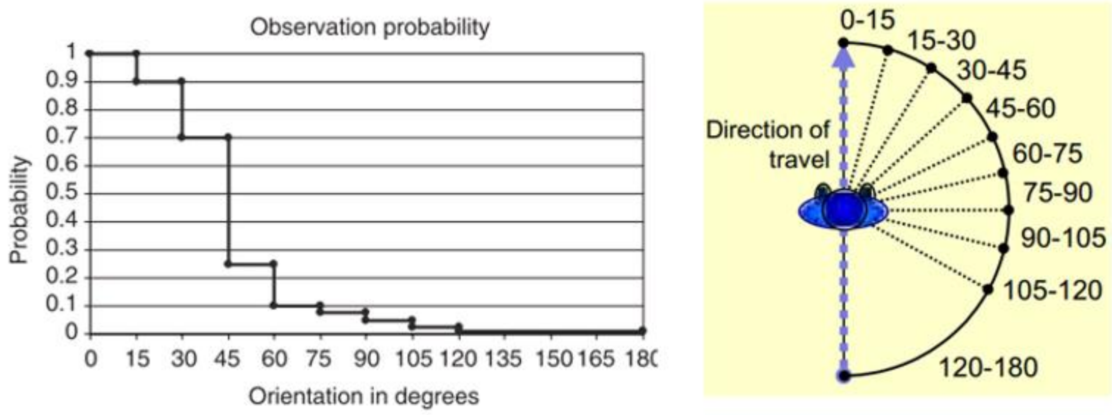


Figure 4.18: (a) Proposed hypothetical visibility probability according to relative orientation between the agent and sign; (b) the space around an agent with angular zone and respective visibility probability of each angular zone Filippidis *et al.*, [2006].

Table 4.1 is a simple representation of Figure 4.18a in a tabular form. Given that a sign is physically visible to the agent [Filippidis *et al.* 2001, 2003, 2006], being in the VCA alone does not guarantee that agent will see the sign. Hence, in future implementation of the new model, another check will be performed to test the relative orientation between the agent's direction of travel and the sign to determine whether the agent can actually discern the sign. To calculate the relative orientation between the agent and sign, the angle between the agent's travel direction and sign will be calculated. This will require the agent's current coordinates and sign's coordinates to calculate the observation angle. Based on the agent's observation angle, the observation probability value will be assigned to the agent to reflect the likelihood of actual detection of a sign. For instance, if the angle between the agent's travel direction and sign is 11.0°, the observation probability will be set to 100%. Or, the angle between the agent's travel direction and sign is 115°, the agent's observation probability will be set to 2%.

Table 4.1: Agent's observation angle and associated visibility probability (adapted from Filippidis *et al.* [2001, 2003, 2006]).

Agent's observation angle	Visibility probability
0.0°-15.0°	1.00 (100%)
15.0°-30.0°	0.90 (90%)
30.0°-45.0°	0.70 (70%)
45.0°-60.0°	0.25 (25%)
60.0°-75.0°	0.10 (10%)
75.0°-90.0°	0.07 (7%)
90.0°-105.0°	0.05 (5%)
105.0°-120.0°	0.02 (2%)
120.0°-180.0°	0.01 (1%)

After a successful detection based on the examination of the relative orientation will be confirmed, it will be further assessed to decide whether the agent's attentiveness allow them to actually detect the sign based on empirical data collected by Xie *et al.* [2012]. If the agent does not detect the sign, he will ignore the sign and maintain their current movement.

Xie *et al.,* [2012] conducted the evacuation trails to find the probability of the occupants who actually detected a sign without any physical obstruction. The signs were installed at the appropriate locations according to the signage standards. In this study, it was found that 38% of the occupants who were unfamiliar with the structure detected the sign and 97% of these occupants used the information provided by the sign for wayfinding. It should be noted that the work of Xie *et al.* [2012] focused on the single sign and it does not cover the detection probability of next sign in a signage chain. In the new signage-based navigation model, the signage perception is responsible for the signage detection which is based on the data collected by Xie *et al.,* [2012].

In the new signage-based navigation model, the interaction between an agent and signage system is simulated in three steps. First and foremost, the sign must be physically visible to the agent i.e., the agent must be in the VCA of the sign [Filippidis *et al.*, 2001, 2003, 2006]. If yes, second, being in the VCA alone does not guarantee that the agent can see the sign. Hence, it is further assessed to decide whether the agent's attentiveness allow them to actually detect the sign. The signage detection in the new model is based on empirical data collected by Xie *et al.,* [2012]. If the agent does not detect the sign, the agent will ignore the sign and maintain the current movement.

Third and lastly, if all tests are successful, the sign is added into the agent's memory provided that the sign is not stored in memory before. If the agent has used the particular sign in the past, the visit is updated in the memory. However, if any of the conditions fails to execute, the agent will ignore the sign information and maintain the current movement.

When the agent enters the VCA of a sign, the memory executes various steps. A key variable called Signage Detection Status decides the next course of the action. Signage detection status is a boolean variable which can only store two values either sign detected or sign undetected. If a sign is not stored in the agent's memory previously, the signage detection status of a sign is simply set to *undetected*. The purpose of using signage detection status is to differentiate which signs are detected and which signs are not detected by the agent. After setting the signage detection status, the sign is stored in the agent's memory along with the sign visit time. The aim of storing the visit time is to compare various visit times if the agent reaches a place with no viable exits present in the structure or missed next expected sign. This will be discussed in detail in Section 4.5.3.1

Figure 4.19 shows how the memory module works with signage perception when the agent enters a VCA of a sign. In order to explain this functionality of the new model, this module is divided into three parts. These are:

- **Part A** covers the working of the module when a sign is not previously stored in the agent's memory.
- **Part B** discusses the working of the module when a sign is already stored in the agent's memory, and
- **Part C** shows the actions based on a successful/unsuccessful sign detection.

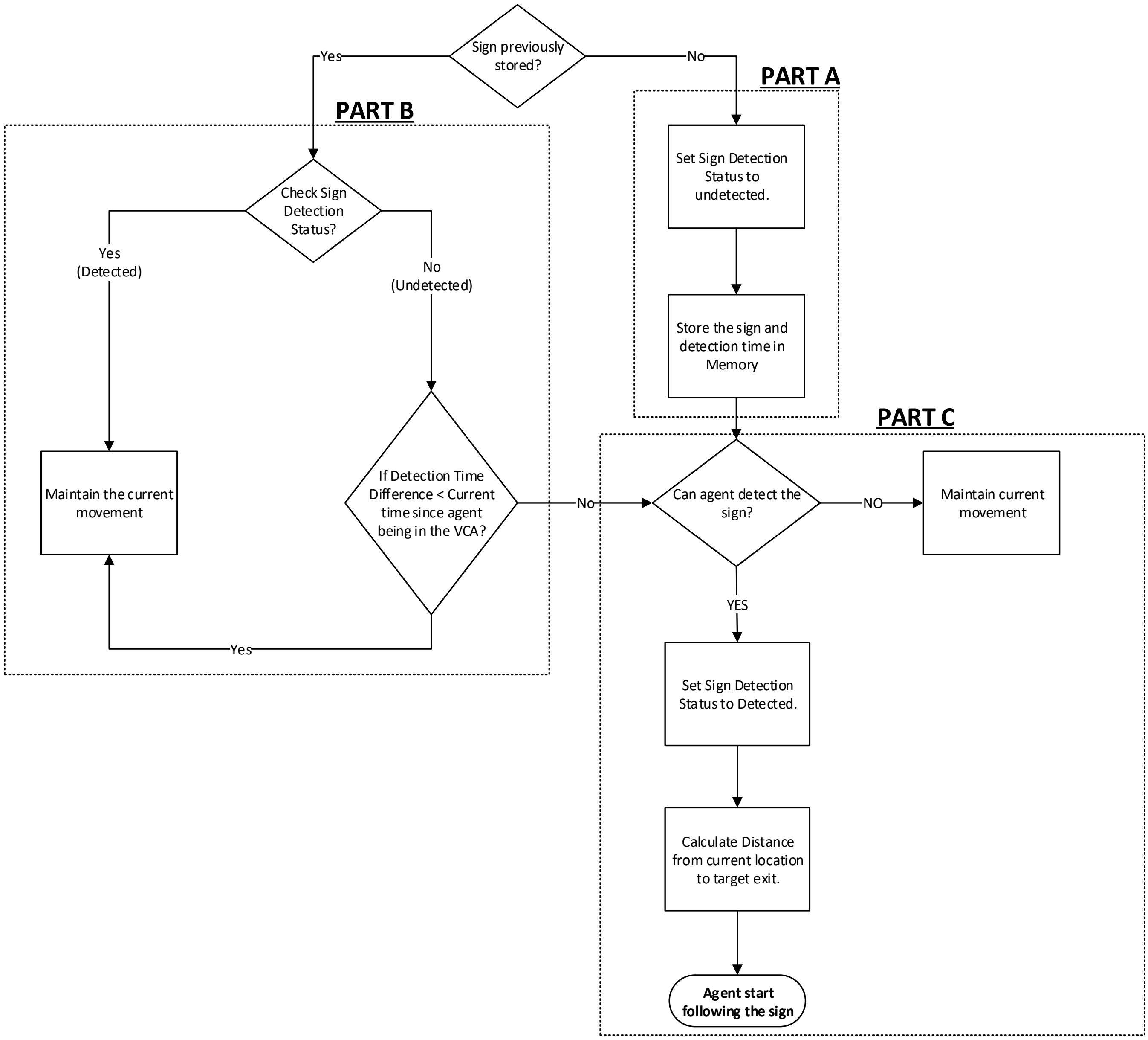


Figure 4.19: Signage perception of an agent.

PART A: If a sign is not stored in the memory

If a sign is not stored in the memory, this would imply that the agent is within the VCA of the particular sign for the first time. Since at this stage successful sign detection is not guaranteed, it is assumed that the agent has not detected the sign yet. Therefore, the signage detection status for the particular sign is set to *undetected*. It is then determined whether the agent can actually detect the sign.

PART B: If a sign is stored in the memory

If the sign is already stored in the memory when the occupant is in the VCA of a sign, this indicates that the agent had entered the VCA of the particular sign previously. However, even if the particular sign is already stored in the agent's memory, signage detection status of the sign will be checked. If it is found to be *detected*, this would mean that agent had been under the influence of the sign and pursuing the direction informed by the sign. If the signage detection status for the particular sign is found to be *undetected*, it would mean that the agent has not still detected the sign despite being in the VCA of this sign. At this stage, a time difference of detection times is calculated using Formula 4.1:

$$\begin{aligned}\boldsymbol{Visit\ Time\ Difference(s)}\\ &= \boldsymbol{Visit\ Time\ when\ agent\ enetred\ the\ VCA}\\ &- \boldsymbol{Visit\ Time\ of\ Sign\ when\ Sign\ added\ to\ the\ Memory}\end{aligned}$$

Formula 4.1: Difference of agent's visit time.

These visit times are the visit time when agent entered the VCA of the sign and the visit time of the sign first stored in the memory. The calculation of total time spent by the occupant since being in the VCA of the sign is calculated using Formula 4.2.

$$\boldsymbol{Total\ Time\ spent\ since\ being\ in\ the\ VCA\ (s)} = \frac{\boldsymbol{Sign\ VCA'\ s\ Termination\ Distance}}{\boldsymbol{Agent\ Travel\ Speed}}$$

Formula 4.2: Calculating agent's total spent being in the VCA.

If the difference between the two visit times is less than total time spent since agent being in the VCA of the sign, this means that agent is still under the VCA of the sign and not be able to detect the sign yet. Therefore, the agent will maintain its current direction and navigation in order to detect another sign.

If, however, the visit time difference exceeds the current time since the agent started to follow the sign, this would signify that the agent has spent a significant amount of time in wayfinding using the sign and has not been able to reach the target yet. Hence, the agent will try to find another sign to begin the active pursuit to the target. This step will trigger the sign detection process.

<u>PART C</u>: Taking actions based on a successful/unsuccessful sign detection

Part C shows how the agent takes an action based on a successful/unsuccessful sign detection. This module establishes whether the agent can detect a sign provided that the agent located within the VCA of a sign. If the agent fails to detect the sign, the agent will ignore the sign information and maintain the current movement. If the agent detects the sign, the original navigation strategy which agent used will be assessed. Based on the navigation strategy, different actions will be taken.

If an agent's navigation is based on full or partial familiarity using the Navigation Strategy 1 (Section 4.5.1), three operations are performed. These are:

- The signage detection status for the particular sign will be set to *detected* from *undetected*.

- The distance travelled by agent since following the sign is called as Distance Memory. The distance memory records the distance covered using the particular sign until the agent detects another sign. When the agent starts following another sign, the distance memory resets and starts recording the distance covered by the immediate sign being followed. The distance memory is further explained in detail in the next section (Section 4.5.2.2).

- The distance between the agent's current location to the target exit defined by potential map or familiarity is calculated.

After following all the above steps, the agent will start following the sign (Section 4.5.2.2).

If the agent originally started wayfinding using Navigation Strategy 3 (Section 4.5.3), i.e., the agent has no knowledge of a viable route to any exit. Unlike the potential map or familiarity approach where the shortest route to exit is provided to an agent, in this method agent relies on their searching behaviour (Section 4.5.3.1).

Therefore, to ensure the agent's wayfinding, a distance parameter called the Expected Distance between Signs (EDBS) is used. EDBS provides an estimate within which an agent should expect to see the next sign. If an agent fails to find the next sign within the EDBS value, this means agent should give up searching for the next sign and switch back to Navigation Strategy 3. Therefore, at this point, in the new model, the value of EDBS is calculated.

At present, there is no real data available prescribing how far signs should be placed to each other. However, in general practice, signs are placed not too far and too close to each other. In the new signage-based navigation model, the value of EDBS is set to 2.5 times of a sign. This implies, when an agent starts following a sign, the agent will continue to follow the direction of the sign till 2.5 times of the detected sign's VCA. The reason for setting the EDBS value set to 2.5 times of sign's VCA is the visibility of two signs or more signs may overlap with each other due to their proximity, location, and orientation. When the agent exceeds the EDBS value, they abandon following the sign and switch to Navigation Strategy 3 to continue their wayfinding. It should be noted that in the current signage model of buildingEXODUS, the default value of EDBS is set to 30m which can be modified by the model user.

In the new signage-based navigation model, the EDBS is calculated using the 2.5 times of the sign's VCA as ideally the VCA of two signs should connect with each other so that the agent leaves the influence zone of the first sign would enter the influence zone of the second sign. To assist the agent's wayfinding in a complex structure, the signs should be placed along the escape route so that the occupant does not get disoriented [BS 5499-4:2013]. Figure 4.20: Overlapping of two VCA's shows an example from BS 5499-4:2013 where sign 1 and sign 2 are located in direct sight. In a simulation environment, the VCA of these two signs may overlap with each other due to their proximity, location, and orientation. When the agent starts following the sign 1, the agent may enter the VCA of sign 2 immediately after sign 1. Hence, it is a rational decision to set the value of EDBS to 2.5 times of the sign's VCA. The 0.5 is added to give the agent a slight tolerance for searching the next sign.

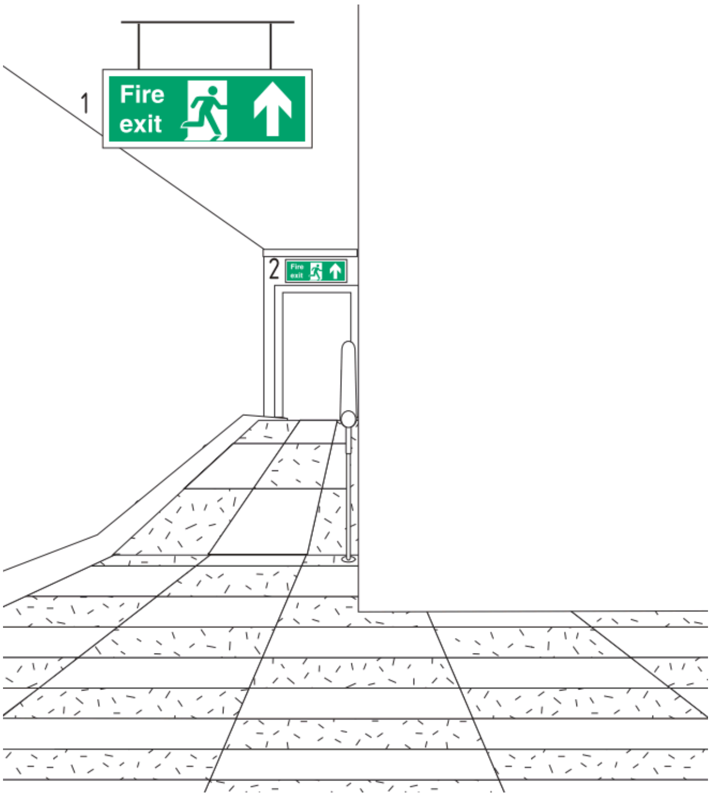


Figure 4.20: Overlapping of two VCA's.

4.5.3.1 *Following a sign*

After detecting and storing the sign into the memory, the next task for an agent is to follow the direction of the sign. The agent in the new model is able to comprehend the direction of the sign. According to BS 5499-4:2013 and ISO 3864, every sign should contain a directional arrow accompanied by a supplementary text. The arrow should indicate the direction of the escape route. The sign should also be correctly oriented in relation to the direction of the escape route and the direction of the arrow.

BS 5499-4:2013 and ISO 3864 prescribe eight recommended combinations of signs containing arrow direction and supplementary text (see Table 4.2). In the new signage-based navigation model, five combinations of supplementary text and signage direction are implemented and tested. These are, sign with an up arrow, sign with a right arrow, sign with a left arrow, sign with an up right arrow and sign with an up left arrow. Due to time constraint, the three signage directions (sign with down to the right arrow, sign with down to the left arrow and sign with a down arrow) have not been implemented within the new signage-based navigation model.

Table 4.2: Escape route signs with direction arrows [BS: 5499-4:2013].

Exit sign with direction arrow	Meaning	Implementation in new signage-based navigation model
	Sign with an up arrow.	✓
	Sign with a right arrow.	✓
	Sign with a left arrow.	✓
	Sign with an up right arrow	✓
	Sign with an up left arrow	✓
	Sign with a down right arrow	X
	Sign with a down left arrow	X
	Sign with a down arrow	X

An agent will not be able to follow the sign unless they understand the arrow direction of a sign. The direction indicated by the arrow in the sign depends on the angle at which sign is installed in the structure. The sign angle is calculated using the tangent function between the x-axis of a plane and the coordinates of the installed sign. This calculation requires the sign's coordinates and, the sign's angle can be retrieved using the angle between the two points formula.

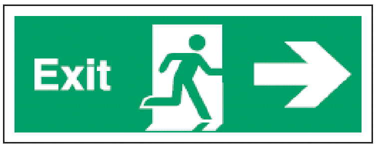
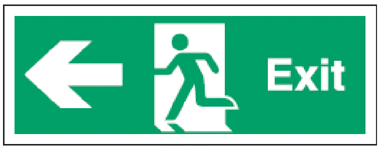
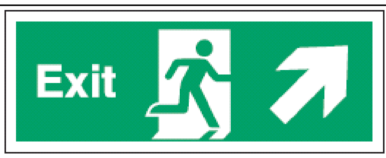
Hence, for any sign placed in the geometry, in order to determine the actual direction indicated by the sign, first, the orientation of the sign is calculated and second, the direction of the arrow on the sign is added. The coordinates of the sign are used to calculate the angle of a sign relative to 0° which is then combined with the angle of the arrow of the sign. Hence, to calculate the direction indicated by the sign, Formula 4.3 is used:

$$Sign\ Direction = Sign\ Angle + Angle\ of\ the\ arrow\ of\ the\ sign$$

Formula 4.3: Calculating the angle of a sign.

Table 4.3 below shows the angle of the arrow for each implemented sign in the new signage model along with the angle of the actual direction indicated by the sign.

Table 4.3: Calculation of angle each sign's arrow direction and sign direction.

Exit sign with direction arrow	Relative angle of the arrow to the sign	Angle of the actual direction indicated by the sign
	$\frac{\pi}{2}$	$Sign\ Angle - \frac{\pi}{2}$
	0°	$Sign\ Angle$
	π	$Sign\ Angle + \pi$
	$\frac{\pi}{4}$	$Sign\ Angle - \frac{\pi}{4}$
	$\frac{3\pi}{4}$	$Sign\ Angle - \frac{3\pi}{4}$

The next task would be to find the closest waypoint in this direction. This process is divided into two parts. First, find all the visible waypoints from the sign's point of view using the intersection between two lines algorithm. –Second, to determine the closest waypoint in the direction of the sign, for each visible waypoint, the difference of sign direction and the angle between the particularly visible waypoint and the sign is calculated. Formula 4.4 is used for this calculation:

$$Angle\ Measure\ of\ sign\ and\ Waypoint = Sign\ Direction - Angle\ between\ agent\ and\ waypoint$$

Formula 4.4: Calculating the angle between sign and the waypoint.

Eventually, the waypoint with the minimum angle difference to the angle of the direction indicated by the sign will be assigned as agent's next target. After detecting the sign, the agent will start following the direction of the sign. In Figure 4.21, when the agent detects the sign, from sign's point of view the visible waypoints are, W1, W2 and W3. Since W3 is located at the minimum angle from signage direction, W3 will be set as the agent's target.

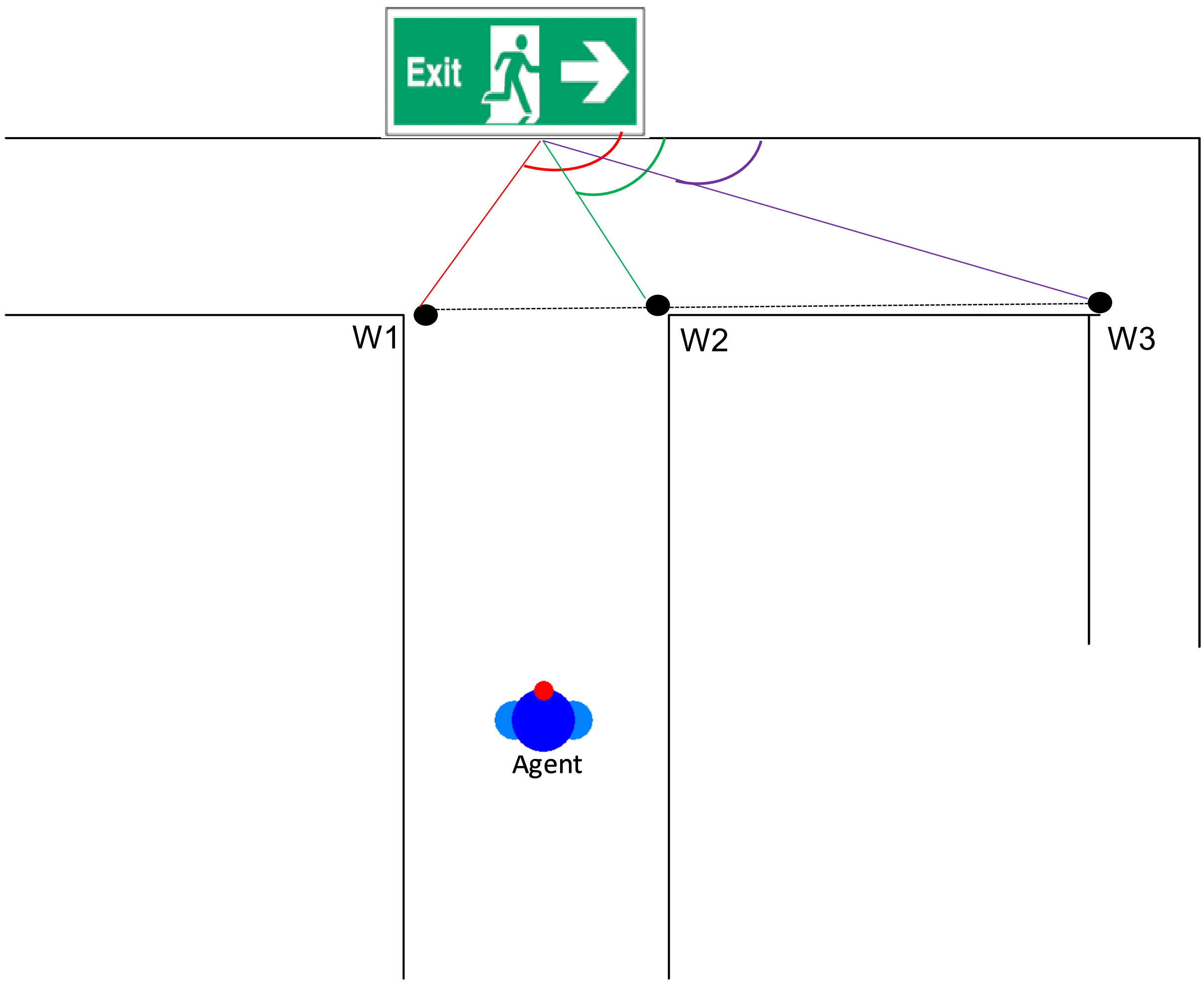


Figure 4.21: Finding closest waypoint in the direction of sign.

When an agent starts following the sign, the agent's distance memory initiates. The aim of using distance memory is to record the distance travelled by the agent since following the sign. When using the Navigation Strategy 1, the agent implicitly has an estimate of their travel distance towards their known exit. During the navigation, when the agent detects and starts following a sign, the distance memory initialises to record the total distance travelled since following the sign. Distance memory informs the agent when they travel more than the distance to their known exit. At this stage, the agent will stop following the sign and change the direction of travel towards their known exit. While moving to their known exit, a possibility may arise of the agent entering the VCA of the previously visited sign. At this stage, the agent will not start following the sign. This is because of the agent's memory which will indicate that the agent has used the sign in past and could not find an exit or next expected sign.

When the agent has full/partial familiarity with the exits (Navigation Strategy 1), if the agent starts following a sign and the distance memory exceeds the estimated distance to their known exit agent will stop following the sign and their navigation will shift back to Navigation Strategy 1. Similarly, when an agent has no exit knowledge (Navigation Strategy 3), if the agent starts following a sign and their distance memory exceeds the EDBS (2.5* maximum visibility distance of the detected sign) value, the agent will abandon following the sign and will switch to (Navigation Strategy 3) for further navigation.

4.5.3 Navigation Strategy 3 (NS3): Agent without familiarity with building layout or with invalid exit knowledge

A possibility may arise when an agent has no previous familiarity with any exit of the structure or the known exits become unavailable (e.g. due to the presence of fire hazards). Under this scenario, an agent relies on their cognitive skills to search for an exit. The Navigation Strategy 3 depicts the scenario where an agent in a building:

- Forgot the entrance location.
- Forgot the route to the entrance location.
- No previous familiarity with any exit of the structure.
- No previous familiarity with any exit of the structure and no signage available.
- Previous known exits/exit routes become unavailable (e.g. due to the presence of fire hazards etc.).

An agent uses Navigation Strategy 3 by visiting nearest unvisited adjacent waypoints. The agent continues to explore the surrounding space by visiting nearest unvisited waypoints until the agent either detects a sign or finds an exit to leave. If during the agent's movement, the agent detects a sign, the agent will start following the direction of the sign using the Navigation Strategy 2 (Section 4.5.2).

4.5.3.1 *Agent's searching behaviour in Navigation Strategy 3 (NS3)*

In Chapter 3, Section 3.2.4, searching algorithms namely, Breadth-First Search (BFS), Depth First Search (DFS), A* algorithm and Dijkstra algorithm were discussed. In this thesis, the searching behaviour of the agents is based on Breadth First Search (BFS) algorithm. This algorithm allows an agent to search the surrounding space first and then gradually spread the search towards the end of the structure. Compared to other discussed well-known searching algorithms in Section 3.2.4, there are some distinctions which make BFS the appropriate choice to be used for searching behaviour.

The selection of BFS algorithm for the agent's searching behaviour is based on an assumption. According to this assumption, in a structure where an agent has no previous familiarity with the internal connectivity and available exits he would prefer to start searching for an exit or sign from close vicinity of the agent's current location [Løvs, 1998]. Using BFS, the traversal search starts from space in close vicinity and then expands into outer space level by level. In the new signage-based navigation model, the navigational graph provides an agent with a sense of internal connectivity of the surrounding environment. By combining the navigational graph and the BFS algorithm, the agent can explore a complete unfamiliar environment to find an exit or clues leading to an exit (such as exit/sign).

Whereas, using the Depth First Search (DFS) algorithm, the traversal initiates from the starting node and expands the search as far as possible from the starting node. Hence, it allows the searching behaviour depth wise. Furthermore, from a design point of view, usually exits in a building are placed at a point which balances the travel distance for occupants rather than placing the exits at the far end of the structure. Hence, if an agent attempts searching in the structure using the DFS algorithm, the agent will start the searching in the depth ward motion. Whereas, BFS algorithm provides an agent with the confidence to search for an exit from either end of the structure.

A* and Dijkstra algorithm provide the shortest route from point A to B. However, both these algorithms were not found to be appropriate for simulating the agent's searching behaviour of an agent with no previous familiarity with the exit. In this special scenario, an agent does not have any prior knowledge of any exits (desired destination). The A* and Dijkstra algorithm require the knowledge of the final target to find the shortest route. Therefore, BFS algorithm was found to be an appropriate choice for the agent's searching behaviour when the agent has no previous familiarity with the exits and no signage available.

In real world, it is not certain how the occupants search for their desired destination in an unfamiliar environment. It is also not certain that if the occupants perform searching in BFS algorithm fashion [Løvs, 1998]. However, BFS algorithm approach depicts a rational searching behaviour. However, further research and data collection need to be performed on the occupants searching behaviours.

Using the Navigation Strategy 3, an agent searches for a nearest unvisited visible waypoint from their current location using the searching behaviour and memory. The searching behaviour allows the agent to follow the route formed of the nearest unvisited visible waypoint. If an agent finds a nearest unvisited waypoint, the agent moves to the waypoint and starts searching for a nearest unvisited waypoint again. This process continues until the agent find an exit or a sign. Similarly, the memory allows the agent to remember the previously visited waypoints. An agent may reach a stage where the agent reaches a place with no viable exits present or the agent did not find next expected sign. In this situation, the agent starts backtracking behaviour using the memory. During backtracking, the agent starts retracing their path to earliest visited waypoints until finding an exit or detecting a sign. If the agent detects a sign, the agent will start following the sign and the agent's navigation will switch to Navigation Strategy 2.

Lastly, it should be noted that the agent's searching behaviour will likely to be influenced by the agent's initial location. This is a limitation of the implemented searching behaviour. The sensitiveness to the agent's initial location is due to the way the current searching algorithm is implemented. An agent using the searching behaviour starts searching for the nearest visible unvisited waypoint. Hence, depended on the agent's initial location, their selection of the first target waypoint may vary. The BFS algorithm approach depicts a rational searching behaviour as it allows an agent to search for an exit or sign from close vicinity of the agent's current location [Løvs, 1998]. Although, further research and data collection are required to examine the occupants searching behaviours in unfamiliar environments. The next section describes the backtracking process in detail.

4.5.3.2 *Backtracking*

If the agent does not have previous familiarity with the structure, while wayfinding a possibility may arise where the agent could not find any adjacent unvisited waypoint. In this situation, the agent starts backtracking process. Using their memory, an agent backtracks to search for any unvisited adjacent waypoints of previously visited waypoints. If the agent finds an unvisited adjacent waypoint, the agent moves to the waypoint and continues the searching process.

Backtracking allows the agent to find an unvisited waypoint from where they can attempt again to search for either an available exit or a sign. If agent backtracks and finds a nearest unvisited waypoint, the agent moves to the waypoint and continues searching. The idea behind backtrack is to go back to the place visited earlier to explore another potentially unvisited areas. The backtracking algorithm maintains two distinct lists, List 1 and List 2 (see Figure 4.22). List 1 stores all the visited adjacent waypoints and List 2 contains all unvisited adjacent waypoints by an agent.

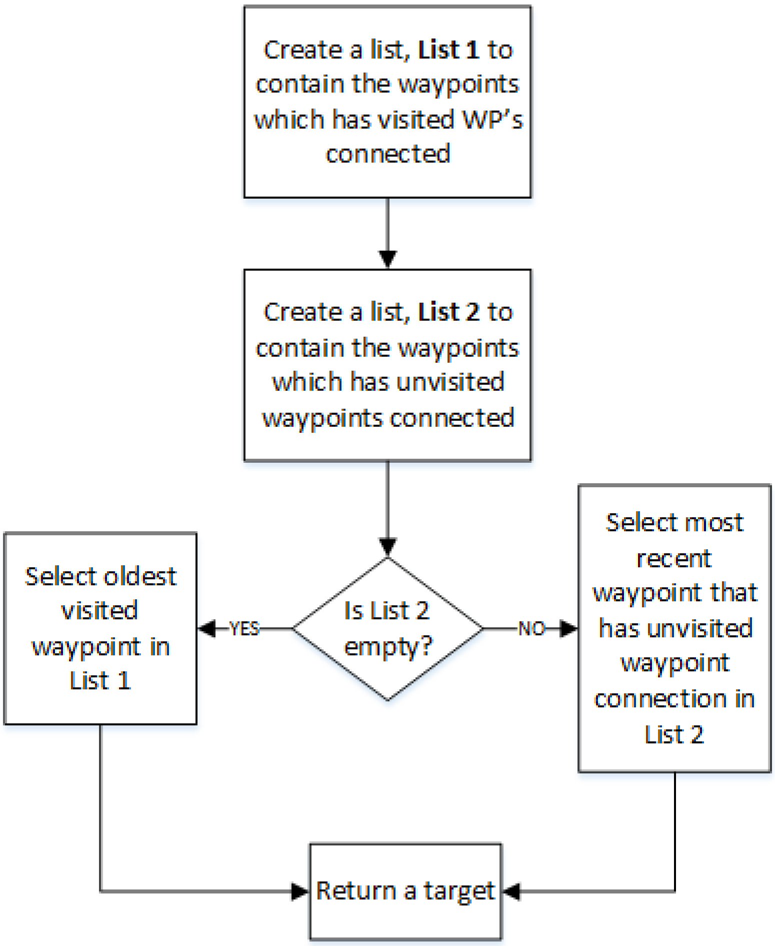


Figure 4.22: Agent's backtrack behaviour.

The process of creating List 1 and List 2 begins with finding all the adjacent waypoints of the initial waypoint. If an adjacent waypoint is already visited by the agent, the particular waypoint can be fetched from the memory module. Therefore, the particular waypoint will be added to List 1. Likewise, if the adjacent waypoint, connected to further adjacent waypoints, is not present in the memory module, the waypoint will be added to List 2.

Once both the lists are created, a check is performed on List 2 to determine whether it is empty i.e., ensuring if there are any unvisited adjacent waypoints. If List 2 is empty, this would mean that agent has visited all the adjacent waypoints of the initial waypoint. At this stage, the agent would prefer to move to the oldest adjacent waypoint they used for navigation. The oldest adjacent waypoint is found using the difference of current time and waypoint detection time retrieved from agent's memory. Formula 4.5 is used for this calculation:

$$Time\ Difference = Current\ Time - Waypoint\ Visited\ Time$$

Formula 4.5: Calculating Time Difference to find the oldest visited waypoint in List 1.

Therefore, the oldest waypoint stored in List 1 is selected as the agent's next target waypoint so that agent can begin searching for unvisited waypoints from the start. Figure 4.23 illustrates a backtracking scenario where the agent's starting location is near to waypoint W1.

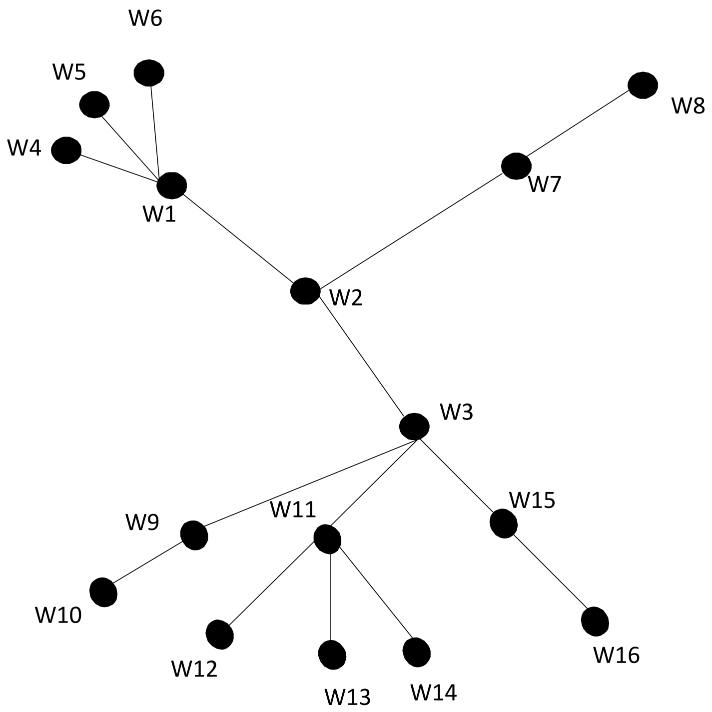


Figure 4.23: Example used for demonstrating agent's backtracking behaviour.

W1 is further connected to waypoints W4, W5, W6 and W2. According to searching behaviour explained in Section 4.5.3.1, the agent search for nearest unvisited waypoint. From W1, the agent visits nearest waypoint W4. Hence, W4 is stored in list 1 and list 2 contains W5, W6 and W2. At this stage, list 1 and list 2 contains the following waypoints:

List 1 = {W4}

List 2 = {W5, W6, W2}

From W4, the agent could not find any further connected unvisited waypoint. Therefore, the agent must backtrack. The backtracking algorithm states that if list 2 is not empty, then the agent should move towards the most recent waypoint which has unvisited adjacent waypoints connected. So far, the oldest visited waypoint by the agent is W4 which has further unvisited waypoints connected. Hence, the agent backtracks to W1. The agent again searches for nearest unvisited waypoints and move to waypoint W5. Waypoint W5 (previously stored in list 2 as unvisited waypoint) will be added to list 1. The agent backtracks to most recent waypoint which has unvisited waypoints, i.e., W1 from W5 as they could not find further unvisited waypoints. The agent backtracks to W1 again and moved to W6 to find further unvisited waypoints. W6 will be added to list 1 and at this point, list 2 contains waypoint W2. From W6 the agent backtracks to W1, as they could not find any further unvisited waypoints. At this stage, list 1 and list 2 contains the following waypoints:

List 1 = {W4, W5, W6}

List 2 = {W2}

The agent nearest unvisited waypoint is W2. When the agent moves to W2, this waypoint is added in list 1 and list 2 contains unvisited waypoints connected to W2 which are W3, W7 and W8.

List 1 = {W4, W5, W6, W2}

List 2 = {W3, W7, W8}

W3 is the nearest unvisited waypoint which has further unvisited waypoints (W9, W11 and W15). The agent moves to W3 which is then added to list 1 and list 2 now contains W7, W8, W9, W11 and W15. From W3, the agent moved to nearest unvisited waypoint W15 and then to W16. At this point, W15 and W16 are added to list 1 and list 2 contains W7, W8 and W9.

List 1 = {W4, W5, W6, W2, W3, W15, W16}

List 2 = {W7, W8, W9, W11}

From W16 the agent could not find any unvisited waypoints, hence, the agent must initiate backtracking process. To backtrack, the agent moved to W3 since this was the most recent waypoint which has further unvisited waypoints. In the similar fashion, the agent then moves to waypoint W11 which is further connected to unvisited waypoints W12, W13 and W14. These waypoints are added to list 2.

List 1 = {W4, W5, W6, W2, W3, W15, W16, W11}

List 2 = {W7, W8, W9, W12, W13, W14}

From W11, the agent moved to W12. The agent again backtracks to W11 to visit other unvisited waypoints W13 and W14.

List 1 = {W4, W5, W6, W2, W3, W15, W16, W11, W12, W13, W14}

List 2 = {W7, W8, W9}

When the agent visited all the connected waypoints to W11, agent backtracks to W3 as it still contains an unvisited waypoint (W9). From W3, the agent moved to nearest unvisited waypoint W9 and then to W10. At this stage, list 1 and list 2 contains the following waypoints:

List 1 = {W4, W5, W6, W2, W3, W15, W16, W11, W12, W13, W14, W9, W10}

List 2 = {W7, W8}

From W10, the agent must backtrack to the waypoint that has an unvisited waypoint connected. From list 2, there are two remaining waypoints, W7 and W8 which are unvisited. These waypoints are connected to previously visited waypoint W2. Hence, from W10 the agent will backtrack to W2 and then visits W7 and W8. At this stage, list 1 and list 2 contains the following waypoints:

List 1 = {W4, W5, W6, W2, W3, W15, W16, W11, W12, W13, W14, W9, W10, W7, W8}

List 2 = {}

At W8, the agent again reaches a point where no further unvisited waypoints are connected. Furthermore, there are no waypoints in list 2 either. Hence, to backtrack, the agent would move to the oldest waypoint added in list 1. This allows the agent to start searching again to find an unvisited waypoint. Therefore, from W8 the agent would move to oldest visited waypoint in list 1, W4 to start searching again.

To produce a realistic simulation of the agents' wayfinding behaviour with no previous familiarity of the structure, further research in following three areas is required:

- First, at present, there is no available data-set to understand how occupants search for their desired destination in an unfamiliar structure with no signage available.

- Second, the agent in the new signage-based navigation model lacks the capability to build their cognitive map and understand the spatial elements of the structure. A data-set is required to understand how occupants using their cognitive map search for their desired target if they do not have the previous knowledge of the structure.

- Third, currently, the empirical data on signage detection is based on a single sign. Furthermore, the method of the agent's stop following a sign is currently postulated. A data set how the signage detection of one sign influences the chance of detecting the other sign and at what stage the agent will give up the signage information would help the new model to further develop.

To further improve and expand the agent's wayfinding behaviour with no previous familiarity, route preference can be added for the agent's navigation. Veeraswamy [2011] conducted surveys and later developed a wayfinding model to select routes and change routes dynamically if they encounter congestion or gaining new exit knowledge. In future, the newly developed model can be expanded based on Veeraswamy's [2011] research to introduce route choices.

4.6 Difference between buildingEXODUS and new signage-based navigation model

Following are the major differences between buildingEXODUS and new signage-based navigation model:

1. In buildingEXODUS, the agents lack a sense space connectivity and they rely on potential or distance map to navigate. In the new signage-based navigation model, the agents have a sense of space connectivity of their surrounding environment. This is achieved through the introduction of navigational graph.

2. The signage model in the buildingEXODUS model adopts a prescriptive approach. The agents are not able to understand and follow the direction of a sign. Therefore, while designing a series of escape route signs, a model user manually connects the signs using a pre-defined list of targets representing the chain signage [Filippidis et *al.*, 2001, 2003, 2006, 2008; Xie et *al.,* 2007, Galea et *al.,* 2011]. Each sign has an associated redirection node which connects the redirection node of the next sign in a series of signs. When an agent starts following a sign, the location of the redirection node associated with next sign is set as the agent's target. This implies that the agent implicitly knows the location of next sign in the chain due to the use redirection node to guide their movement. In summary, the agents follow the signage chain deterministically with no sense of direction in the signage model in buildingEXODUS.

   In contrast, in the new signage-based navigation model, the agents can understand and follow the direction of the sign. Hence, agents perceive and follow the direction informed by the sign without visiting any predefined target. This is achieved through combining the signage visibility and navigational graph. When the agent starts following the sign, from sign's point of view, a waypoint located at minimum angle in the direction of the sign is set as the agent's target (Section 4.5.3.1). Hence, in the new model, agent's movement while following the signage is a better representation of the interaction with signage as compared with the buildingEXODUS signage model.

3. The agents in buildingEXODUS model lack the capability to store their wayfinding experiences. Due to lack of memory, when an agent reaches a place with no viable exits present in the structure or missed next expected sign, the agent initiates an arbitrary searching behaviour. Memory is an integral part of the wayfinding process. In the context of real world, wayfinding is a process of receiving, storing and processing information while in navigation [Arthur and Passini, 1992].

   In the new signage-based navigation model, each agent is equipped with their individual memory to store the visited waypoints and signs. The implemented memory is a simple representation of agent's past visited waypoints and signs. The memory allows the agent to differentiate between visited space and unvisited space. Furthermore, when the agent reaches a place with no viable exits present in the structure or missed the next expected sign along the escape route, using their memory the agent can backtrack to explore other area searching for an exit and avoid revisiting the visited places.

4. buildingEXODUS can simulate the agent's wayfinding either with full familiarity or partial familiarity with the exits. The navigation method to represent the agent's full familiarity and partial familiarity with exits is represented using potential map and distance map respectively. Both approaches (potential map and distance map) are well-suited for scenarios where the agents have at least some familiarity with the available exits and estimating the structure's egress efficiency. The potential map provides distance information from any node within the building to its nearest exit. Hence, by selecting a neighbouring node that lowers the potential value the agents can take the shortest route to the nearest exit. A distance map provides the distance information from any node within the building to a known exit or target. By selecting the neighbouring

node that lowers the distance to this exit or target, the agent is able to move towards the target gradually.

The new signage-based navigation model can simulate the agent's wayfinding behaviour under full familiarity or partial familiarity with the exits. In addition, the new model can also simulate the agent's wayfinding behaviour with no previous familiarity with any exits (Section 4.5.3). The new model simulates the agent's navigation using the navigational graph. To model the agent's wayfinding behaviour with full familiarity with the exits, the agent checks all visible waypoints from their current location and selects the one with minimum potential value to their intended exit or target. Similarly, when an agent has partial familiarity, the agent checks all visible waypoints from their current location and selects the one with minimum distance value to their intended exit or target. Lastly, to model the agent's wayfinding behaviour with no previous familiarity with any exits, the agent checks all visible waypoints from their current location and selects the one with minimum distance value to their current location. This process continues until either the agent finds an exit or detects a sign.

5. buildingEXODUS can simulate the agents' wayfinding behaviour in evacuation/circulation scenarios over multi-storey built structures.

At present, the new signage-based navigation model can simulate only a single floor. Each floor has a navigational graph and the linking of navigational graphs on multiple floors has not been implemented. This is a technical constraint rather than the limitation of the new model. To enable the new model to work on multiple floors, the new model needs further implementation. At present, the implementation to connect navigational graph between multiple floors has not been attempted. This is considered as a future work.

When simulating multiple floors, new behaviour rules would be introduced for the agents' navigation. If a waypoint representing stairs is defined, the agent's behaviour may produce unrealistic results. For instance, at present, in a scenario where an agent with no previous familiarity with the exits and no signage available, the agent selects the nearest visible waypoint from their current location. During an evacuation simulation, if the agent's location is near to stairs, the agent may take the stairs to travel to another level. Hence, the agent's new behavioural rules also need to be introduced to simulate their wayfinding behaviour correctly on multiple floors. This is considered as a future work.

6. The new modelling work mainly focuses on representing the agent's interaction with multiple signs along the escape route (i.e. chain signage). As part of the interaction, the probability of perception and following a sign is implemented in the model. The implementation is mainly based on the results of previous research [Filippidis *et al.*, 2006, 2008, Xie *et al.*, 2012].

In the early study by Filippidis *et al.*, [2006, 2008] on modelling signage, an arbitrary visibility probability was introduced due to the lack of empirical data. When an agent is travelling within the visual catchment area of a sign and can physically see the sign, it was assumed that there is a 50% of chance per time step that the agent will detect the sign. If the agent detects the sign, then a compliance probability is applied to represent the chance of the agent correctly comprehending and following the information conveyed by the sign. The compliance probability was arbitrarily set to 100% due to the same reason.

Later, Xie *et al.*, [2012] collected empirical data on the signage perception probability. It was found that in general there is a 38% of chance that occupants would detect a sign directly in the front of their travel direction. Of the people who perceived the sign, there is a 97% of chance that they would then follow the sign. This result was included in the buildingEXODUS signage model by assigning the detection probability and compliance probability accordingly in the simulation of the interaction with signage. However, this work focusses on the interaction with a single sign. Although it is suggested that people who detect a sign in the experiment are more likely to use other signs down the route, there is no quantitative data that defines the probability of successively detecting signs along an escape route.

Given the limitation of the available empirical data, the newly developed model simulates the interaction with each sign as an independent process using the detection and compliance probability based on empirical data [Xie *et al.*, 2012]. This represents a conservative estimation of the effectiveness of the signage system. However, it does not necessarily mean that an agent needs to successively perceive all the signs on the route to be able to use the target exit indicated by the signs. If the agent detects a sign and decides to move in the signage direction, the agent will continuously walk certain distance along that direction, during which there will be accumulated chances to detect other signs along the route. Thus, the actual probability of following a route to the target exit indicated by the signs is higher than the value obtained by multiplying the detection probability of the signs together. These results are consistent with the intention in the signage standard and signage system design guide to position multiple signs along each evacuation route to ensure that occupants are guided throughout to the final exit.

7. In buildingEXODUS, the impact of smoke on the agents' wayfinding behaviour is based on [Jin, (1978); Jin and Yamada, (1989)] data-sets. These studies have demonstrated that occupant's movement rate decreases as the smoke concentration increases. In smoke, the agent's mobility also reduces their travel speed. Hence, based on smoke density, a walking agent may leap or even crawl in smoke.

   The current implementation of the new signage-based navigation model does not include the impact of smoke on signage visibility. This is considered as a future work and can be implemented based on the research work [Jin, 1978, 1997; Jin & Yamada, 1985, 1989].

8. In buildingEXODUS, the VCA functionality is part of the congestion. The congestion is observed by installing a sign above an exit or in the close vicinity of the exit. Hence,

when the agent is in the VCA of the sign, they can observe congestion around an exit. If the agent encounters high congestion at an exit, the agent may select an alternative exit based on their exit knowledge.

The new signage-based navigation model also represents the visibility of signs using the VCA. This allows an agent in the new model to monitor the congestion around the exits. Hence, like buildingEXODUS, the new model is able to interact with the congestion level at an exit. However, the impact of congestion on agent exit selection [Gwynne, 2000] is not implemented yet. This is considered as a future work.

9. In buildingEXODUS, there are two kinds of behaviours namely, general (depicts circulation scenario) and extreme (depicts emergency scenario). There are also two types of exits, normal exits (for normal circulation) and emergency exits (for emergency evacuation only) [Gwynne *et al.*, 2001a]. If the model user selects general behaviour, then the agent will use only the normal exits. If, extreme behaviour is enabled, prioritisation of exits (normal/emergency) is solely based on the agents' current location from either type of exit.

   Similar to buildingEXODUS, the new signage-based navigation model also checks the exit types and simulation mode. If the agent's behaviour is set to general, the agent will use the normal exits and ignore the emergency exits. However, if extreme behaviour is enabled, emergency exits, and normal exits will be used.

4.7 The requirement of implementing the new signage-based navigation model in other models

Other than buildingEXODUS, the new signage-based navigation model can also be implemented within other evacuation and circulation simulation tools under certain conditions. To host the new model in other models, the following functionalities are required:

- A navigational graph to provide the agents a sense of direction and internal connectivity of the structure.
- A defined region in which agent can see the sign such as VCA.
- Agents must be treated as individuals rather than the uniform blocks. If agents are treated uniformly, the implementation of agents' memory will be unsuccessful.

The implementation of the new model relies on the method employed by other models to represent the geometry. The three ways to represent a geometry in evacuation and circulation scenarios was discussed in Chapter 3, Section 3.2.3. For each type of model, the following are the requirements that would need to be present in the other models:

- **Coarse network model** models consider agents as uniform particles. This does not allow to identify the agents individually. Hence, the new signage-based navigation cannot be implemented within a coarse network model.

- **Fine network model** implementation will be the same as the present model implemented within buildingEXODUS.

- **Continuous model** implementation process will mostly the same as the fine network models provided that the model needs to generate a navigational graph and define an area to represent the visibility of sign.

At present, no other evacuation and circulation simulation tools offer all the required functionalities to host the new signage-based navigation model. However, with the required functionalities included, potentially the new signage-based navigation model can be implemented in other evacuation and circulation models, for instance, MASSEgress [Pan 2009]. This would require a few implementation amendments in MASSEgress. As discussed in Chapter 2 (see Section 3.2.6.3), in MASSEgress each agent is equipped with a perception system which allows the agent to perceive the environment (including signage) through simulated vision. Therefore, there is no need to implement the signage perception part, except the signage detection and compliance probabilities. However, the agents do not have a sense of space connectivity and they are unable to follow the signage information in a successive manor to a final exit. Hence, the navigational graph should be added to provide the agents a sense of direction and internal connectivity of the structure. Similarly, the functionality to represent the signage direction should also be implemented to allow the agents to correctly follow the sign direction. With the above proposed amendments implemented, MASSEgress can host the new signage-based navigation model.

4.8 Summary

In this chapter, a new signage-based navigation model is presented and explained. The approaches taken towards the design and implementation of the new model is also discussed. The aim to implement a new model was to enhance the capability of evacuation research beyond the current state-of-the-art in wayfinding. This research focusses on the interaction between agent and signage under emergency conditions and represent the subsequent impact of the interaction on agent's behaviour within multi-agent simulation.

The new signage-based navigation model has been developed as a plug-in to the buildingEXODUS evacuation software. In Section 4.4, the overview of the new signage-based navigation model was discussed. The new model consists of three modules namely, Memory module, Navigation module and Movement module. Each agent in the new model is equipped with a sense of direction, space connectivity and memory to store the wayfinding experience. The agents' sense of direction and space connectivity is provided by combining the signage and the navigational graph (Section 4.2.1.1). The navigational graph is a network of waypoints and path segments. Waypoints act as a point of reference and guides the agents towards the target.

In Section 4.4, memory module was discussed which is responsible for storing visited waypoints and detected signs in a list. The memory also stores the time stamps of visited waypoints and detected signs.

In Section 4.5, navigation module was presented which allows the agent to search for the in-between targets towards the final exit or target. This module ensures the agent's wayfinding behaviour and movement using three different navigation strategies. The Navigation Strategy 1 (Section 4.5.1) allows the agent navigation with full or partial familiarity. The potential map demonstrates the scenario where an agent is familiar with all exits. Hence, the agent uses the nearest exit (defined by the potential) to leave the structure from their current location. The distance map depicts a scenario where an agent has either a target exit assigned or partial familiarity with one or more exits. Hence, the agent selects a waypoint with minimum distance to the target exit until reaching the exit or seeing a sign (agent switch to Navigation Strategy 2).

The Navigation Strategy 2 (Section 4.5.2) allows the agent navigation using signage. If agent detects a sign, they follow the direction of the sign until reaching an exit. Using this strategy, when an agent detects a sign, if sign is not previously stored in the memory, the sign is stored in the memory. To follow the direction of the sign, agent chooses the closest waypoint in the direction of a sign. Currently there are eight recommended combinations of signs containing arrow direction and supplementary text [BS 5499-4:2013]. Due to time constraint, in this research, five combinations of supplementary text and signage direction are implemented and tested. These are, sign up, right, left, up to the right and up to the left.

Lastly, using the Navigation Strategy 3 (Section 4.5.3) agent's navigation with no previous familiarity can be modelled. In this scenario, agent searches the surrounding space using Breadth First Search (BFS) algorithm by visiting the nearest unvisited visible waypoint until reaching an exit or seeing a sign (agent switch to Navigation Strategy 2).

In the next chapter, the verification and validation of the new signage model is explained through identifying the suitable component test cases. The aim of the validating the new signage model is to ensure that implemented behavioural and movement algorithms are working appropriately.

Chapter 5 Verification and Validation of the New Signage-based Navigation Model

5.1 Introduction

Chapter 4 described the development of the new signage-based navigation model. The aim of this chapter is to verify the major components of the new signage-based navigation model and validate the model as a whole qualitatively. In Section 5.2, the meaning of verification and validation in terms of evacuation modelling is discussed.

Section 5.3 describes the verification of the model using a series of test cases. The verification of the model verifies the three distinct navigation strategies which were introduced and explained in Chapter 4. These strategies are:

- **Navigation Strategy 1 (NS1): Agent navigation with full or partial familiarity (Chapter 4, Section 4.5.1).** In this scenario, it is assumed that either agent has full or partial familiarity with the structure. In the real world, the agent's full familiarity scenario depicts an ideal situation in which an occupant is familiar with all the exits. Hence, while evacuating, the occupant would normally prefer to use the nearest available exit.

  When an agent has partial familiarity, this would mean that they are familiar with one or some of the exits of the structure. This exit selected by the agent may not necessarily be the nearest exit. In the real world, this scenario demonstrates a situation where an occupant uses their previous exit knowledge to select an exit. Normally this selected exit can be the entry point from which they entered the building.

- **Navigation Strategy 2 (NS2): Agent following the signs along the escape route (Chapter 4, Section 4.5.2).** In this scenario, an agent detects and follows the signs along the escape route during an evacuation to reach a place of safety. This scenario in the real world shows the wayfinding behaviour of an occupant guided by the signage chain to escape.

- **Navigation Strategy 3 (NS3): Agent with no previous or invalidated familiarity or exit knowledge (Chapter 4, Section 4.5.3).** This is a special scenario where the agent has no previous familiarity with the structure or any available exit. Hence, to wayfind agent performs searching behaviour to find an exit/sign. For instance, this scenario in the real world may depict a naïve passenger who is travelling through an airport with no previous experience of using the airport. Under this scenario, the passenger would rely on their cognitive skills and external source of information to search for their desired target or an exit if there is an emergency. This may also depict a scenario where an occupant has to find an alternative exit given that their known exits may become unavailable.

Furthermore, the following are two important features of the new signage-based navigation model which are also verified in Section 5.3:

- **Agent's following the signage direction (Chapter 4, Section 4.5.3.1)**

In the new model, the agents' sense of space connectivity is achieved through the navigational graph [Chooramun, 2011]. The navigational graph consists of waypoints located at places where the boundary curves inward and lines connecting the waypoints that are visible to each other. By checking the adjacent visible waypoints and the associated lines, the agents obtain a sense of space connectivity within their range of vision. Then combining the signage visibility [Filippidis *et al.,* 2001, 2003, 2006, 2008; Xie *et al.,* 2007] and the navigational graph, the agents are able to identify and follow the direction indicated by the signs, i.e. the direction of the escape routes.

- **Adaptive navigation behaviour using memory (Chapter 4, Section 4.4).**

Agent memory is introduced in the new model to create an individual navigation experience. The memory stores agent's acquired wayfinding information including visited places and perceived signs. The information is used in exit route selection when necessary to differentiate visited and unvisited spaces and routes as well as used and unused signs. This allows the agents to avoid repeatedly visiting the space where they could not find viable exits or repeatedly using the same sign which may not provide sufficient information. In addition, the memory allows the agents to visit spaces without always depending on an assigned target. This is particularly useful in modelling agent exploring unvisited spaces.

Lastly, in Section 5.4, qualitative validation of the new model is presented. To validate the signage-based navigation model qualitatively as a whole, the new model is validated against one of the BS 5499-4:2013 signage demonstration cases. Qualitative validation demonstrates the comparison of predicted human behaviour with informed expectations through four full simulation cases.

5.2 Verification and validation

Verification is a process that determines whether the programming implementation of the model is working as intended [Balci, 1998]. This process involves debugging of the model and verifying the components. In fire safety engineering and evacuation modelling community, the definition of verification from the International Standards Organization [2008] is widely accepted. It says

"The process of determining that a calculation method implementation accurately represents the developer's conceptual description of the calculation method and the solution to the calculation method".

The following are the quintessential questions which require to be answered during verification [Petty, 2010]:

1. Does the software code of the newly developed model correctly implement the conceptual model?
2. Does the conceptual model answer the intended uses of the model?
3. Does the newly developed model produce results when needed and in the required format?

Validation is a crucial stage in the development of a simulation model [Sargent, 2009]. In modelling and simulation, validation determines the magnitude to which the model is an accurate depiction of the real-world item of interest [Petty, 2002]. According to Galea [1997], validation is

"Systematic comparison of model predictions with reliable information."

Similarly, according to Kuligowski *et al.*, [2010], the validation is a process of establishing the degree to which the model and empirical data depicts the accurate representation of the real-world scenario. Following are the methods used to validate the evacuation models [Kuligowski *et al.*, 2010]:

- Validation against code requirements.
- Validation against fire drills or other people movement experiments/trials.
- Validation against literature on past evacuation experiments.
- Validation against other models.
- Third-party validation.

At present, there is a lack of quantitative validation data for evacuation models [Gwynne *et al.*, (2005); Averill *et al.*, (2008); Ronchi *et al.*, (2013)]. The majority of the evacuation trials are not organised for the validation purpose [the Tsukuba evacuation exercise (Kose *et al.*, 1986), the Millburn Evacuation Experiment in 1993 (Butler, 1993), the Fire Safety Engineering Group trails in 2012 (Xie *et al.*, 2012)]. These evacuation trials, such as fire drill, procedure testing, are conducted to indicate the structure's design or to observe the compliance with regulations. In most of these trials, little data is collected to allow full validation of the evacuation models.

This poses a challenge in validating an evacuation model quantitatively. As a result, in this chapter the new signage-based navigation model is verified through component testing and validated against one of BS 5499-4:2013 demonstration case with series of signs.

BS 5499-4:2013 provided 22 cases in Annex A to illustrate how escape route signs should be used in various typical situations in buildings. Of them, the 18th case shows a complete building structure with multiple rooms, doorways and two exits (one main exit and one emergency exit) (see Figure 5.1). BS 5499-4:2013 plans two escape routes for this building and correspondingly creates two sets of escape route signs to indicate these two routes. This case is selected and used for conducting the component test and validation of the model for its completeness in using a complete escape route signage system to guide the evacuation of the premises.

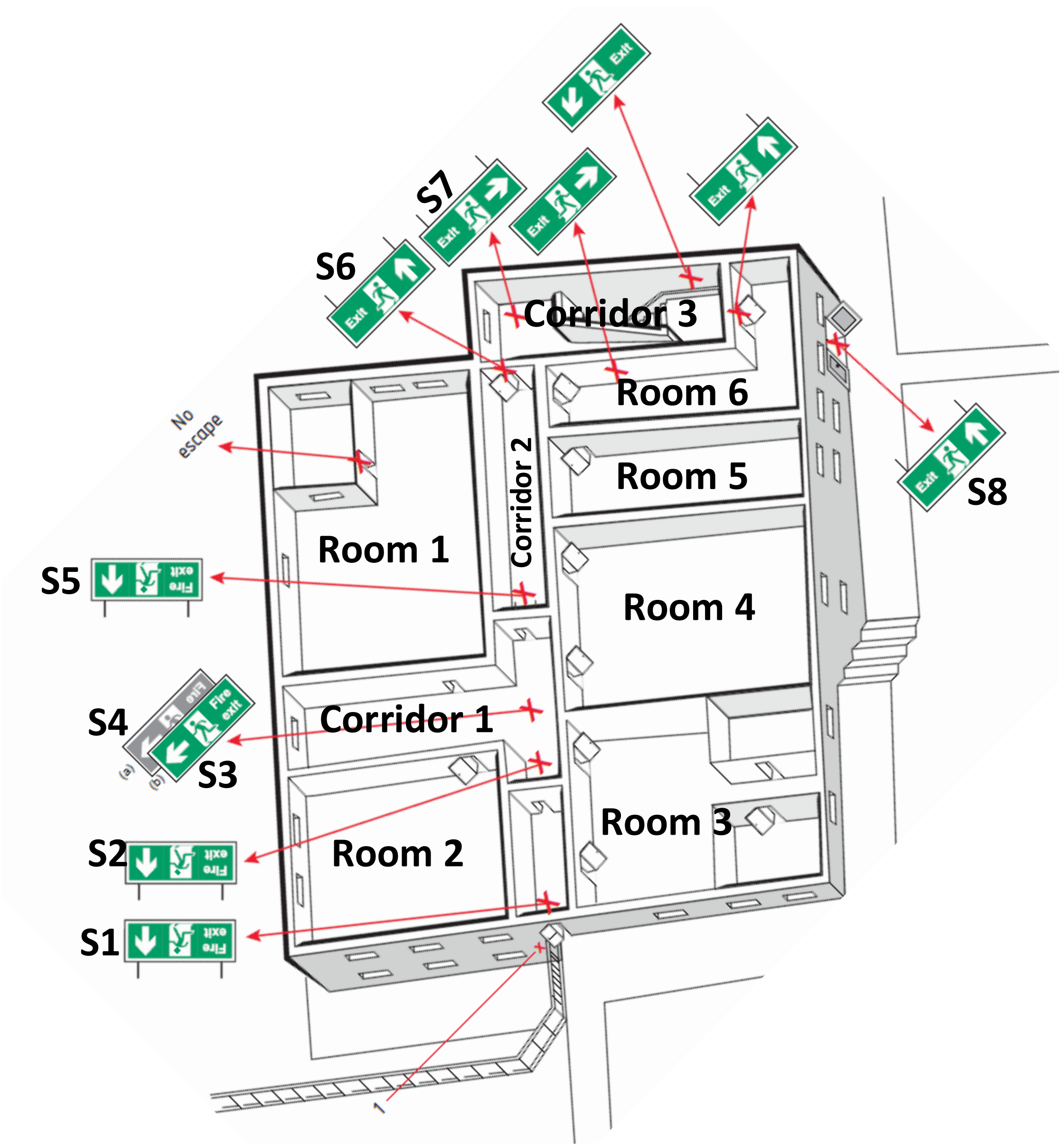


Figure 5.1: A demonstration case from BS 5499:2013.

5.3 Verification of the new signage-based navigation model

The main function of the new signage-based navigation model is to simulate three navigation strategies as discussed in Chapter 4. The model is verified through component tests of these three navigation strategies and two important features (agent's following signage direction and memory) in this section.

In verification of the model, the main function and the components are verified separately to ensure the implemented model is working as intended. The following are the five verification tests performed:

1. **Navigation Strategy 1 (NS1):** Agent navigation with full or partial familiarity (Chapter 4, Section 4.5.1).
2. **Navigation Strategy 2 (NS2):** Agent following the signs along the escape route (Chapter 4, Section 4.5.2).
3. **Navigation Strategy 3 (NS3):** Agent with no previous or invalid familiarity or exit knowledge (Chapter 4, Section 4.5.3).
4. **Agent's following the signage direction** (Chapter 4, Section 4.5.2.2)
5. **Adaptive navigation behaviour using memory** (Chapter 4, Section 4.4).

5.3.1 Navigation Strategy 1: Agent's full or partial familiarity with the exits

5.3.1.1 Aim of this test

The aim of this test is to verify the agents' wayfinding behaviour when they have full or partial familiarity with the exits/exit as expected. The verification of this function is through the comparison with buildingEXODUS by running the same simulation scenario and comparing the simulation results. This scenario will allow the model user to simulate the agents' wayfinding behaviour with full or partial familiarity with the exits/exit.

5.3.1.2 Expected occupant behaviour

In the real world, when the occupants are familiar with all exits of a structure, they tend to choose the nearest available exit to leave the building [Hirtle and Gärling, 1992]. buildingEXODUS models this behaviour using the potential map. The potential map provides distance information from any node within the building to its nearest exit. Hence, by selecting a neighbouring node that lowers the potential value the agents can take the shortest route to the nearest exit. The new signage-based navigation model simulates this behaviour using the navigational graph. In the model, the agent checks all visible waypoints from their current location and selects the one with minimum potential value as the target, also taking into account the distances to these waypoints, to guide their movement. While moving towards this target waypoint the agent continuously examine the other visible waypoints and reset the target if a new waypoint with a lower potential value is found. This process continues until either the agent reaches an exit or detects a sign.

In the real world, when occupants are familiar with one or some exits of a structure, according to Sime [1985], Benthorn & Frantzich [1999] and Shields & Boyce [2000], occupants prefer to leave the building via the same route they enter or the routes with which they are familiar. buildingEXODUS models this behaviour using the distance map. A distance map provides the distance information from any node within the building to a known exit or target. By selecting the neighbouring node that lowers the distance to this exit or target, the agent is able to move towards the target gradually. The signage-based navigation model simulates this behaviour using the navigational graph too. In the model, the agent checks all visible waypoints from their current location and selects the one with minimum distance value to their intended exit or target, also taking into account the distances to these waypoints, to guide their movement. While moving towards this target waypoint the agent continuously examine the other visible waypoints and reset the target if a new waypoint with a lower distance value is found. This process continues until either the agent reaches their intended exit or target or detects a sign.

5.3.1.3 Description of the test structure

As explained in Section 5.2, the 18th case in BS 5499-4:2013 is selected for conducting the component test of the model. The reproduced version of this case using buildingEXODUS is shown in Figure 5.2.

buildingEXODUS allows the model user to view the catchment area of each exit which represents the particular region within which the agents should use the corresponding nearest exit. Figure 5.2 shows the catchment areas of the two exits. The catchment area 1 is associated with the main exit. This implies that the main exit is the nearest exit for all the agents located within catchment area 1.

A total of 66 randomly generated agents are used to represent a general population. The agents are located throughout the geometry.

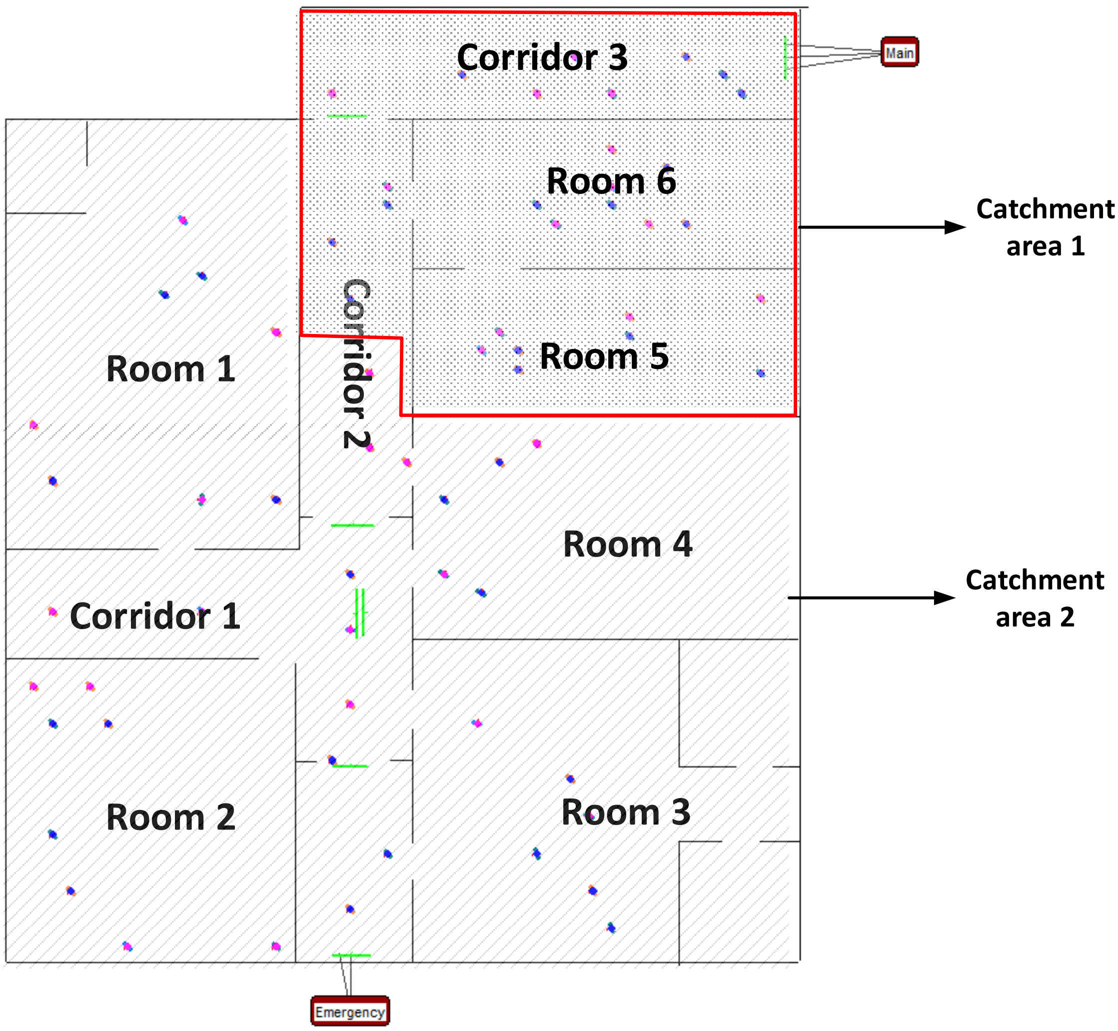


Figure 5.2: Generated catchment area of main and emergency exit using buildingEXODUS.

Lastly, the generated navigation graph for the above structure is depicted in Figure 5.3.

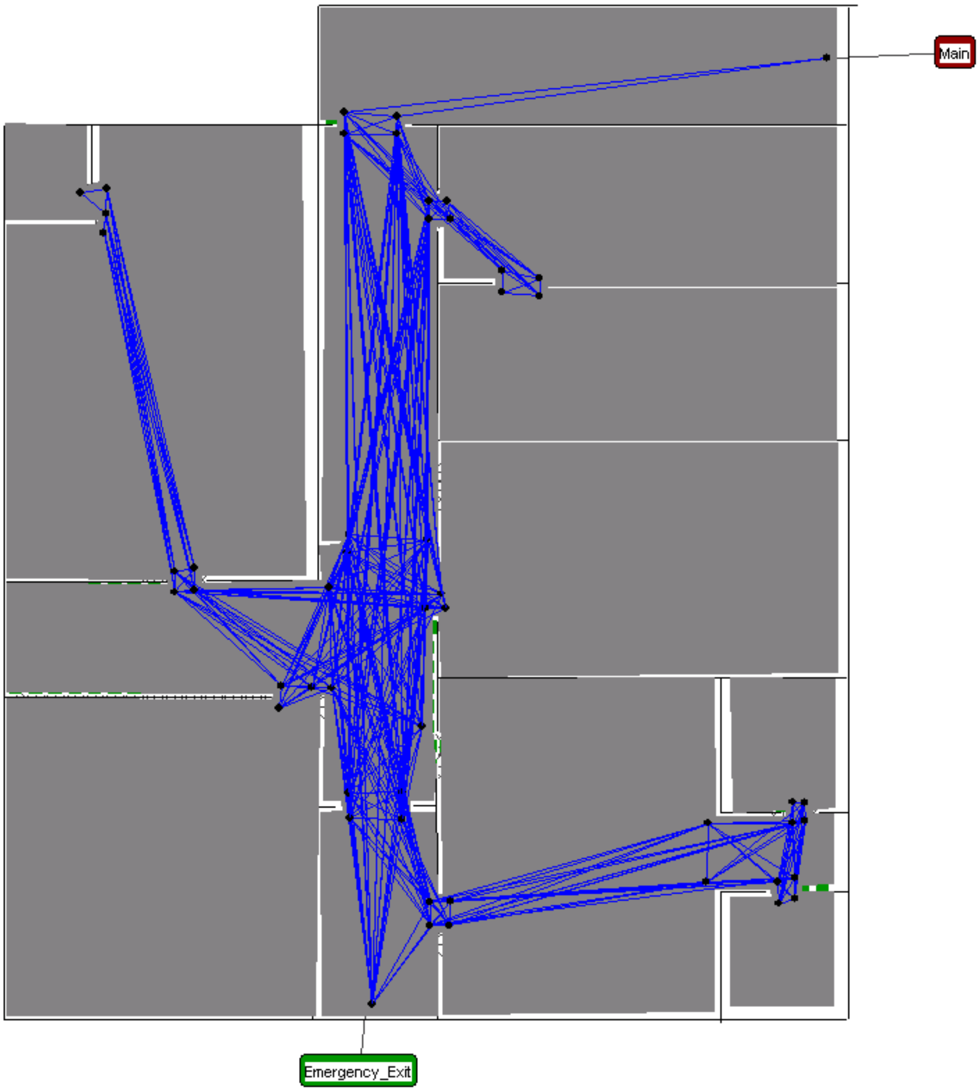


Figure 5.3: The generated navigational graph.

5.3.1.4 Simulate occupant evacuation behaviour with full and partial familiarity using buildingEXODUS

In buildingEXODUS, the potential map is used to simulate agent evacuation behaviour with full knowledge of all available exits. The potential map provides distance information from any node within a geometry to its nearest exit. Therefore, using the potential map the agents can move towards their nearest exit from their starting location to evacuate. The nearest exit from agents starting location can be illustrated through the exit catchment area. In Figure 5.2 the agents located in catchment area 1 should use the main exit whereas those who located in catchment area 2 should use the emergency exit. Using buildingEXODUS, the travel paths of the agents with full familiarity located in catchment area 1 and 2 are shown in Table 5.1.

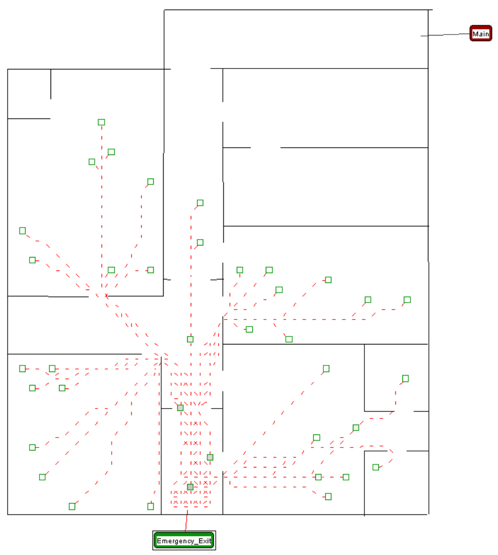
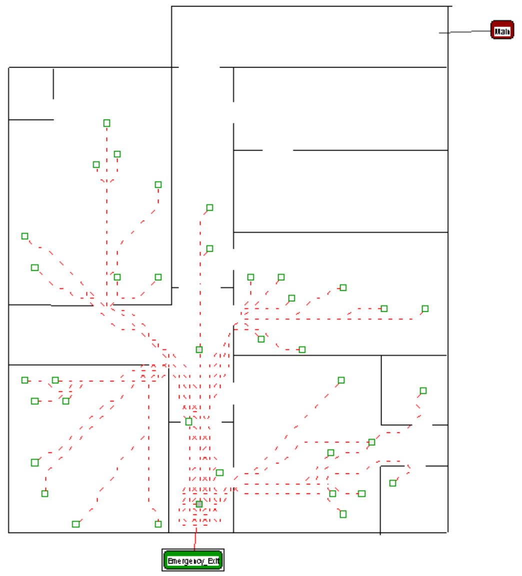
In a scenario with partial familiarity, buildingEXODUS uses the distance map in simulation. In the simulation, all agents used the main exit and ignored the emergency exit. This behaviour created congestion around the main exit (see

Table 5.2). The travel paths of all agents who are familiar with the main exit only are shown in Table 5.3.

5.3.1.5 Simulate occupant evacuation behaviour with full and partial familiarity using the new model

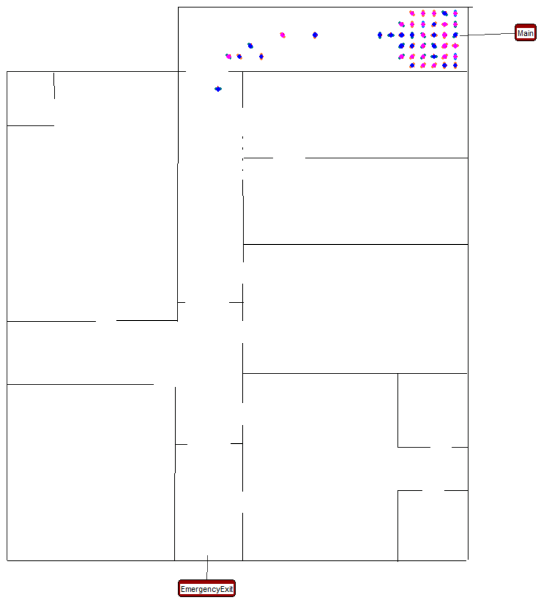
Unlike buildingEXODUS, the new signage-based navigation model uses the navigational graph and waypoints for agents' navigation. In the new model, the agent moves along the route consisting of visible waypoints from their locations. In a scenario where the agent has full familiarity with the exits, the agent selects the visible waypoint with minimum potential until either agent reach an exit or detects a sign. Similar to the simulation results produced by buildingEXODUS, the agents located in catchment area 1 used the main exit whereas the agents located in catchment area 2 used the emergency exit. The comparison of their travel paths of the agents with the full familiarity of the exits generated by buildingEXODUS and the new model are shown in Table 5.1.

Table 5.1: Travel paths of agents with familiarity located in catchment area 1and 2 using buildingEXODUS and new signage-based navigation model.

Catchment area 1 (buildingEXODUS)	Catchment area 1 (New signage-based navigation model)
	
Catchment area 2 (buildingEXODUS)	**Catchment area 2 (New signage-based navigation model)**
	

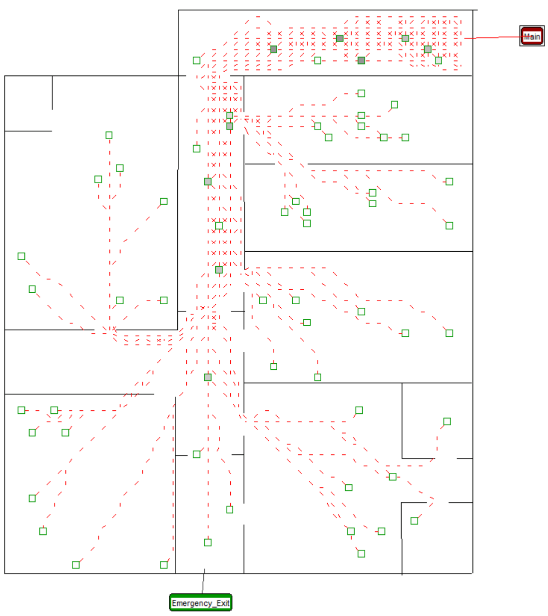
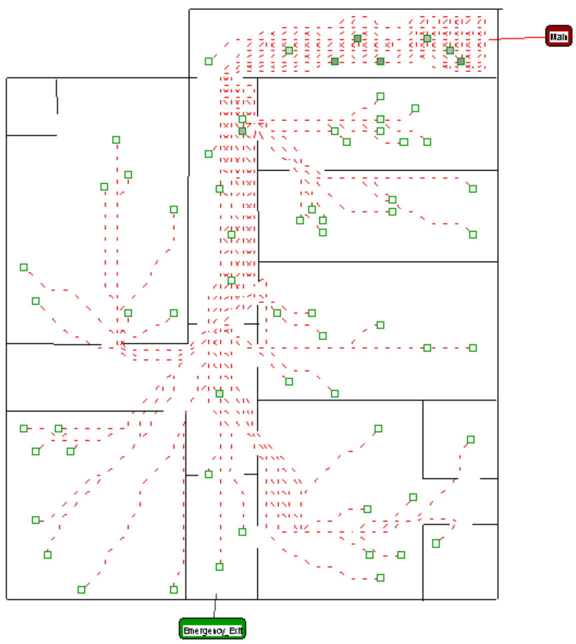
In the new signage-based navigation model, an agent with the partial familiarity selects the visible waypoint with the minimum distance to a known exit until either they reach an exit. Like buildingEXODUS, in the new model the entire population used the main exit to leave the building which led to congestion around the main exit (see Table 5.2).

Table 5.2: Congestion around the main exit in buildingEXODUS and the model.

buildingEXODUS	New signage-based navigation model
	

The comparison of travel paths of the agents with partial familiarity of the exits using buildingEXODUS and the new model are shown in Table 5.3.

Table 5.3: Travel paths of all agents who are familiar with main exit only in buildingEXODUS and the new model.

buildingEXODUS	New signage-based navigation model
	

5.3.1.6 Results and discussion

The figures in Table 5.1 demonstrated that buildingEXODUS and the new model produced almost the same travel paths of the agents in the simulation of the two scenarios. More simulations are then performed to measure the evacuation performance. The simulations were run 10 times to produce a range of results. In each case, agents' starting locations were kept constant. Presented in Table 5.4 are the average values with (±) two standard deviations for some key parameters from the simulations.

Table 5.4: Average evacuation performance for agents with full familiarity with the exits.

Model	Total evacuation time (s)	Average congestion time (s)	Average distance travelled (s)	Average individual evacuation time (s)	Average usage of emergency exits
buildingEXODUS	71.3 ± 1.6	9.5 ± 0.7	14.5 ± 3.2	38.1 ± 0.7	39
New model	72.4 ± 1.6	11.1 ± 0.8	15.3 ± 0.1	39.6 ± 0.7	38

The data in Table 5.4 demonstrates that there is no big difference in the simulation results of buildingEXODUS and the new model. This is further examined using the Mann– Whitney U statistical test. The test is focussed on average distance travelled and average personal evacuation time in this simulation scenario.

The result demonstrated that the difference in distance travelled between buildingEXODUS and the new model is not statistically significant (Mann– Whitney U=2079, n1=10, n2=10, P=0.65>0.05, two-tailed). Similarly, the difference in the agents' personal evacuation time between buildingEXODUS and the new model is also not statistically significant (Mann– Whitney U=2174, n1=10, n2=10, P=0.98>0.05, two-tailed). On comparing the results with buildingEXODUS, the new signage-based navigation model produced similar results using the navigational graph in simulating the scenario in which the agents are full familiar with the building.

The comparison of travel paths for agents with the partial familiarity of the exits using buildingEXODUS and the new model produced similar results. To gain confidence in results, more simulations are then conducted to measure the evacuation performance. 10 simulations were run for this scenario using buildingEXODUS and the new model to produce a range of results. In each case, agents' starting locations were kept constant. Demonstrated in Table 5.5 are the average values with (±) two standard deviations for some key parameters from the simulations.

Table 5.5: Average evacuation performance for verifying partial familiarity using buildingEXODUS and the new model.

Scenarios	Total evacuation time (s)	Average congestion time (s)	Average distance travelled (s)	Average individual evacuation time (s)	Average usage of emergency exits
buildingEXODUS	117.4 ± 2.6	27.2 ± 1.4	27.6 ± 0.2	64.7 ± 1.4	0
New model	117.6 ± 2.1	28.4 ± 1.0	26.8 ± 0.2	65.4 ± 1.1	0

The data in Table 5.5 demonstrates that buildingEXODUS and the new model produced similar and close results. This is confirmed by the Mann– Whitney U test. The test is focussed on average distance travelled and average personal evacuation time in this simulation scenario.

In this scenario, the difference in average distance generated by buildingEXODUS and the new model is not statistically significant (Mann– Whitney U=2188.5, n1=10, n2=10, P=0.92>0.05, two-tailed). The difference in the agents' average personal evacuation time between buildingEXODUS and the new model is also not found statistically significant (Mann– Whitney U=2088, n1=10, n2=10, P=0.58>0.05, two-tailed).

The comparison of the evacuation performance produced by buildingEXODUS and the new model demonstrated that both models produced similar and closer results. Hence, this verifies that new signage-based navigation model can simulate the scenario where an agent has full or partial familiarity with the exits.

5.3.2 Navigation Strategy 2: Agent following the signs along the escape route

5.3.2.1 Aim and description of this test

The aim of this test is to verify that the agents located in different parts of a structure with no previous knowledge of the layout of the structure can find an exit using the signs configured as a signage chain along the intended escape route. In this scenario when the agents start following the signs, their navigation is controlled by Navigation Strategy 2 (Chapter 4, Section 4.5.2). Using this scenario, the new model will allow to simulate the agents' wayfinding behaviour following a signage chain.

5.3.2.2 Expected occupant behaviour

In the UK, BS 5499-4:2013 provides the guidelines on the design and location of escape route signs as well as the advice on the use of arrows to provide directional information. According to BS 5499-4:2013, the signage information consists of text and an arrow symbol. When an occupant sees a sign, they start following the arrow direction of the sign [BS 5499-4:2013].

In buildingEXODUS, an agent is not capable to follow the direction of the sign. Hence, to create a chain signage in buildingEXODUS, a model user has to manually connect the signs to indicate a particular escape route. In the new signage-based navigation model, the agents can follow the signage direction (defined according to BS 5499-4:2013), taking into account both the position of the sign and the arrow direction in the sign. Unlike buildingEXODUS, the signs are not required to be connected by the model user in the new model. It is expected that if the agents can successfully perceive the signs that form a correct signage chain along the intended escape route they should be able to utilise the signs to identify the route to an exit.

5.3.2.3 Description of the test structure

Figure 5.4 shows the test structure used to verify the wayfinding behaviour using Navigation Strategy 2. This structure contains a single exit. Four agents are randomly placed in different parts of the structure with no familiarity with Door 1 (see Figure 5.4).

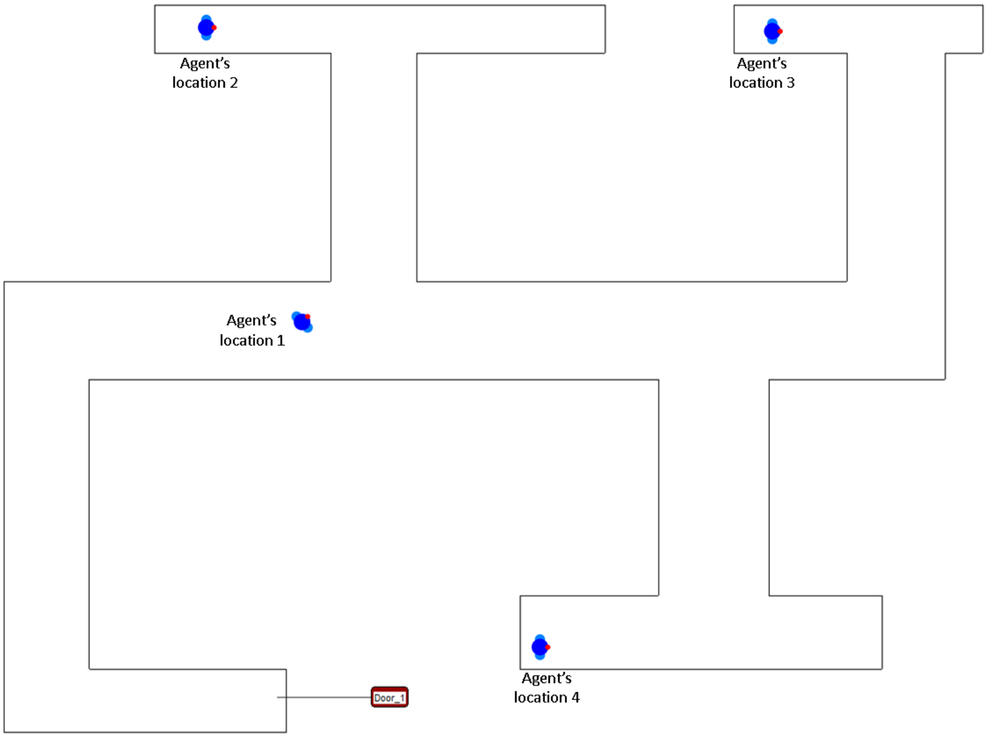


Figure 5.4: Agent's starting position for verifying agents using chain signage.

The navigational graph of the above structure is shown in Figure 5.5.

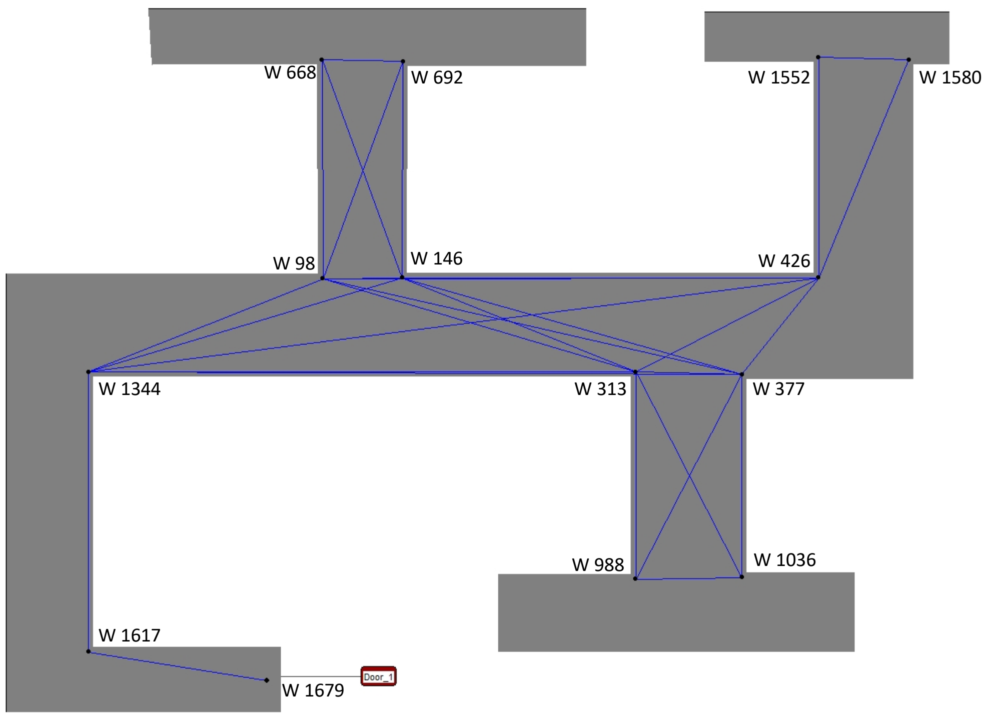


Figure 5.5: The generated navigational graph for verifying agent following signs along the route.

In this test, to simulate the agent's wayfinding behaviour using chain signage, the signs are installed according to the guidelines provided by BS 5499-4:2013 (see Figure 5.6). The escape route signage system should establish that from any location in a structure where an exit is not direct visible, a sign or series of signs should be installed [BS 5499-4:2013]. The escape route signs should be positioned to complete an escape route by avoiding potential points of confusion. Additional signs should be installed where the direct sight of the line is not possible, and confusion might exist in its position [BS 5499-4:2013, BS 5499-10:2014].

The following are the three signage chains used in this case:

- The first signage chain includes sign S5/S6, S4, S3, S2 and S1 leading towards Door 1 (red dashed path, see Figure 5.6).
- The second signage chain includes sign S10/S11, S9, S8/S7, S4, S3, S2 and S1 leading towards Door 1 (black path, see Figure 5.6).
- The third signage chain includes sign S13/S14, S12, S9, S8/S7, S4, S3, S2 and S1 leading towards Door 1 (blue dashed path, see Figure 5.6).

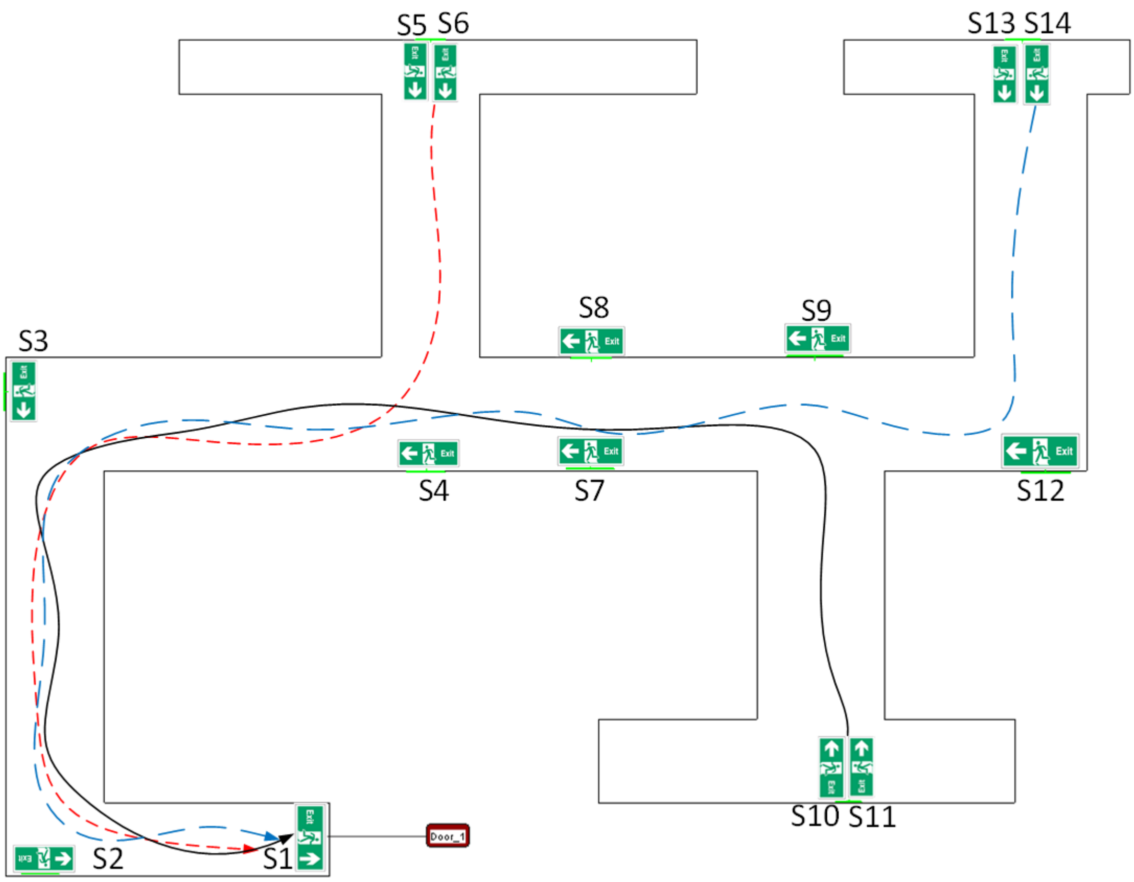


Figure 5.6: Three signage chains of signs leading to Door 1.

In this test, 14 signs were used to create the escape route chain signage system. Each sign installed in the geometry produces a Visibility Catchment Area (VCA) of approximately 10m^2 [BS 5499-4:2013]. Figure 5.7 shows the VCA coverage in this test case.

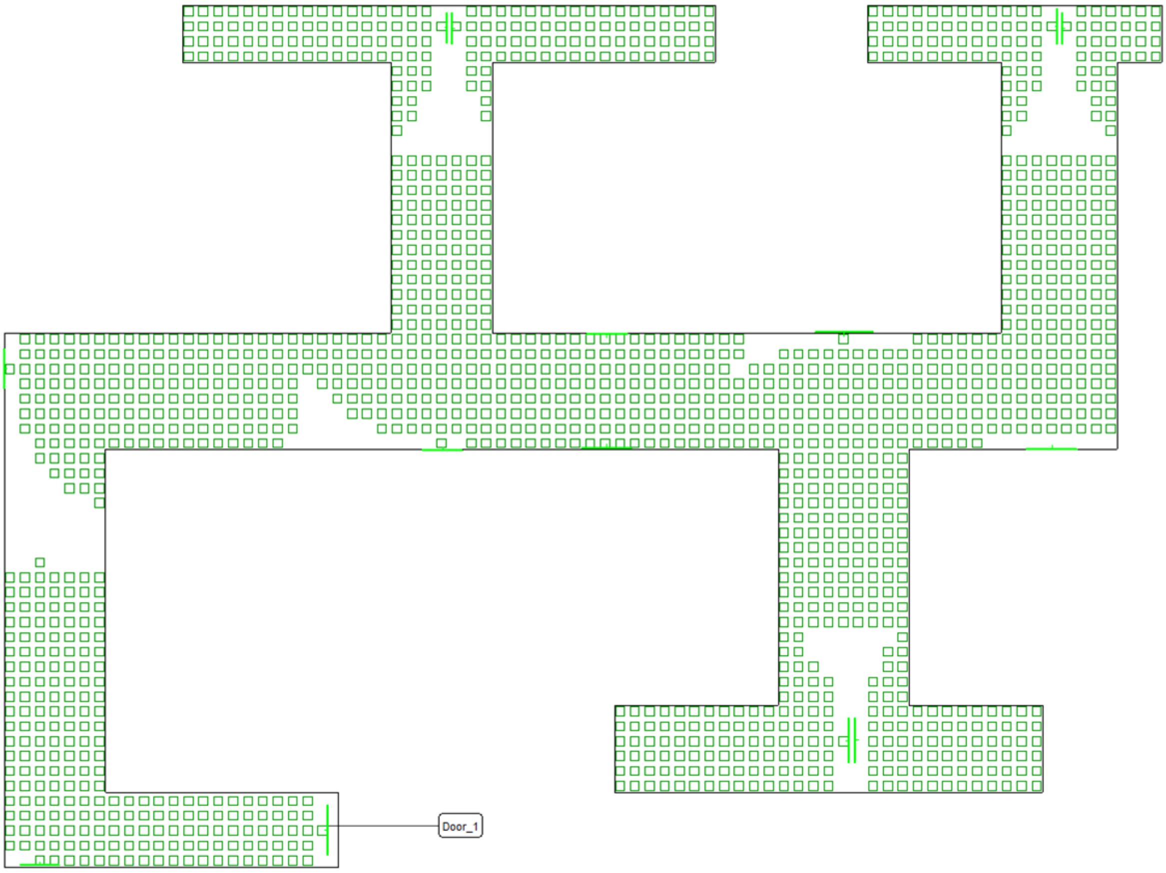


Figure 5.7: The entire VCA coverage.

5.3.2.4 Simulate occupant evacuation behaviour following chain signage using the new model

This simulation case is to verify NS2 designed to guide the agent to follow the chain signage in wayfinding. In order to examine whether the agent can use the escape route signs to find a previously unknown exit, it is assumed in the scenario that the agent has no knowledge of any exit location. The only available source of wayfinding information is from the signs which are positioned along the intended escape route (see Figure 5.7). The detection and compliance probabilities of the signs are set to be 100%.

From the starting location 1 (see Figure 5.8), the agent firstly tried to move to waypoint W98 to start exploring the space as W98 is the nearest visible waypoint. The agent then entered the VCA of sign S4 and detected the sign. The arrow in S4 is pointing to the left direction. According to NS2, the agent changed his target and moved towards the closest waypoint in this direction, which is W1344. While the agent was moving towards W1344, the agent detected the second sign S3, which has an arrow pointing down the route. Sign S3 led the agent towards waypoint W1617. While the agent was moving towards W1617, the agent detected the third sign S2 in the signage chain and followed the direction indicated by sign S2 to the right. Eventually the agent detected the fourth sign S1 and its associated exit Door 1 and left the building through Door 1 (see Figure 5.8).

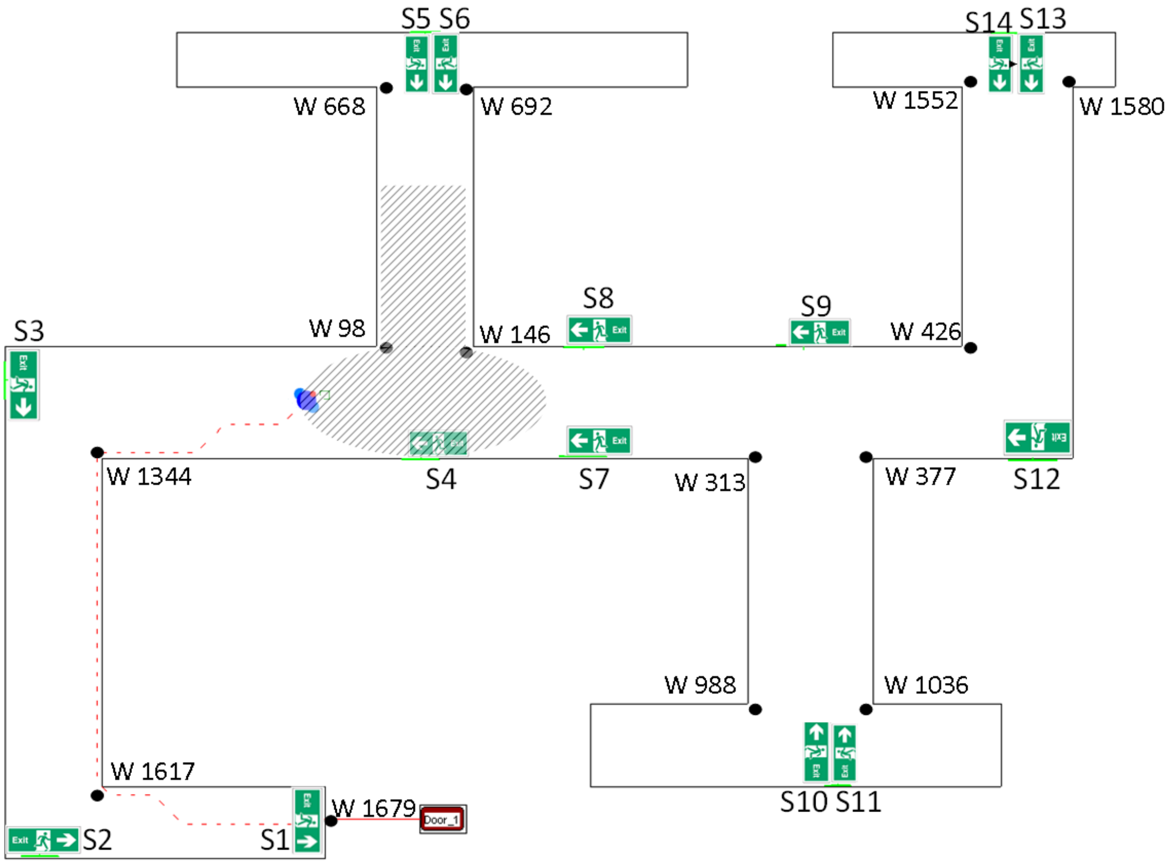


Figure 5.8: Agent's travel path using signage from location 1.

From the starting location 2, the agent started exploring the space by moving towards W668 and then entered the VCA of sign S5. The agent detected this sign and started moving in the direction of sign S5 towards W98. While moving towards W98 the agent detected sign S4 and changed the direction of movement towards waypoint W1344. Then similar to the agent started from location 1, this agent followed sign S3, S2 and lastly S1 to find Door 1 and exit through it (see Figure 5.9).

For the agents started from location 3 and 4, they demonstrated the same behaviour as the other two agents who started from location 1 and 2, i.e. they all successfully followed the planned escape route indicated by the chain signage to find and exit through the final exit. During this process, they did not reply on any prior knowledge of the location of the exit or any map system. Instead, they correctly followed the direction indicted by the signs they detected.

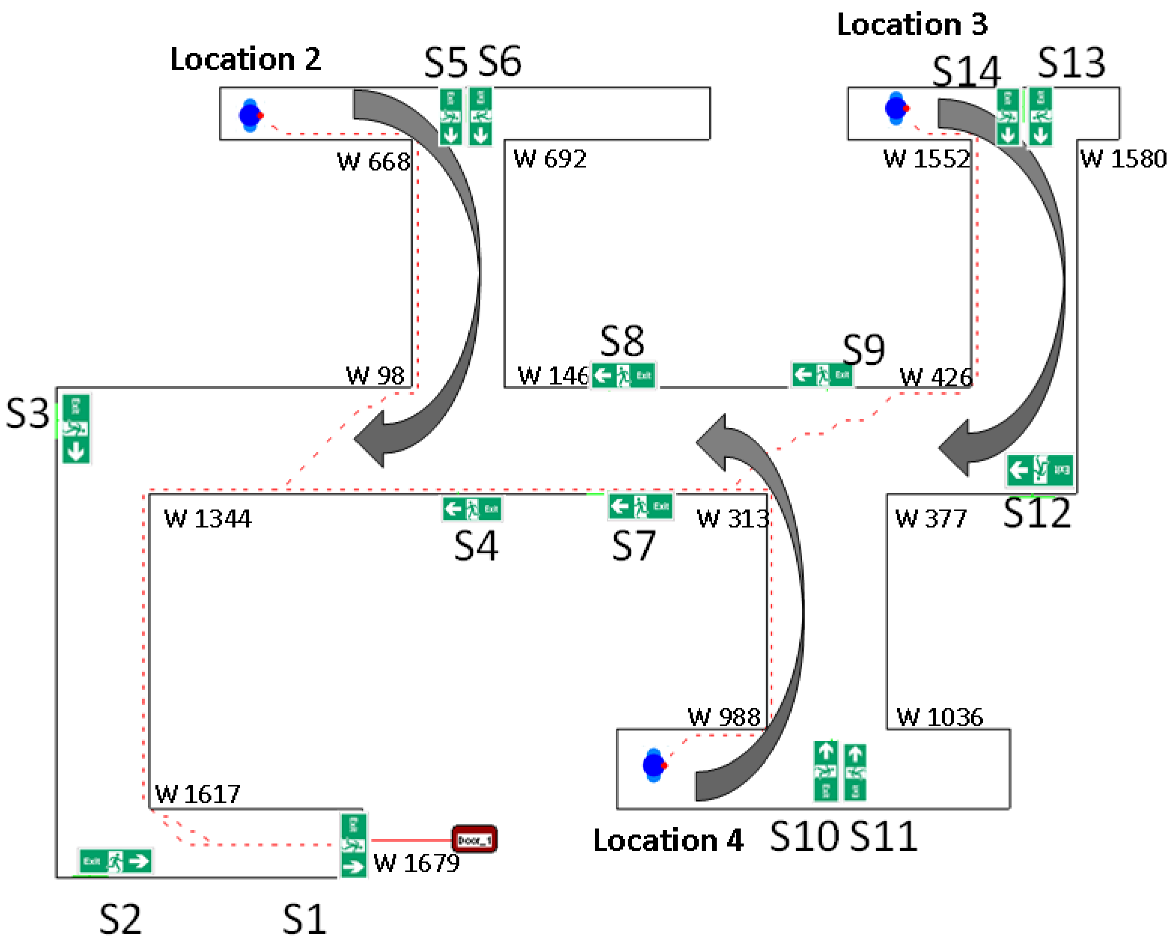


Figure 5.9: Agent's travel path using signage from agent's location 2, 3 and 4.

5.3.2.5 *Results and discussion*

This aim of designing and running this case is to verify that NS2 implemented within the new model is able to correctly simulate the behaviour of occupant detecting and following escape route signs to navigate an unfamiliar environment and find a way out. In this case, 14 escape route signs were positioned in the test geometry according to the guidance of BS 5499-4:2013.

These signs form a signage chain indicating the escape route towards Door 1. The simulation results show that all 4 agents started from different location within the geometry can follow the planned escape route indicated by the chain signage to find and exit through the final exit. It firms that the implemented NS2 meets the original development objective.

5.3.3 Navigation Strategy 3: Agent without familiarity with building layout or with invalid exit knowledge

5.3.3.1 Aim and description of this test

The aim of this test is to demonstrate four agents with no previous familiarity with the structure can find an exit without using signage (see Figure 5.10). In this scenario, the agent has no previous familiarity with the structure and the available exit. Under the scenario where no signage is used, the agent performs searching behaviour to find an exit using the Navigation Strategy 3 (Chapter 4, Section 4.5.3). This scenario will allow the model user to simulate the agents' wayfinding behaviour without any previous familiarity with the building layout or exit.

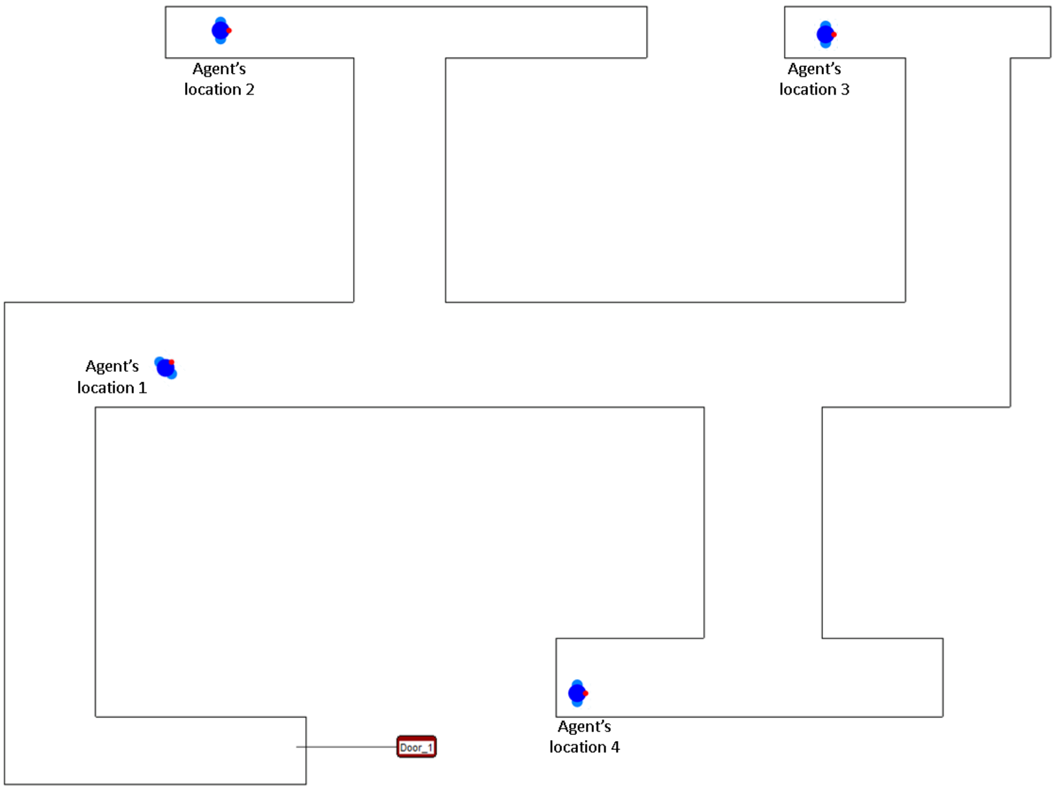


Figure 5.10: Agent's starting position in each test for verifying NS3 searching behaviour.

5.3.3.2 Expected occupant behaviour

At present, there is no available data-set to help understand how occupants search for their desired destination in an unfamiliar environment with a lack of external information such as signage. Hence, when developing the Navigation Strategy 3, it was assumed that agent would prefer to explore the immediate surrounding space in an unfamiliar structure before exploring the space deeper. The agents' searching behaviour in Navigation Strategy 3 is implemented using the Breadth First Search (BFS) algorithm which allows to search the surrounding space first and then gradually expand the search towards the end of the structure (Chapter 4, Section 4.5.3.1). Using the Navigation Strategy 3, the agent continuously explores the space until they find an exit/next sign. If the agent could not find any unvisited space, the agent can perform backtracking (Chapter 4, Section 4.5.3.2). Using the memory, an agent can backtrack and move to the other area which may still be unvisited.

5.3.3.3 Description of the test structure

Figure 5.4 shows the test structure used to model this scenario. This structure contains a single exit. The navigational graph of this structure is shown in Figure 5.5.

5.3.3.4 Simulate occupant searching behaviour without exit knowledge and signage using the new model

To simulate this scenario, an agent in the new signage-based navigation model uses Navigation Strategy 3 by visiting nearest unvisited adjacent waypoints. The agent continues to search the surrounding space using the Breadth First Search (BFS) algorithm by visiting nearest unvisited waypoints until the agent either detects a sign or finds an exit to leave.

Since the agent has neither exit knowledge nor space knowledge, from the starting location 1, the agent started with a movement towards the nearest visible waypoint, W1344. From W1344, the agent continuously searched for the next nearest unvisited waypoints, which form the following path: W1344 → W98 → W146 → W692 → W668. At W668, there are no more unvisited waypoints nearby nor an exit. Therefore, the agent backtracked to the most recent visited waypoint W146 within visible range which has unvisited waypoints connected to it, i.e. there is still unvisited space from W146. From W146, the agent continuously searched for the next nearest unvisited waypoints, which form the following path: W146 → W313 → W377 → W426 → W1552 → W1580. At W1580, there are no more unvisited waypoints nearby nor visited waypoints with unvisited waypoints connected. Therefore, the agent backtracked to the oldest visited waypoint W426 within visible range. At W426, the agent found that there are no more unvisited visible waypoints. However, W377 is the most recent visited waypoint which has unvisited waypoints connected to it. Thus, the agent moved towards W377 and further went down to the previously unvisited space that consists of W1036 and W988, At W988, all visible waypoints have been visited and none of them has unvisited waypoints connected to it. Therefore, the agent backtracked to the oldest visited waypoint W313 within visible range. At W313, the agent found that W1344 is the only visited waypoint which still has unvisited waypoint connected to it. Therefore, the agent went left towards W1344 and further went down to unvisited W1617. At W1617, the agent saw the last visible unvisited waypoint W1679 which connects the final exit and exited through it. Finally, the complete path (see Figure 5.11) taken by the agent is:

W1344→W98→W146→W692→W668→W146→W146→W313→W377→W426→W1552
→W1580→W426→W377→W1036→W988→W313→W1344→W1617→W1679→Door 1

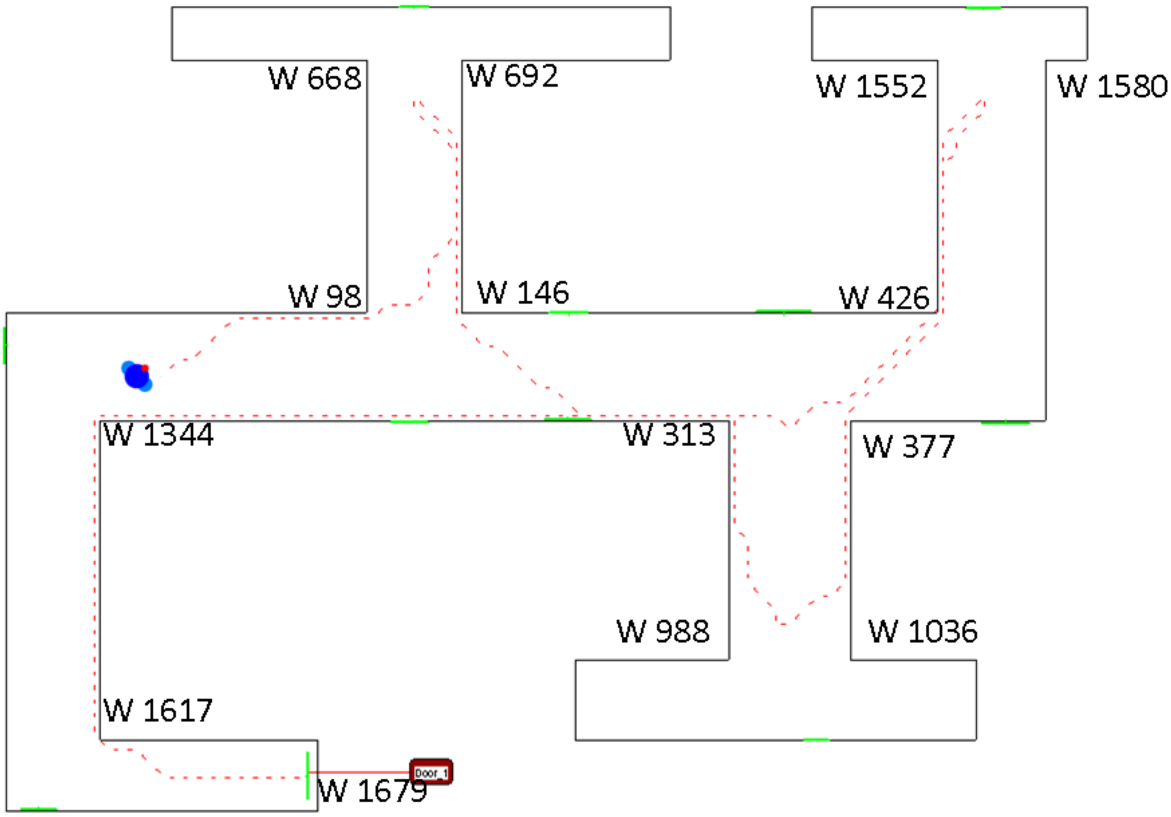


Figure 5.11: Agent's travel path without signage at agent location 1.

From the starting location 2, the agent started with a movement towards the nearest visible waypoint, W668. From W668, the agent continuously searched for the next nearest unvisited waypoints, which form the following path: W668→ W692→ W146→ W98→ W1344. From waypoint W1344 and further went down to unvisited W1617. At W1617, the agent saw the visible unvisited waypoint W1679 which connects the final exit and exited through it. Finally, the complete path (see Figure 5.12) taken by the agent is:

W668→ W692→ W146→ W98→ W1344→W1344→W1617→W1679→Door 1

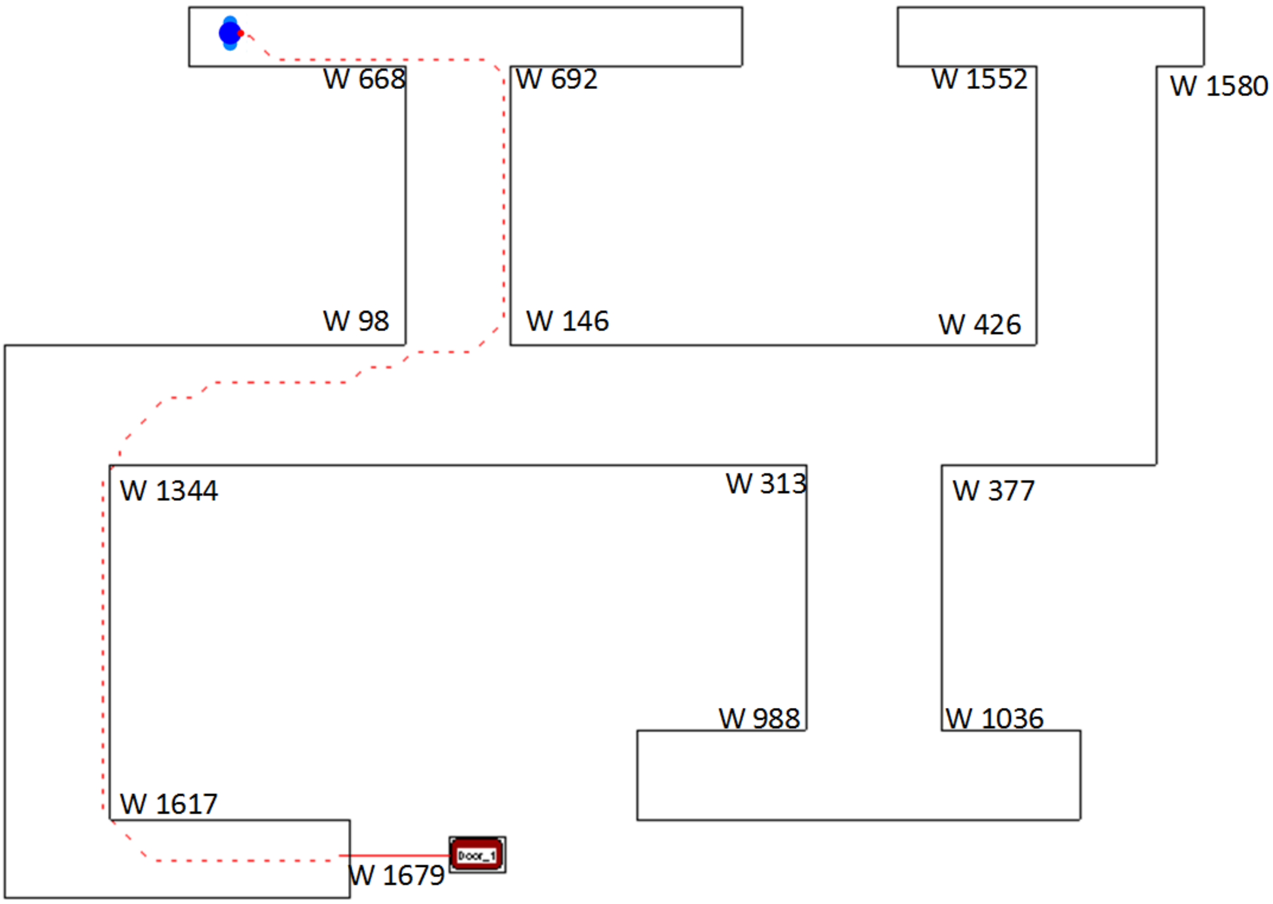


Figure 5.12: Agent's travel path without signage at agent location 2.

From the starting location 3, the agent started with a movement towards the nearest visible waypoint, W1552. From W1552, the agent continuously searched for the next nearest unvisited waypoints, which form the following path: W1552 → W1580→ W426→ W377→ W313→W988→W1036. At W1036, there are no more unvisited waypoints nearby nor an exit. Therefore, the agent backtracked to the most recent visited waypoint W313 within visible range which has unvisited waypoints connected to it, i.e. there is still unvisited space from W313. From W313, the agent continuously searched for the next nearest unvisited waypoints, which form the following path: W146 → W98→ W668→ W692. At W692, there are no more unvisited waypoints nearby nor visited waypoints with unvisited waypoints connected. Therefore, the agent backtracked to the oldest visited waypoint W98 within visible range. At W98, waypoint W1344 is directly connected unvisited waypoint. Therefore, the agent went left towards W1344 and further went down to unvisited W1617. At W1617, the agent saw the last visible unvisited waypoint W1679 which connects the final exit and exited through it. Finally, the complete path (see Figure 5.13) taken by the agent is:

W1552→W1580→W426→W377→W1036→W988→W313→W146→W98→W668→W692→W98→W1344→W1617→W1679→Door 1

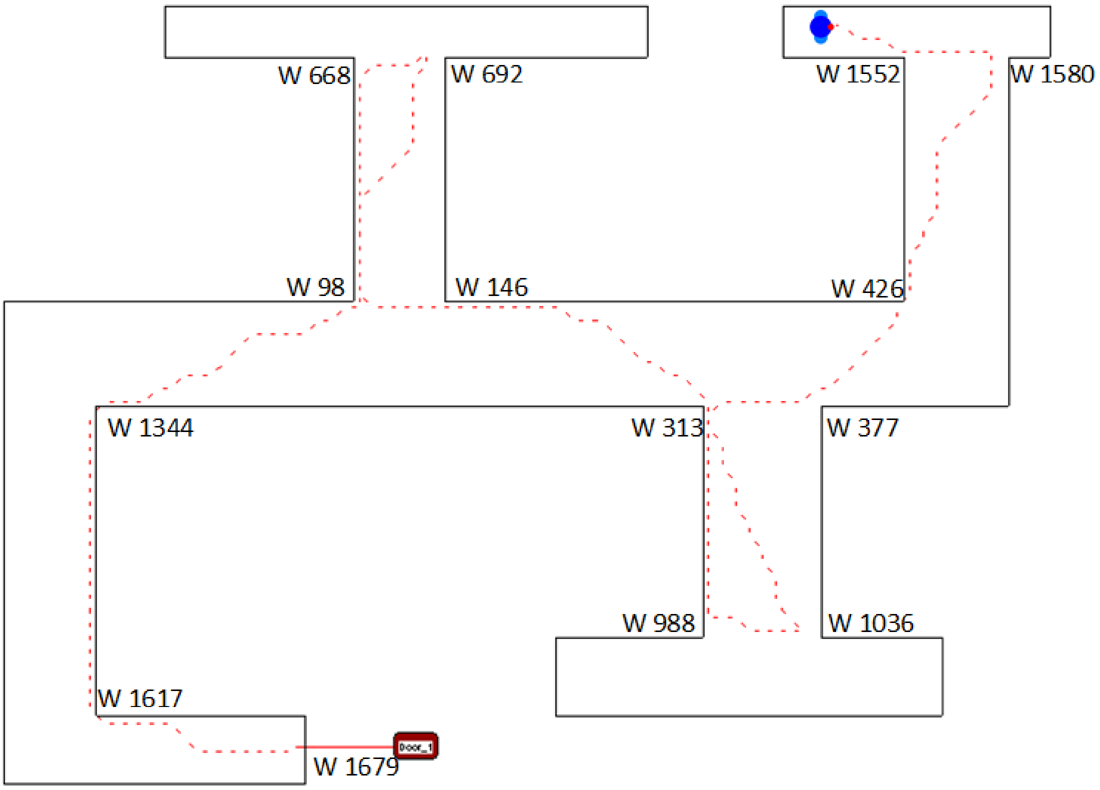


Figure 5.13: Agent's travel path without signage at agent location 3.

From the starting location 4, the agent started with a movement towards the nearest visible waypoint, W988. From W988, the agent continuously searched for the next nearest unvisited waypoints, which form the following path: W988 → W1036→ W377→ W313→ W426→W1552→W1580. At W1580, there are no more unvisited waypoints nearby nor an exit. Therefore, the agent backtracked to the most recent visited waypoint W426 within visible range which has unvisited waypoints connected to it, i.e. there is still unvisited space from W426. From W426, the agent continuously searched for the next nearest unvisited waypoints, which form the following path: W146 → W98→ W668→ W692. At W692, there are no more unvisited waypoints nearby nor visited waypoints with unvisited waypoints connected. Therefore, the agent backtracked to the oldest visited waypoint W98 within visible range. At W98, waypoint W1344 is directly connected unvisited waypoint. Therefore, the agent went left towards W1344 and further went down to unvisited W1617. At W1617, the agent saw the last visible unvisited waypoint W1679 which connects the final exit and exited through it. Finally, the complete path (see Figure 5.14) taken by the agent is:

W988→W1036→W377→W313→W426→W1552→W1580→W426→W146→W98→W668→W692→W98→W1344→W1617→W1679→Door 1

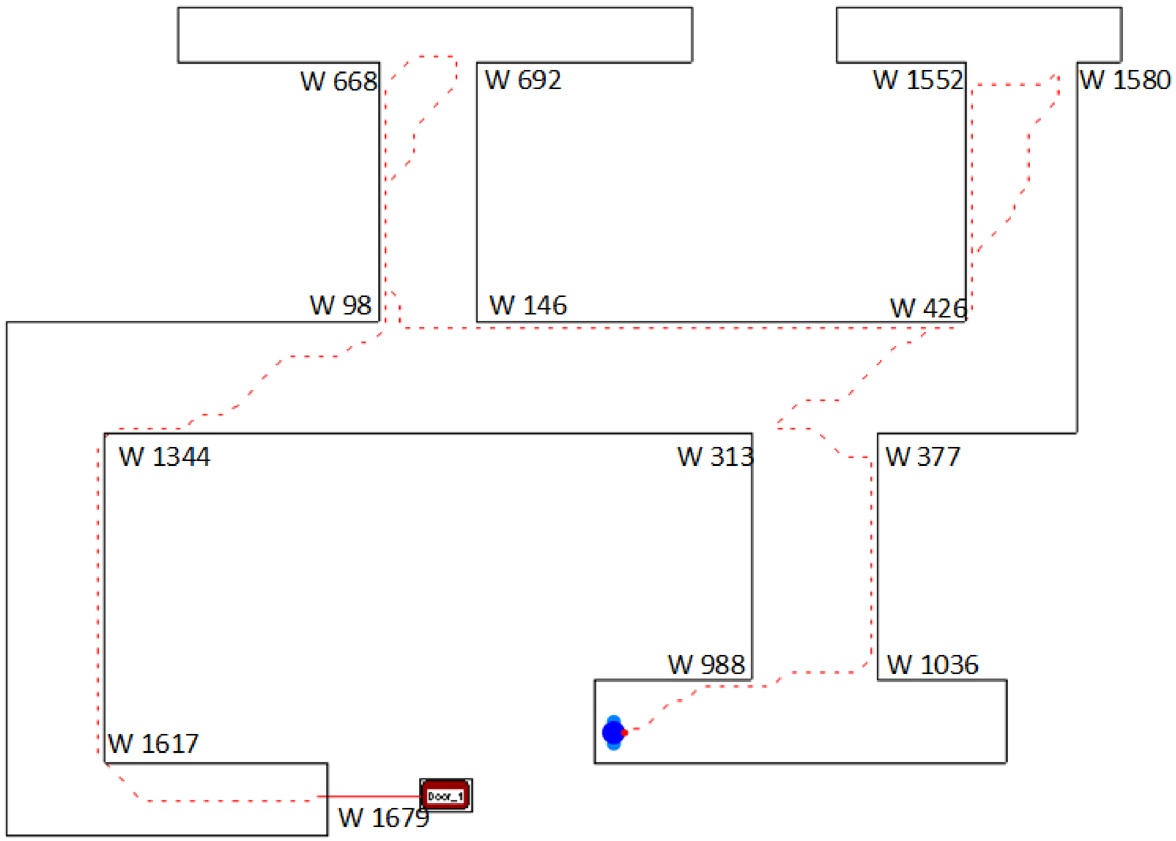


Figure 5.14: Agent's travel path without signage at agent location 4.

5.3.3.5 Results and discussion

The aim of this test was to investigate how an agent perform wayfinding if they have no previous familiarity with the exit. The new model passed this verification test.

5.3.4 Agent's following the signage direction

5.3.4.1 Aim of this test

The aim of this test is to examine whether agents are able to perceive and follow the direction of the sign as implemented in the new model. In this verification case, all five implemented signage directions (sign with an up arrow, sign with a right arrow, sign with a left arrow, sign with an up right arrow and sign with an up left arrow) are tested individually. Using this scenario, the agent will be able to follow the signage direction.

5.3.4.2 Expected occupant behaviour

According to BS5499-4:2013, every escape route sign should contain a directional arrow and supplementary text. The arrow should indicate the egress direction which leads to an exit or a place of safety. When occupants in an evacuation see such an escape route sign, it is expected that they would follow the direction of the sign [BS5499-4:2013; Xie *et al.,* (2011), Xie (2012)]. The signage directional arrows defined in BS 5499-4:2013 and the corresponding occupant behaviour of following the direction indicated by an arrow are modelled in the new model.

5.3.4.3 Description of the test structure

This test case is designed to verify that an agent can correctly interpret and follow the signage direction as implemented in the new model. The test structure is a hypothetical building with five exits in five different directions (see Figure 5.15). A sign with a directional arrow pointing at one exit at a time is placed at the location where an agent needs to take a wayfinding decision. In this scenario, it is assumed that the agent has no previous familiarity with any of the exits. Figure 5.16 shows the test structure with five exits along with the agent's starting location.

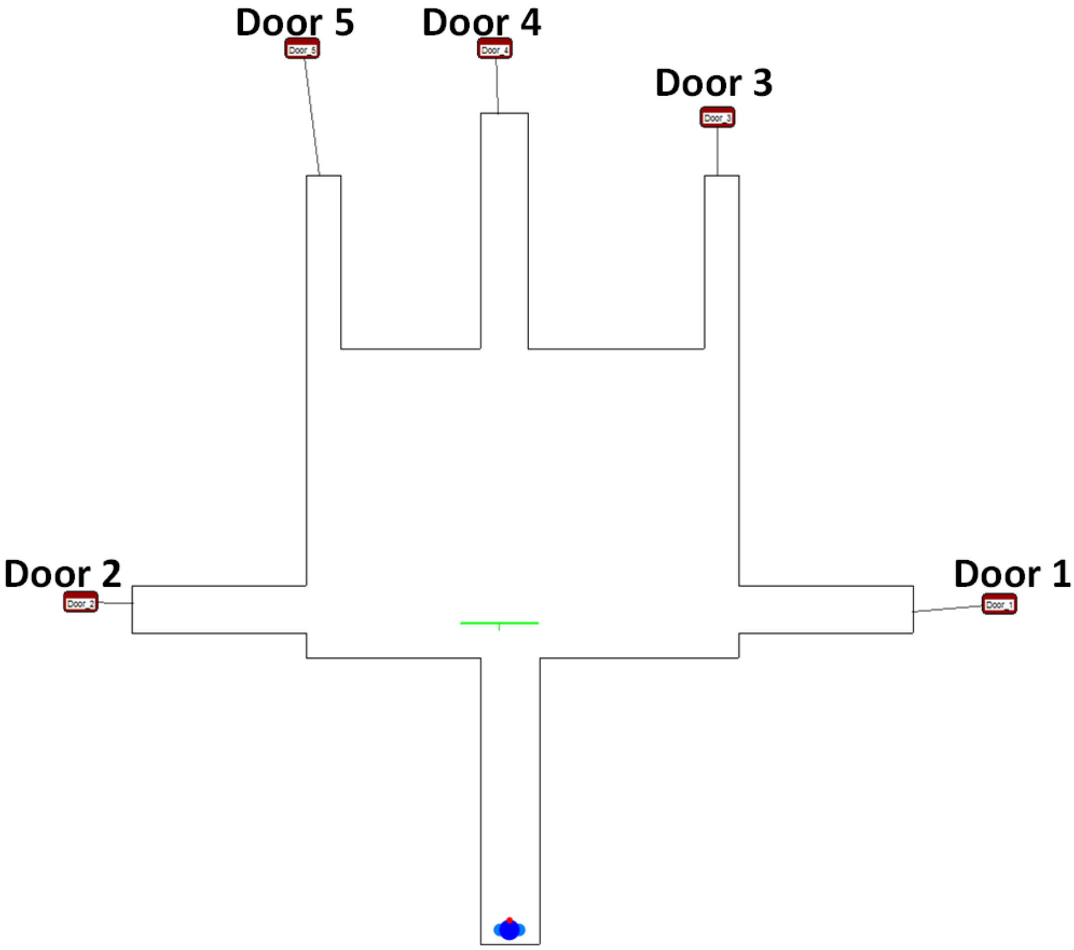


Figure 5.15: Structure used for testing the sign direction.

The VCA of the sign is 9.5m^2 (see Figure 5.16).

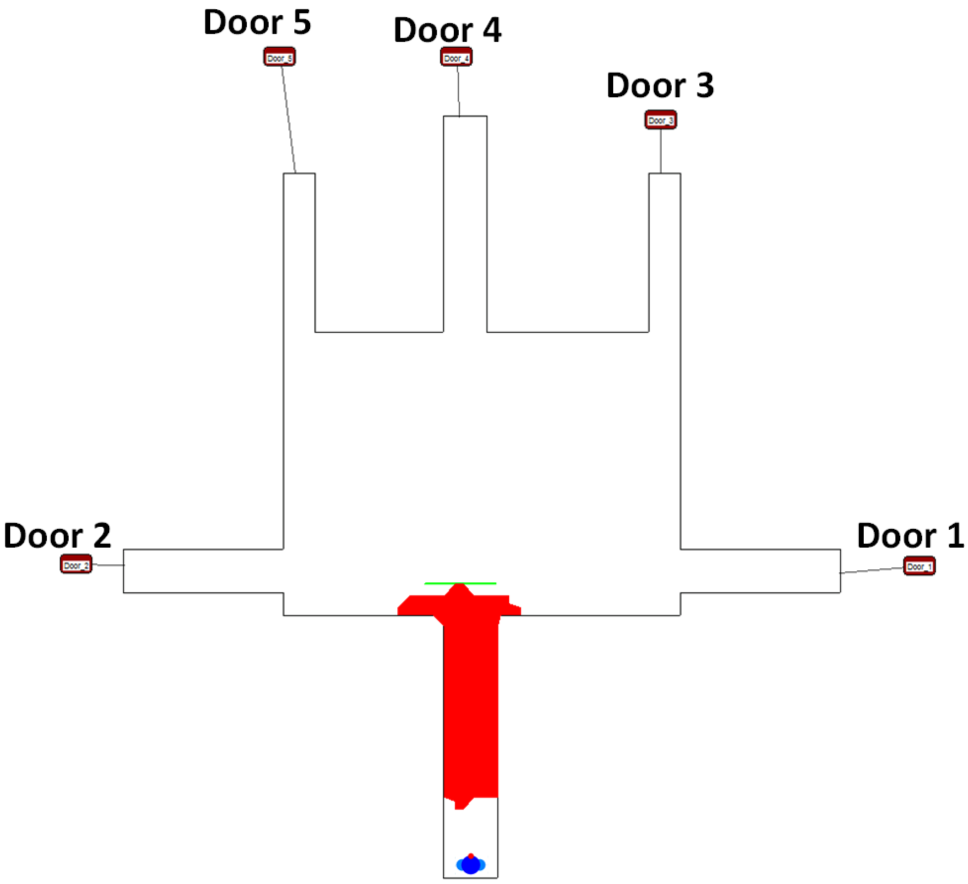


Figure 5.16: VCA of the testing sign.

The navigational graph generated for this geometry is shown in Figure 5.17.

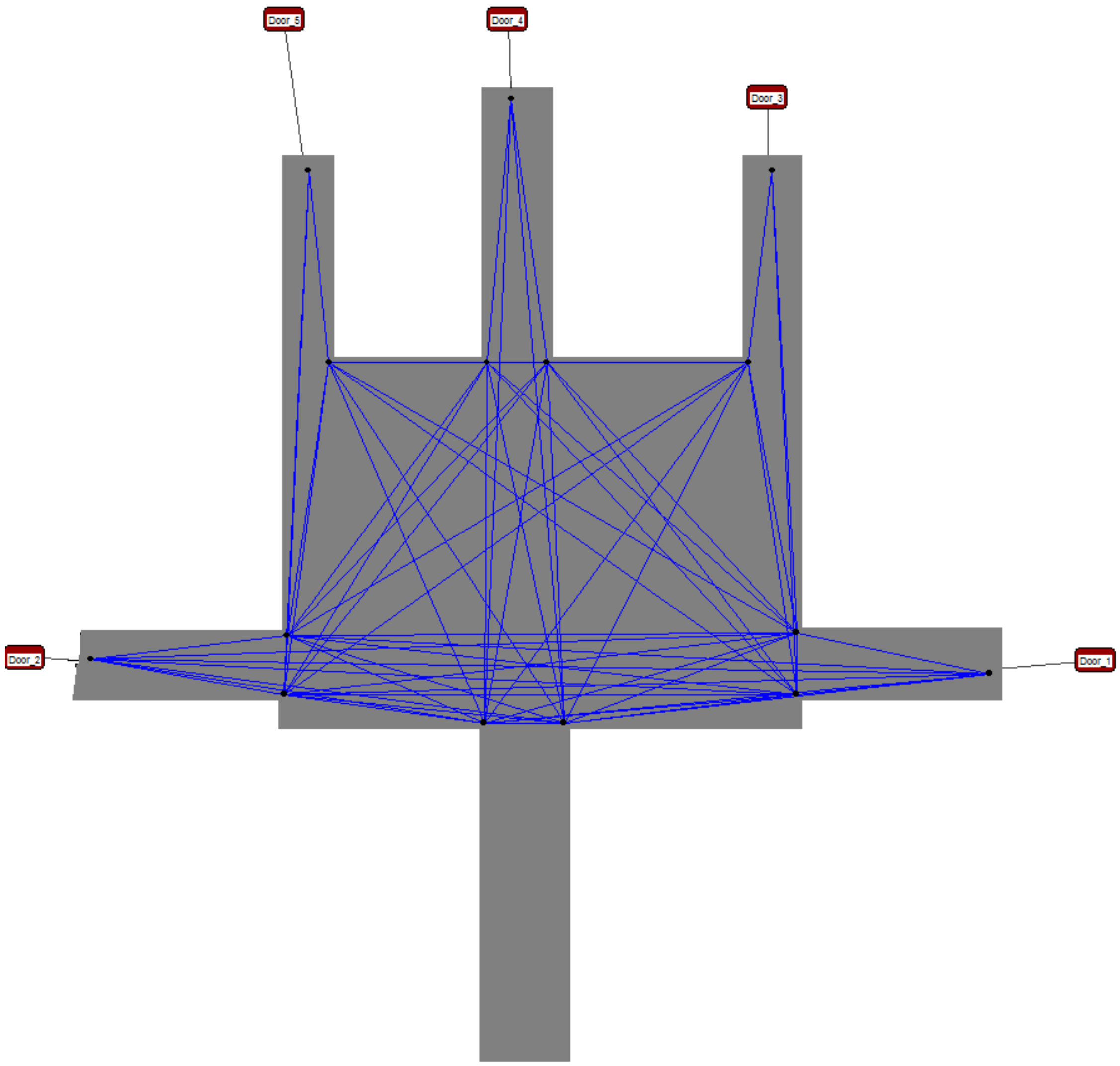


Figure 5.17: The navigational graph of the test structure.

5.3.4.4 Current buildingEXODUS implementation

In buildingEXODUS, there is no representation of the signage direction. Therefore, agents have to rely on the redirection node to be able to follow the intended direction of escape indicated by the signs. In buildingEXODUS, the signs are linked by redirection nodes. When an agent detects a sign, using the redirection node associated with the sign, the agent implicitly “knows” the location the next sign in the signage chain or a target exit hence moving towards it. Therefore, the current approach of modelling the agent behaviour of following signage in an evacuation is based on the assigning of the redirection nodes rather than the signage direction indicated by the directional arrow on each sign.

5.3.4.5 New signage-based navigation model implementation

As explained in Chapter 4 (4.5.2), in the signage-based navigation model, an agent is able to get the direction of a sign and follow the direction provided they detect the sign. In this section, a test case is designed to verify that agent can correctly follow these five implemented signage directions (sign with an up arrow, sign with a right arrow, sign with a left arrow, sign with an up right arrow and sign with an up left arrow) in the new signage-based navigation model.

Sign with an up arrow

In this test case, the sign placed in the structure has an up arrow (see Figure 5.18). According to BS 5499-4:2013, the meaning of a sign with an up arrow is to '*progress forward from here*'. In this particular structure, this sign indicates the escape direction leading to Door 4.

On entering the VCA of the sign, the agent perceived the sign and obtained the direction. Using the signage following algorithm explained in Chapter 4 (Section 4.5.2), the agent moved to the visible waypoint with the minimum deviation to the direction indicated by the sign i.e., waypoint 356. From waypoint 356, Door 4 was directly in front. Hence, the agent continued moving towards Door 4 and left the structure. The path taken by the agent is shown in Figure 5.18.

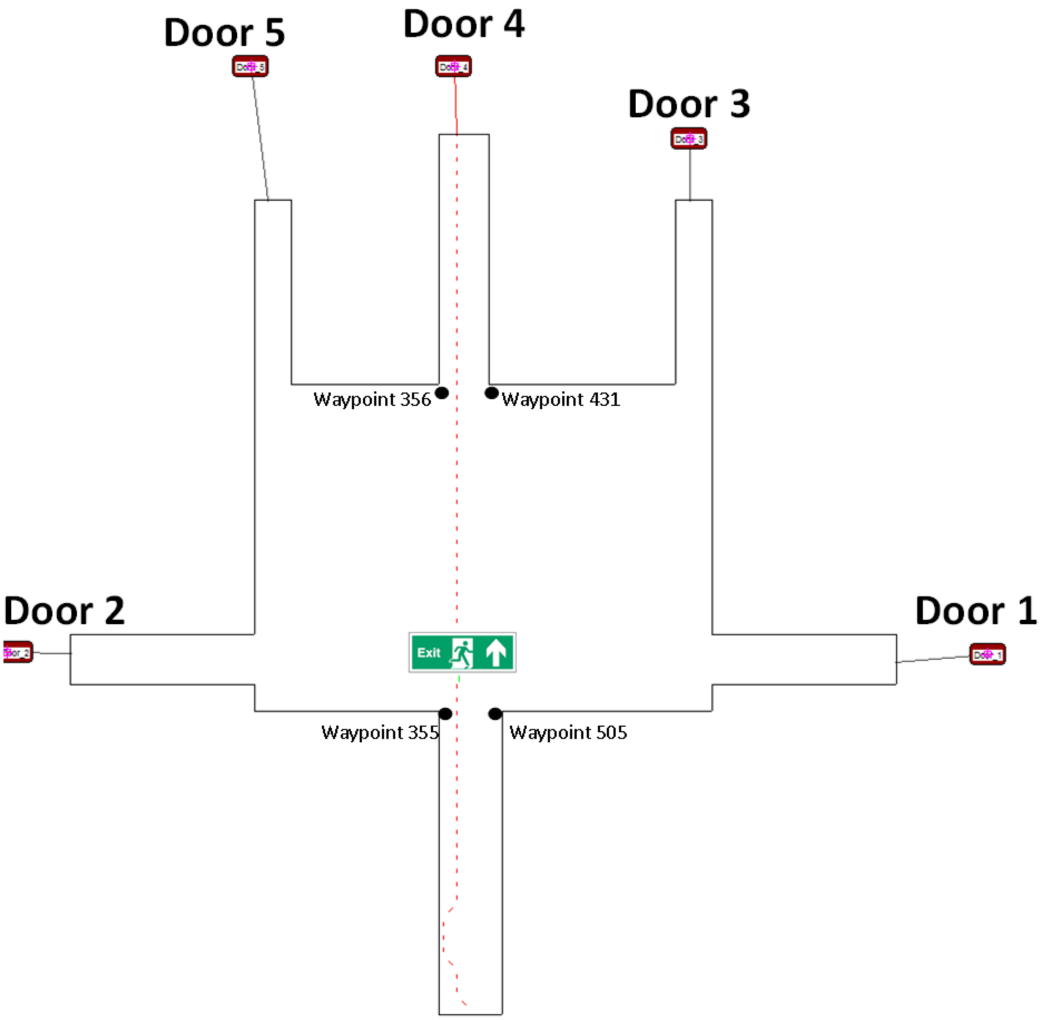


Figure 5.18: Testing the sign with an up arrow and agent's travel path while following the up sign.

Sign with a right arrow

In this test case, the sign placed in the structure has a right arrow (see Table 5.6a). According to BS 5499-4:2013, the meaning of a sign with a right arrow is to '*progress to the right from here*'. In this particular structure, this sign indicates the escape direction leading to Door 1.

When testing the sign with the right arrow, on entering the VCA of the sign, the agent moved to the waypoint with the minimum deviation to the direction indicated by the sign i.e, waypoint 878. At waypoint 878, the agent noticed the directly connected Door 1. Hence, the agent went towards Door 1 and left the structure. The complete path taken by the agent is shown in Table 5.6.

Sign with a left arrow

In this test case, the sign placed in the structure has a left arrow (see Table 5.6b). According to BS 5499-4:2013, the meaning of a sign with a left arrow is to '*progress to the left from here'*. In this particular structure, this sign indicates the escape direction leading to Door 2.

During the sign with left arrow, on entering the VCA of the sign, agent moved to waypoint 1051 with the minimum angle to the angle of the direction indicated by the sign. At waypoint 1051, the agent had a direct path to Door 2. Therefore, the agent moved towards Door 2 and left the structure. The complete path taken by the agent is shown in Table 5.6.

Sign with an up right arrow

In this test case, the sign placed in the structure has an up right arrow (see Table 5.6c). According to BS 5499-4:2013, the meaning of a sign with an up right arrow is to '*Progress forward and across to the right from here*. In this particular structure, this sign indicates the escape direction leading to Door 3.

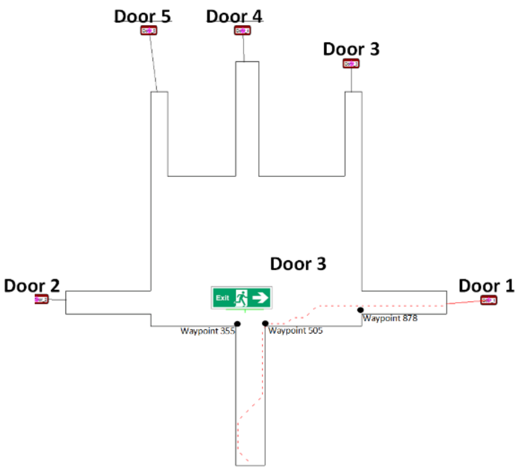
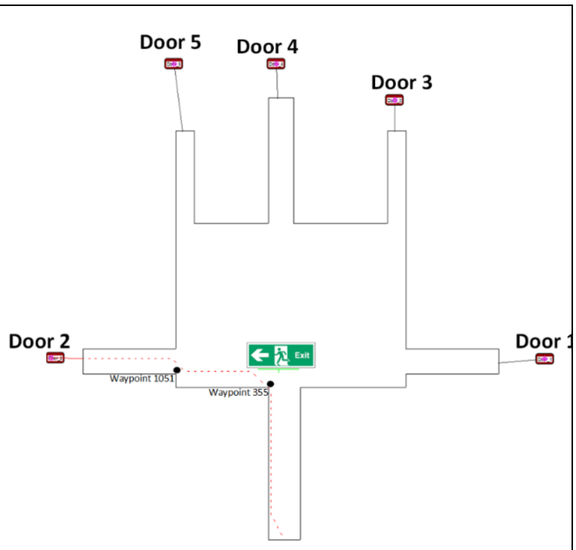
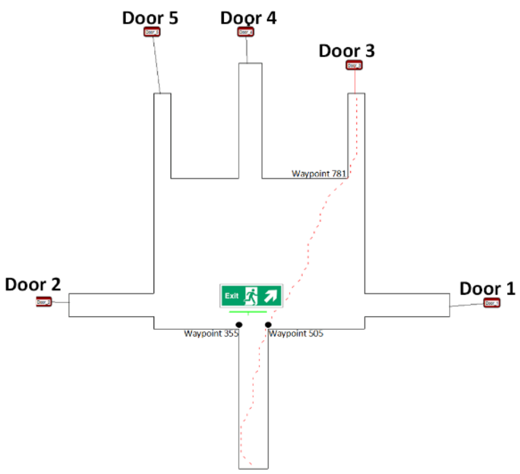
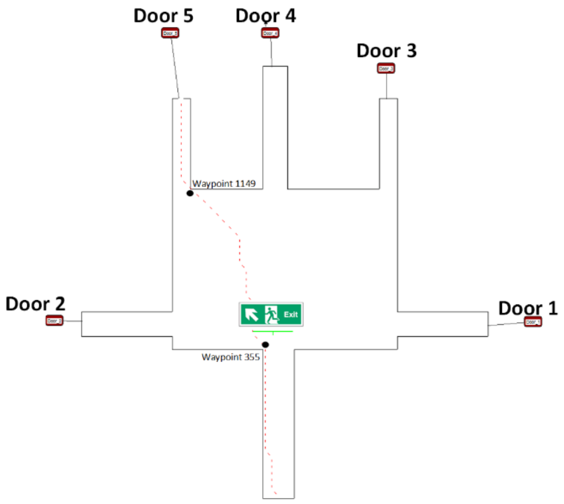
When testing the sign with up-right arrow, on entering the VCA of the sign, the agent moved to waypoint 781 as this waypoint was located at the minimum angle to the angle of the direction indicated by the sign. From waypoint 781, Door 3 was directly connected. Hence, the agent used Door 3 and left the structure. The complete path taken by the agent is shown in Table 5.6.

Sign with an up left arrow

In this test case, the sign placed in the structure has an up left arrow (see Table 5.6d). According to BS 5499-4:2013, the meaning of a sign with an up left arrow is to '*Progress forward and across to the left from here'*. In this particular structure, this sign indicates the escape direction leading to Door 5.

When testing the sign with up left arrow, on entering the VCA of the sign, the agent moved to the waypoint with the minimum angle to the angle of the direction provided by the sign i.e., waypoint 1149. From waypoint 1149, Door 5 was directly connected. Therefore, the agent moved towards Door 5 and left the structure. The complete path taken by the agent is shown in Table 5.6.

Table 5.6: Agent's travel path while following signage.

 (a)	 (b)
 (c)	 (d)

5.3.4.6 *Results and conclusion*

This test successfully demonstrated that in the newly developed model an agent is able to understand and follow the signage direction. Unlike the prescriptive approach used in the current signage model in buildingEXODUS, the new signage-based navigation model can represent the agent's movement of following a signage direction. This test successfully verified that an agent is able to correctly understand and follow the five signage directions defined in BS 5499-4:2013 and implemented within the new model.

5.3.5 Adaptive navigation behaviour using memory

5.3.5.1 Aim of this Test

The aim of this test is to verify an agent's ability to avoid reusing the previously visited sign using the signage memory. This scenario will allow the new model to simulate the agent's individual memory.

5.3.5.2 Expected occupant behaviour

At present, further research is required to understand how occupants utilise their memory to search for their desired target if they do not have the previous knowledge of the structure.

In an emergency scenario, an occupant who is unfamiliar with the layout of a building may follow signage to wayfind to an emergency exit. In buildingEXODUS if an agent fails to find next exit/sign when following a sign, the agent may backtrack, start random searching or leave the building from the nearest available exit. During their backtracking and searching, they may repeatedly use the same route or the same sign since they do not store their navigation experience.

In the new signage-based navigation model, agents have individual memory to store their past visited places and perceived signs. The memory allows the agents to differentiate between visited and unvisited space, used and unused signs. This helps the agents avoid revisiting previously visited places where there are no viable exits or reusing previously perceived signs which fail to lead them to an exit.

5.3.5.3 Description of the test structure

Figure 5.19 shows the "T" shape test structure with two exits (Door 1 and an emergency exit) along with the agent's starting location. In the simulation scenario, the agent is familiar with Door 1 only and has no previous knowledge of the emergency exit. An exit sign is located in the middle of the corridor pointing at the emergency exit.

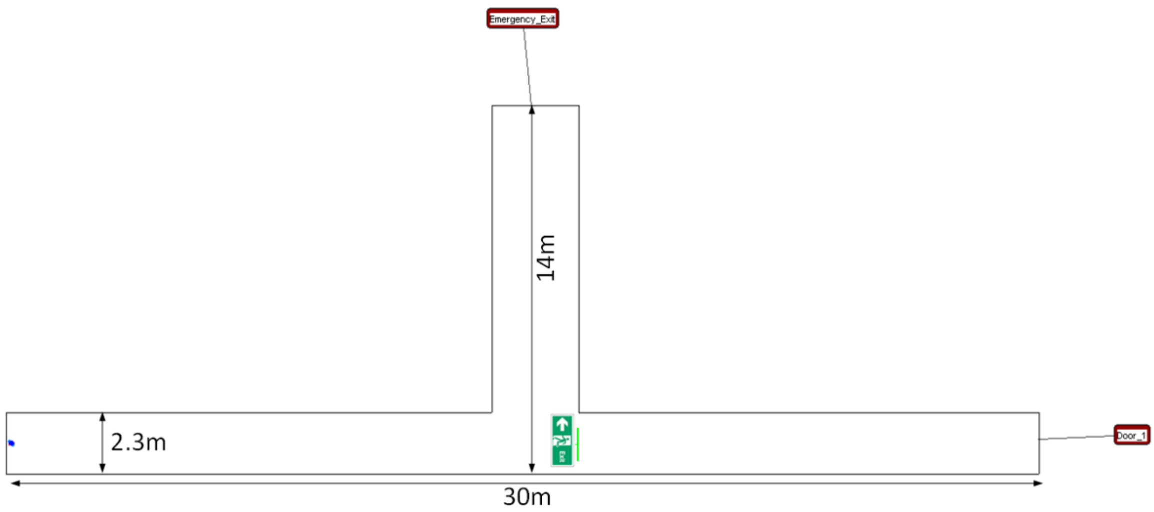


Figure 5.19: The test structure and agent's starting location for testing agent's signage memory.

The VCA of the sign is set to 25m^2 (see Figure 5.20). In the newly developed model, signage detection probability is based on the empirical data collected by Xie [2011]. Therefore, when the agent enters the VCA of the sign, there is a 38% probability of detecting the sign and after detecting the sign, a 97% probability of complying the information provided by the sign.

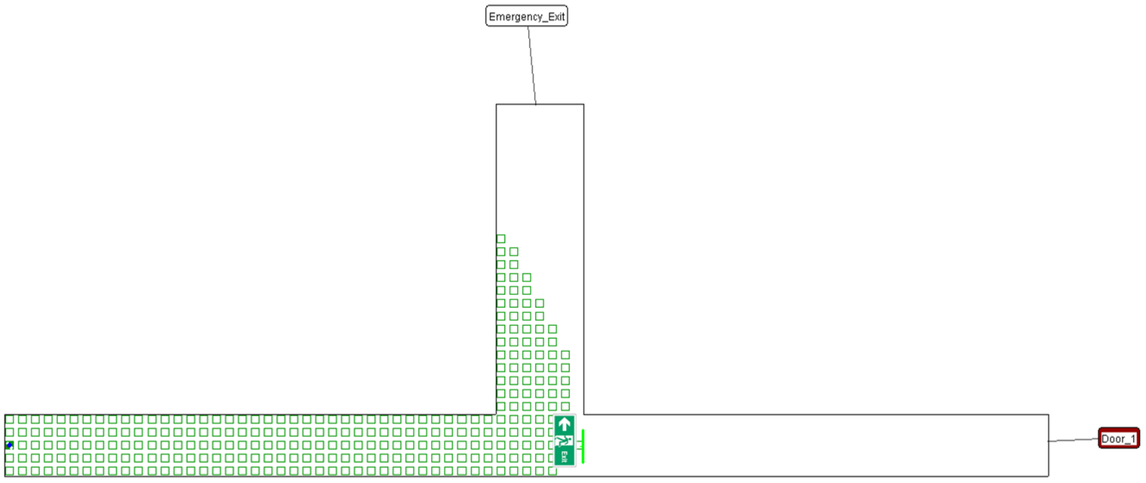


Figure 5.20: The VCA of the sign.

The navigational graph generated for this structure is shown in Figure 5.21.

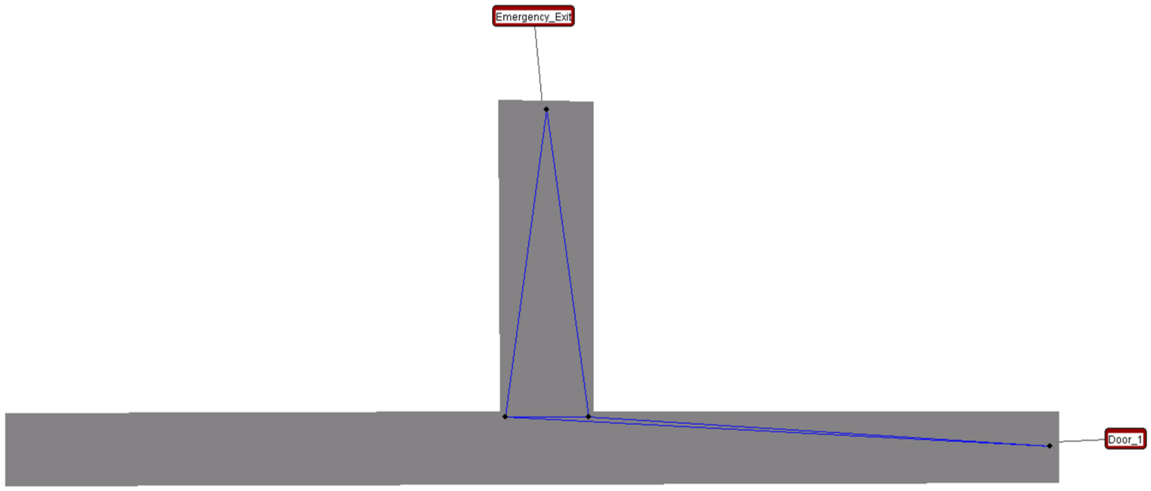


Figure 5.21: The generated navigational graph for testing signage memory.

5.3.5.4 Current buildingEXODUS implementation

In buildingEXODUS, first, agent lacks the capability to store the past wayfinding experience. Second, if an agent following a sign fails to detect the next sign/exit in the structure, some or all four behaviours may be executed (Chapter 3, Section 3.2.6.2).

These behaviours are searching behaviour, backtracking behaviour, lost behaviour and fail-safe behaviour [Filippidis *et al.*, 2008]. These behaviours encourage the agent to move back to the last visited sign and start looking for clues again. At last, if the agent fails to find an exit/sign, the agent gives up the searching for clues and leaves the structure by the nearest exit.

5.3.5.5 New Signage-based navigation model implementation

In this test, the agent is familiar with Door 1. Hence, when the agent detected the sign, the agent estimated the travel distance from his current location to the known exit (Door 1) as 30m and saved this distance in memory.

According to the algorithm developed for the Navigation Strategy 2 (Chapter 4, Section 4.5.2), when agents detect a sign, they store the sign and the detection time into their memory. Then, the agents start moving towards the waypoint located at the minimum angle in the direction of the sign. In this test, when the agent detected the sign, the agent started moving towards waypoint W280.

From the beginning of the simulation, the agent travelled 18m from his starting position to the sign. And then the agent moved towards waypoint W 280 in the sign direction. When he travelled 13m in the direction of the sign, the total distance travelled since he started following the sign is equal to the distance to his original known target, Door 1 (i.e. 30m measured from where he decided to follow the sign), and the agent still did not reach the exit. At this point, as there is no additional sign to indicate the emergency exit, therefore the agent stopped following the sign and started moving towards Door 1 using the Navigation Strategy 1 (Chapter 4, Section 4.5.1). Note that although the agent was very close to the emergency exit at this point, it is assumed that he would not use it due to the lack of information to confirm it is an available exit.

While moving back towards Door 1, the agent would enter the VCA of the sign again. However, using their memory, the agent realised that the sign has been previously perceived, but he could not find a viable exit using the sign. Hence, the agent ignored the sign and continued moving towards the known exit, Door 1. At last, the agent left the structure through Door 1 (see Figure 5.22).

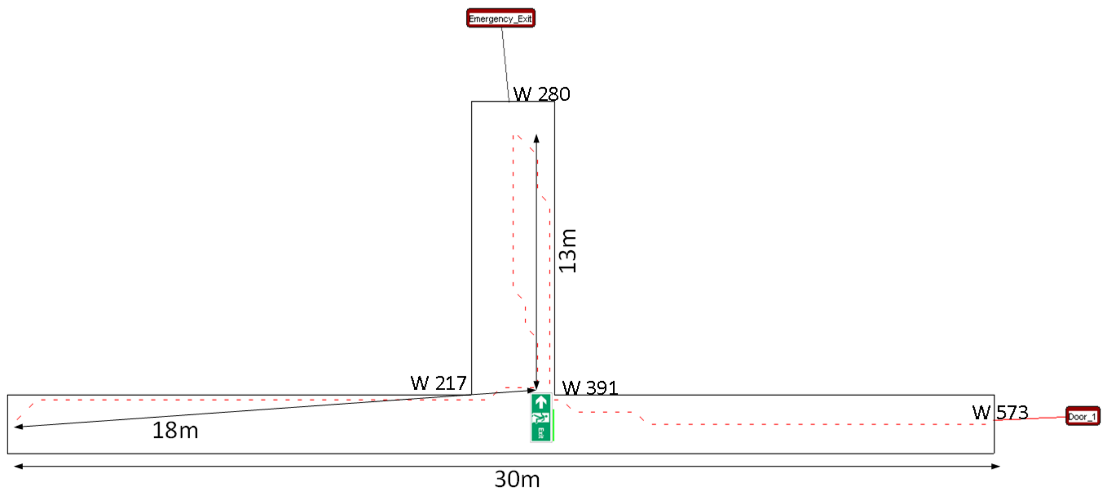


Figure 5.22: Agent's travel path using the memory.

5.3.5.6 Results and discussion

This test successfully verified that the implemented signage-based navigation model allows the agents to use their memory to differentiate between an unused sign and previously used sign. In buildingEXODUS, if an agent fails to find the next exit/sign when following a sign, the agent either starts random searching or leaves the model from the nearest available exit. During this process, if the agent encounters the same sign again, he may reuse the sign which results in unnecessary movement. Whereas, the memory function in the new model allows agents to ignore previously perceived signs if agents cannot find an exit accordingly. In this way, the introduction of agent's memory provides a rational wayfinding behaviour compared to buildingEXODUS.

5.4 Validation of the new signage-based navigation model

In Section 5.3, the components of the signage-based navigation model (three navigation strategies, agent's capability of following the signage direction and agent's memory) were verified individually through the verification tests. As discussed in Section 5.2, to validate the model quantitatively is a challenging task. This is because of the lack of quantitative validation data available for evacuation models [Gwynne *et al.,* 2005], especially comprehensive dataset which could be used to validate the model as a whole. Therefore, the new model was validated primarily against the existing modelling approaches (such as buildingEXODUS) and some available empirical data collected.

The new signage-based navigation model can simulate the wayfinding behaviour of the agents with full or partial familiarity with the exits (Chapter 4, Section 4.5.1, Navigation Strategy 1), agents following signage along the escape route (Chapter 4, Section 4.5.2, Navigation Strategy 2) and the agents without familiarity with building layout or with invalid exit knowledge (Chapter 4, Section 4.5.3, Navigation Strategy 3). The navigation of agents with full familiarity and partial familiarity can be modelled by various evacuation modelling tools [buildingEXODUS (Galea *et al.,* 2011), PathFinder (2013), FDS-Evac (Korhonen and Hostikka, 2008), STEPS (2010)]. Since buildingEXODUS is selected as the testing platform for the new model, the navigation of agents with full familiarity and partial familiarity using Navigation Strategy 1 can be validated against buildingEXODUS which can simulate the navigation of agents with full/partial familiarity. buildingEXODUS has been subjected to significant testing and validation and it is deemed, for these purposes, to be a reasonable benchmark [Galea *et al.,* 2011]. At present, no evacuation model can simulate the wayfinding behaviour of agents with no previous familiarity with the structure. This is a constraint in the validation of this aspect of the new model, i.e. navigation using Navigation Strategy 3.

As for the validation of Navigation Strategy 2, the work of [Xie *et al.,* 2011; Xie, 2012] studying the signage detection probability is valuable for this research. According to this empirical data collected, when an occupant is within the visible range of a sign, there is a 38% chance that the occupant will perceive the sign and a further 97% chance of following the sign [Xie *et al.,* 2012]. The interaction with signage using the detection and compliance probabilities based on this empirical data has been implemented in the new model and is validated against the implementation of the same behaviour within buildingEXODUS. It should be noted that since the new model simulates the interaction between agents and multiple signs along the escape route, an attempt was made to compare the simulation outcomes produced by both models (i.e. the performance of the signage system as a whole) rather than the percentage of signage use generated for each sign.

Another important feature of the new model is the agent's following the signage direction. According to BS 5499-4:2013, each sign should contain a directional arrow which indicates the direction of escape. When occupants perceive a sign, they should be able to understand the arrow direction of the sign and then start moving in the direction. This behaviour is implemented in the new signage-based navigation model. Hence, this behaviour can be validated against BS 5499-4:2013.

Lastly, to validate the signage-based navigation model as a whole, one of BS 5499-4:2013 demonstration case (see Figure 5.23) is used. This demonstration case provides two chains of signage configuration indicating two escape routes. Qualitative validation performs the comparison of predicted human behaviour with informed expectations. This is an important part of validation as it signifies whether the model is able to produce realistic behaviours.

Identifying escape routes to design chain signage network

BS 5499-4:2013 defines means of escape as escape routes from any place within the structure to a place of safety or an exit. Usually, in a built structure, it is required to have multiple escape routes. This is to address the possibility of losing an escape route due to a structural disaster, fire or smoke. The escape routes from each place within the built structure should usually have the shortest travel distance to a place of safety [BS 5499-4:2013]. Escape route signing system must be implemented to provide clear and simple identification of the escape routes [BS 5499-4:2013, BS EN ISO 7010].

BS 5499-4:2013 provides the guidelines on the design and location of escape route signs in addition with advice on the use of arrows to provide directional information. The escape route signs should be positioned to complete an escape route by avoiding potential points of confusion. Additional signs should be installed where the direct sight of the escape route is not possible, and confusion might exist in its position [BS 5499-4:2013, BS 5499-10:2014].

Modelling approach to chain signage

In the past, the implemented modelling approaches to simulate the agent interaction with chain signage were limited by the lack of agent's capability of understanding the space connectivity. In buildingEXODUS, to model the chain signage, the concept of redirection node is used [Filippidis *et al.,* 2008]. The signs in the chain are linked by redirection node which provides the location of another redirection node associated with next sign in the signage chain. Therefore, the agent's movement of following the signage chain is implicitly guided by the redirection nodes. Hence, the agent "hops" from one redirection node to another redirection node until they find an exit.

The new signage-based navigation model uses a different approach. The new model combines signage and navigational graph to expand agent's visual perception of the environment and sense of direction, introduces a preliminary form of cognitive understanding of the building layout through memory and provides individual level decision-making capability for wayfinding.

5.4.1 Definition of geometry and test population

The British signage standard BS 5499-4:2013 provides 22 cases in annex to illustrate the correct use of escape route signs in various typical situations in buildings.

To validate the signage-based navigation model as a whole, one of the demonstration cases in BS 5499-4:2013 is selected as the test case (see Figure 5.23). The reason for selecting this case is because it provides the configuration of a complete signage system for a structure. This demonstration case shows how to design a signage system to direct occupants to use two separate escape routes to escape the building. This demonstration case with a typical escape route signage system configuration from BS 5499-4:2013 is an ideal case to verify the new signage model as a whole through simulating how building occupants utilise the signage system in an evacuation.

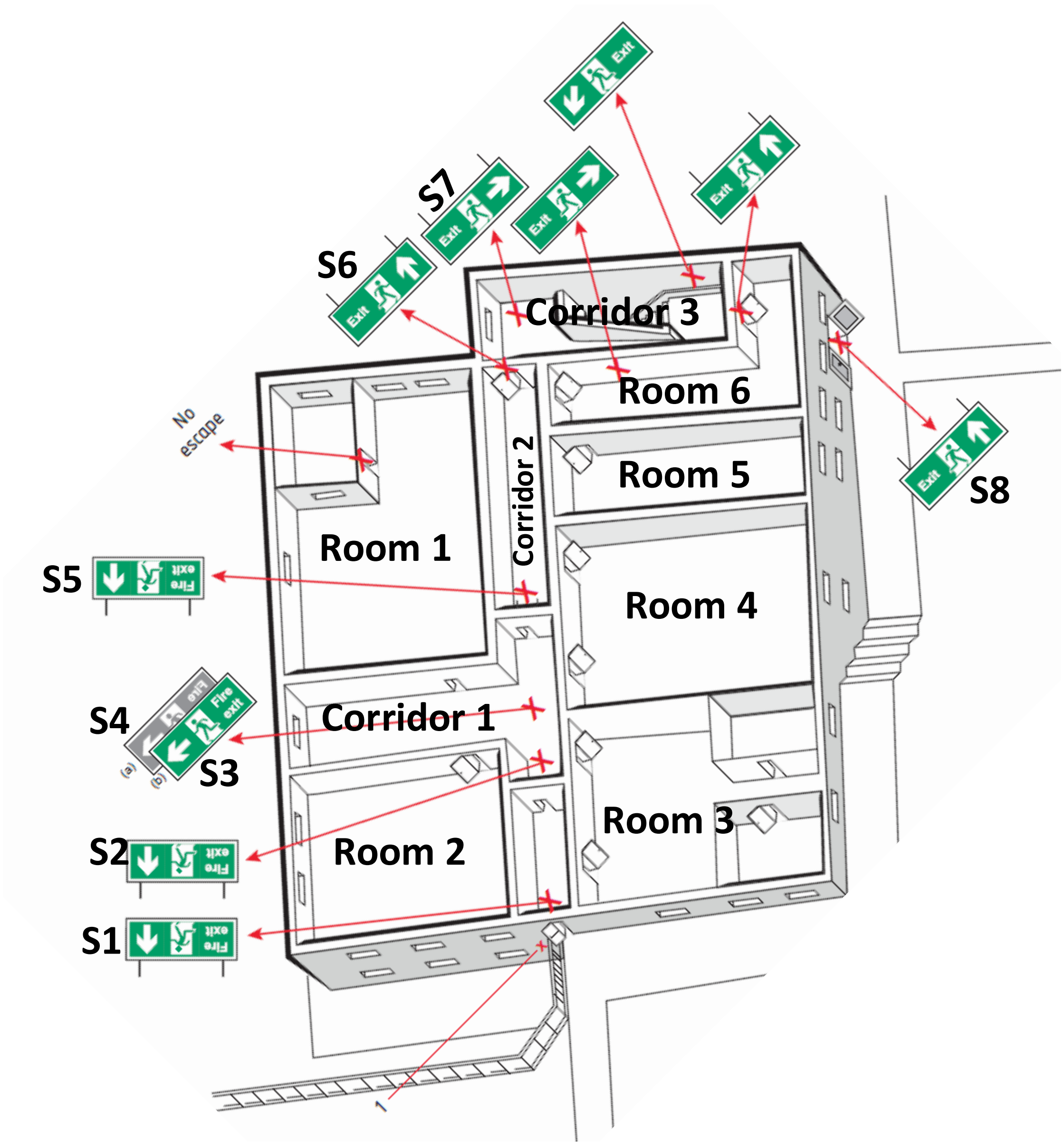


Figure 5.23: The selected BS 5499-4:2013 demonstration case with a typical signage system configuration in a building.

The reproduced version of this case using buildingEXODUS is shown in Figure 5.24. A total of 66 agents are used to represent a general population. The agents are randomly generated and located throughout the geometry (see Figure 5.24).

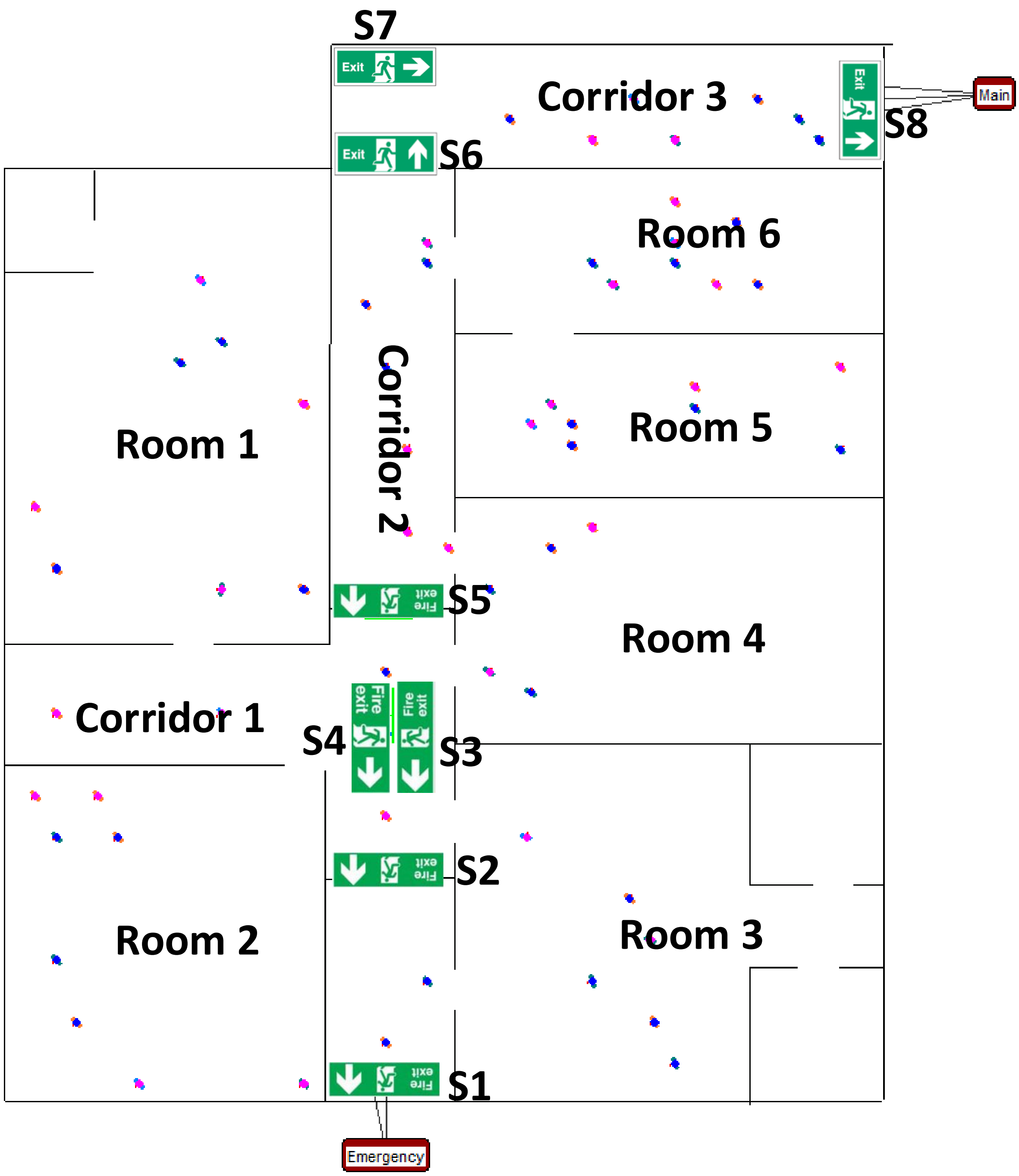


Figure 5.24: BS 5499-4:2013 demonstration case reproduced in buildingEXODUS.

The configuration of signage using BS 5499-4:2013

According to the UK standards [BS 5499-4:2013, BS 5499-10:2014] and international standards [BS ISO 3864-1, BS EN ISO 7010], each escape route usually require series of signs to form a signage chain along the route. By correctly identifying the signage symbol, reading the text and following the direction of the escape route signs, the occupants, who may be unfamiliar with the premises and possibly under conditions of stress, can escape from any place in the building to a place of safety using a planned escape route without assistance. The escape routes from each location within the building should normally have the shortest travel distance to an exit [BS 5499-4:2013]. buildingEXODUS allows the model user to view the catchment area of each exit which represents the region from where the shortest routes lead to that particular exit. In the demonstration case, the catchment areas of the two exits are shown in Figure 5.25. Catchment area 1 is associated with the main exit, i.e. the main exit is the nearest exit for those agents who are located within catchment area 1. Hence, in catchment area 1, the signs are installed to guide the agents towards the main exit. Similarly, the emergency exit is associated with catchment area 2, which means the emergency exit is the nearest exit for the agents who are located in catchment area 2. The signs installed in catchment area 2 guide the agents towards the emergency exit.

In buildingEXODUS, the signs are divided into *zero*, *first* and *higher* order signs (Chapter 3, Section 3.2.6.2). In this case (see Figure 5.26), sign S1 and S8 installed directly above the exits are *zero*-order signs. Sign S2 and S7 pointing at zero order signs are *first* order signs. Lastly, sign S3, S4, S5 and S6 are *higher* order signs which point at first order signs. Higher order signs lead the agents to an area where another sign of the chain signage system is present and is nearer to the target exit. In buildingEXODUS, an agent is not capable to understand the direction of the sign. Hence, to create a chain signage in buildingEXODUS, a model user manually connects the signs in order to form a signage chain along the intended escape route. However, in the new signage-based navigation model, the signs are not required to be connected by the model user. In the model, once an agent detects a sign, the agent comprehends the signage arrow direction and starts following the direction of the sign.

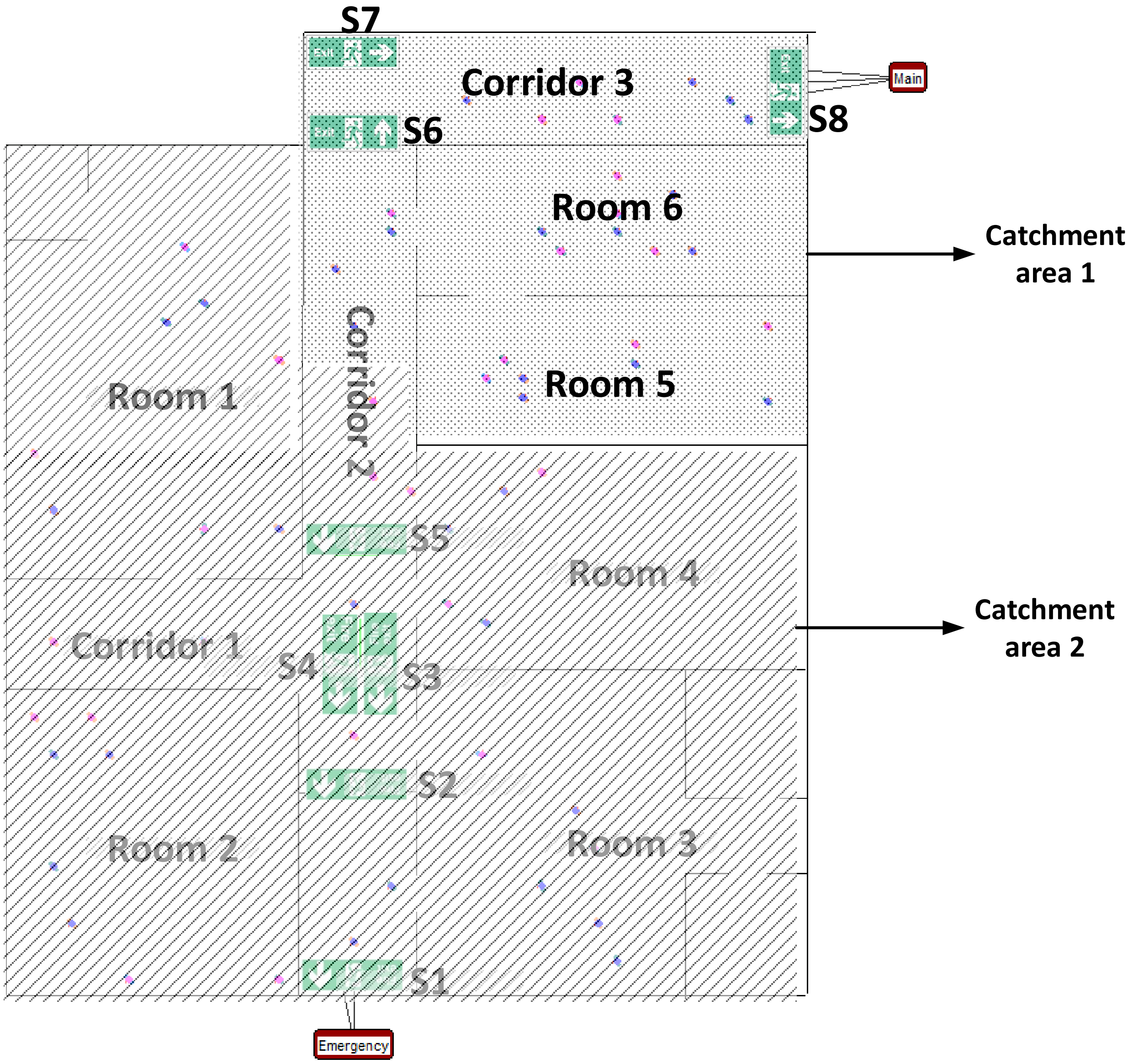


Figure 5.25: Catchment areas of main and emergency exit produced in buildingEXODUS.

There are two signage chains used in this case (see Figure 5.26). First, the circulation signage chain which includes sign S6, S7 and S8 leads to the main exit. Second, the emergency escape route signage chain which includes sign S1, S2, S3, S4 and S5 leads towards the emergency exit. For instance, to egress, an agent located in room 1 will enter corridor 1 and detect sign S4. While following sign S4, the agent should detect the next sign S2 which points to sign S1. At this stage, the agent will use the emergency exit to leave the structure. Similarly, to leave the test structure, an agent located in room 5 will firstly enter room 6 and then corridor 2. The agent should detect sign S6 and then sign S7. Sign S7 directs the agent towards sign S8 and the main exit. Hence, the agent will use the main exit to leave the structure.

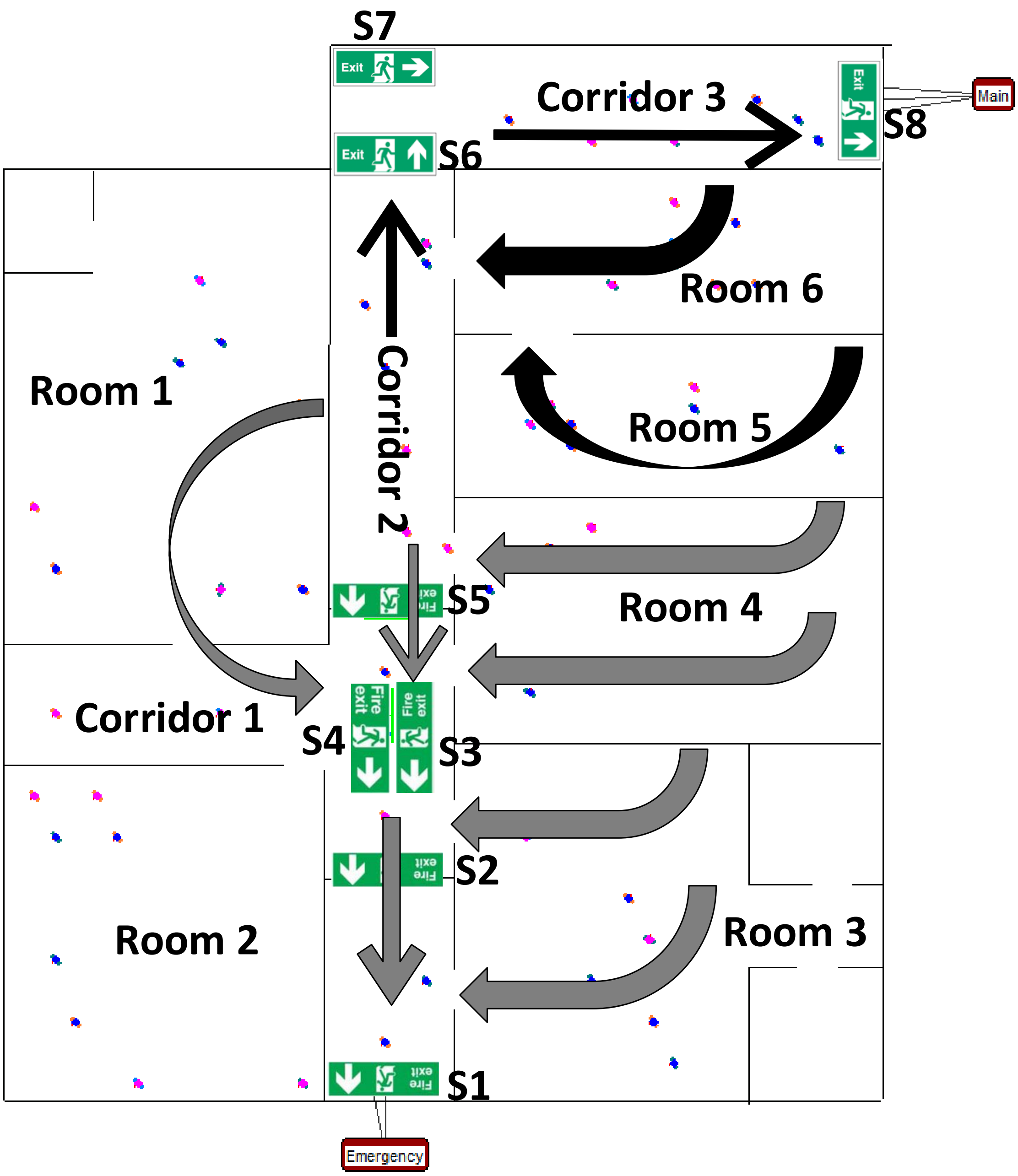


Figure 5.26: Two different chain of signs leading to main exit and emergency exit.

5.4.2 Description of validation scenarios

Four simulation scenarios are designed and run to validate the new signage-based navigation model as a whole.

Scenario 1: In this scenario, signage is not included. The entire population are aware of the main exit only. In the real world, this depicts a normal circulation scenario or the worst evacuation scenario, i.e. all occupants leave the structure from their entry point without fully utilising the escape capacity of the building. The purpose of this simulation scenario is to compare with the agents' wayfinding behaviour using the chain signage in the other scenarios.

Scenario 2: Like Scenario 1, signage is not included. In this scenario, it is assumed that all agents are familiar with the internal layout of the structure. All agents are aware of the location of the two exits; hence, they can use the nearest available exit. This scenario produces the most optimal egress results. However, it should be noted that this is an ideal but not realistic situation, as in a complex built environment it is unlikely that all occupants are well familiar with the building layout and know the locations of all exit. This scenario is used to compare with the evacuation performance when the signage system is introduced in Scenario 3.

Scenario 3: In a realistic situation, it would be unlikely that the entire population are familiar with the structure as assumed in Scenario 2. Some occupants may be familiar with structure and can work out which is the nearest available exit from their current location. There may be others with limited knowledge about the structure. Hence, to provide the necessary wayfinding information, the signage system is introduced. If all occupants follow the correctly positioned escape route signs which lead them to their nearest exits, it is expected that the evacuation performance should be comparable to that of Scenario 2.

. It is often assumed by architects, safety engineers and managers that when occupants are within the visible range of a sign, they will perceive the sign, i.e. the signage detection probability is set to 100%. It is also assumed that if the occupants perceive the sign, they will follow the direction of the sign, i.e. the signage compliance probability is set to 100%. In this scenario, the entire population are aware of the main exit only. However, if they perceive a sign, they will use signage information perceived during the simulation to wayfind to another exit.

Scenario 4: In this scenario, the empirical data is adopted to examine the impact of the signage detection and compliance probabilities on the interaction between occupants and signage [Xie *et al.*, 2012]. This means when an agent is within the VCA of a sign and is travelling in the general direction of that sign there is a 38% chance of detecting the sign by the agent and if detected, a 97% chance of complying with the signage information. In this scenario, the entire population are aware of the main exit only and will use signage information perceived during the simulation to wayfind to another exit. Xie *et al.*, [2012] work focussed on the single sign and it does not cover the detection probability of next sign in a chain. Since the validation case contains multiple signage systems, hence, the comparison and discussion in this scenario is based on the performance of the signage system as a whole rather than validating the detection probability of a single sign.

5.4.3 Results and discussion

Each scenario was run 10 times to produce a range of results. In each simulation, the agents' starting locations were kept constant. Table 5.7 shows the average values along with the two standard deviations for some key parameters from the simulations.

Table 5.7: Average results for qualitative validation case.

Scenario	Level of Familiarity	Use of signage	Total evacuation time (s)	Average congestion time (s)	Average distance travelled (m)	Average individual evacuation time (s)	Average usage of emergency exits
1	Main exit	No	117.9 ± 1.5	28.3 ± 0.8	27.0 ± 0.1	65.3 ± 0.8	0
2	Main and emergency exit	No	46.6 ± 0.8	1.5 ± 0.3	15.1 ± 0.1	29.7 ± 0.3	38 ± 0
3	Main exit	Yes	46.9 ±0.6	1.8 ± 0.1	15.1 ± 0.1	30.0 ± 0.2	39 ± 0
4	Main exit	Yes	55.5 ± 3.9	0.8 ± 0.3	17.8 ± 0.7	31.1 ± 2.0	34 ± 2

In **Scenario 1**, no signage information was included. The agents located in all rooms (room 1-6) and corridors (corridor 1-3) used their knowledge of the main exit to go to the main exit to leave the structure (see Figure 5.27). In this scenario, the average travel distance is 27.0 m. Due to a large number of arrivals at the main exit within a short period of time, on average the agents spent 28.3 s in congestion which accounts for 43% of their average individual evacuation time (65.3 s).

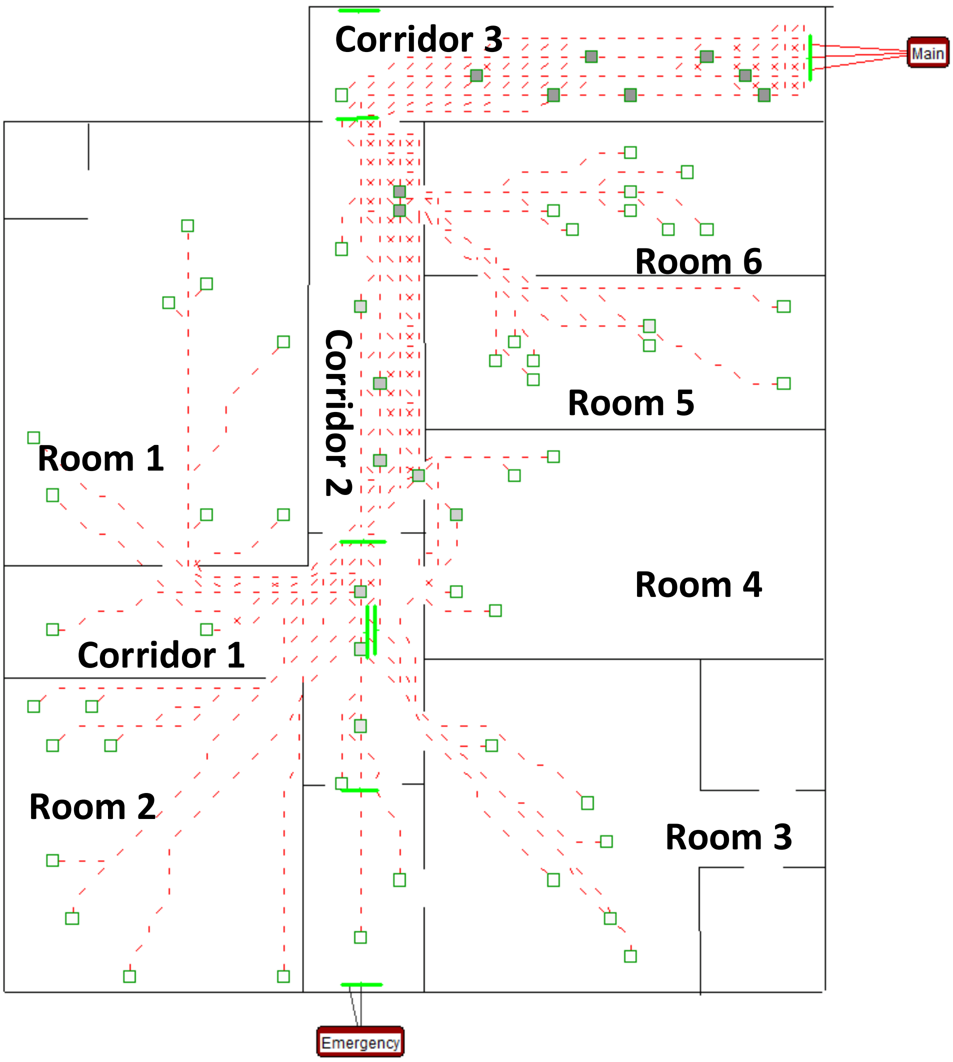


Figure 5.27: Travel path of agents in Scenario 1.

Scenario 2 represents an ideal situation, where it is assumed that the entire population are aware of all exits. Hence, the agents used both exit to leave the structure. Their choice of exit was based on the comparison of the distance to the two exits, i.e. the agents located in catchment area 1 used the main exit and the agents located in catchment area 2 used the emergency exit to leave the structure (see Figure 5.28).

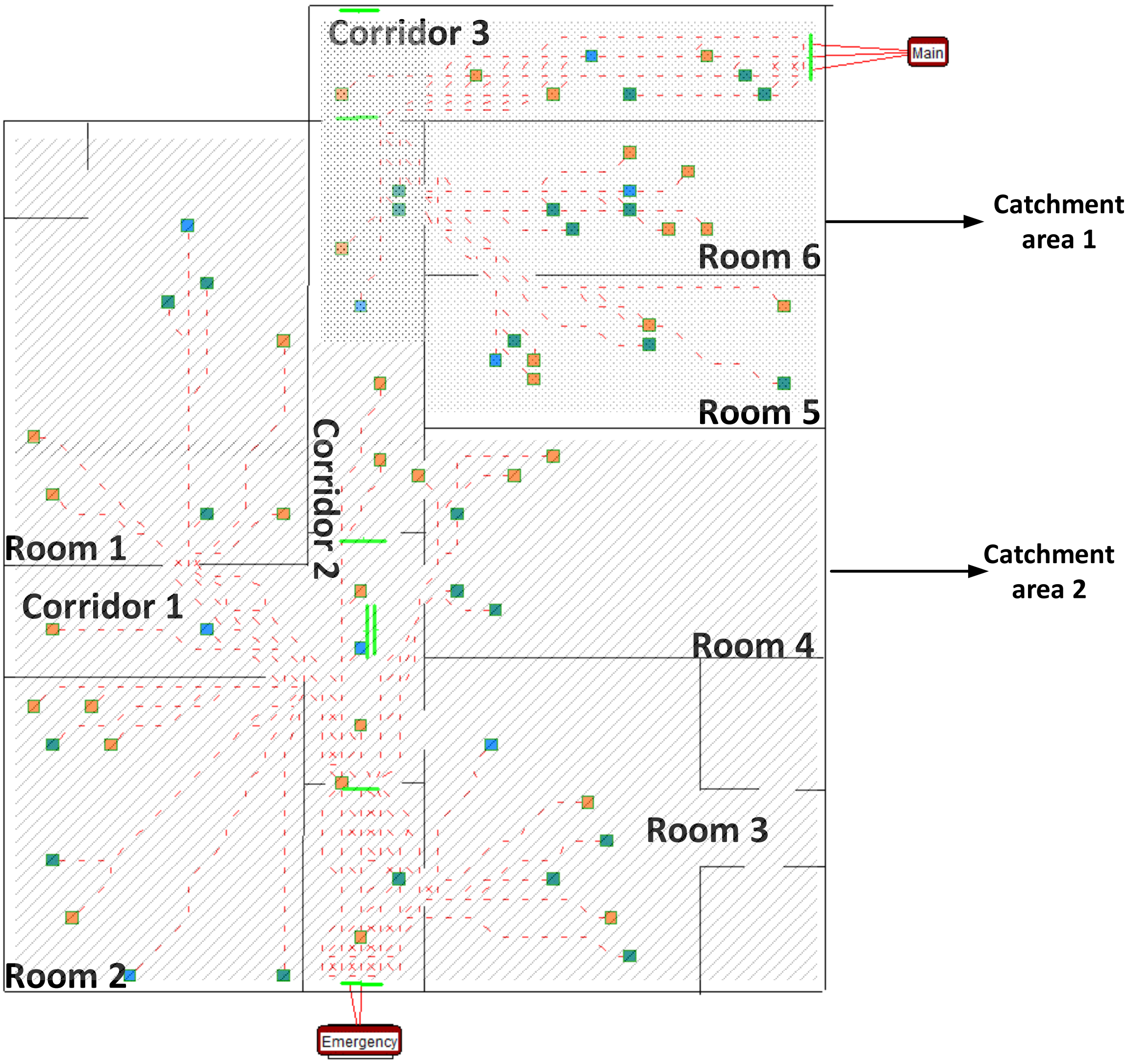


Figure 5.28: Travel path of agents in Scenario 2.

In this scenario, the average travel distance is significantly reduced to 15.1 m, demonstrating that the agents were making use of the full escape capacity of the building. In addition, compared to Scenario 1, the total evacuation time is more than halved to 46.6 s. The average time spent in the congestion is also substantially reduced to 1.5 s which accounts for 5% of their average individual evacuation time.

Due to the assumption that the entire population are aware of all exits, this scenario produces the most optimal results possible in an evacuation. In a more realistic situation, it cannot be assumed that the entire population are aware of all the available exits. In order to compensate the lack of familiarity with the building layout among building occupants, signage is used to allow occupants to effectively wayfind to an exit. This is further discussed in analysing the simulation results of Scenario 3.

In **Scenario 3**, a complete signage system recommended by BS 5499-4:2013 is introduced. BS 5499-4:2013 provides the guidelines on the design and location of escape route signs and advice on the use of arrows to provide directional information. In this scenario, the signage detection probability and compliance probability are set to be 100%. This means when an agent enters the VCA of a sign, he has a 100% chance of detecting and following the information provided by the sign.

In this scenario, two agents located in catchment area 1 (circled red, see Figure 5.29) detected sign S5 and followed the emergency escape route signage chain, i.e. sign S5, S3, S2 and then sign S1. Finally, they left the structure using the emergency exit. All the agents in catchment area 2 followed the emergency escape route signage chain and used the emergency exit (see Figure 5.29).

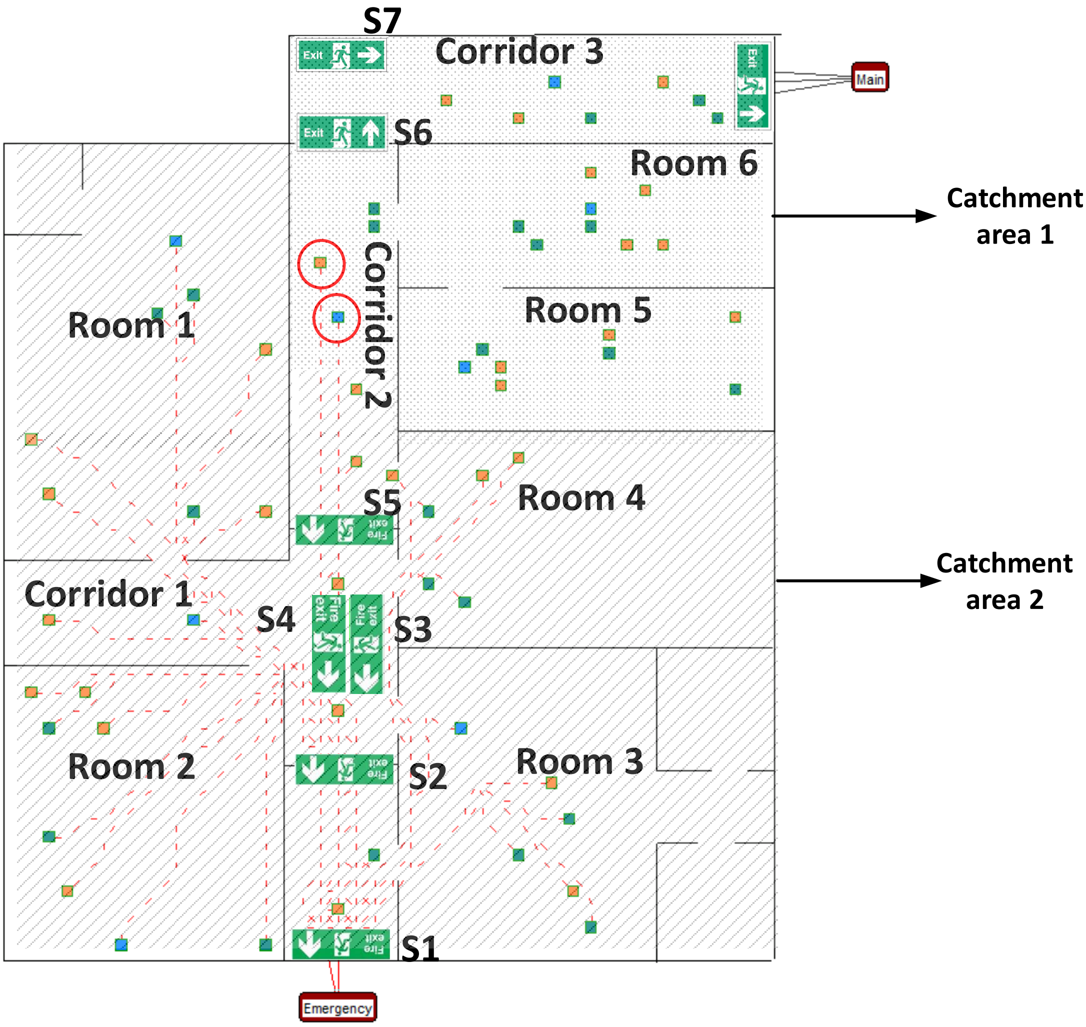


Figure 5.29: Travel path of agents in Scenario 3.

In this scenario, the total evacuation time is 46.9 s which is 1% more than the total evacuation time in Scenario 2 (entire population used the nearest exit) and 60% smaller than that of Scenario 1 (entire population used only the main exit). When compared to Scenario 1, the use of signage system (with a 100% signage detection probability and a 100% compliance probability) in an evacuation led to a large number of agents using the emergency exits. On comparing the emergency exit usage with Scenario 2, on average 39 agents used the emergency exit compared to 38 agents in Scenario 2. The average congestion time is 94% less than Scenario 1 and 17% more than Scenario 2. The average individual evacuation time is 1% more than Scenario 2 and 54% less than Scenario 1.

By introducing signage, Scenario 3 achieved the same level of optimal evacuation performance as in Scenario 2. However, Scenario 3 is based on an assumption that occupants will perceive and follow a sign when it is physically visible. In a more realistic situation, occupants may miss a sign even it is within visible range and they may also choose not to follow a sign. This is further discussed in analysing the simulation results of Scenario 4.

Scenario 4 is similar to Scenario 3 except the use of empirical data in the settings of signage detection and compliance probabilities in Scenario 4. Xie *et al.*, [2012] collected empirical data on the signage detection and compliance probabilities. The data was included in the buildingEXODUS signage model by assigning the detection probability to be 38% and the compliance probability to be 97%. Xie *et al.,* [2012] work focussed on the single sign and it does not cover the detection probability of next sign in a chain.

In this scenario, if the agents are located within the VCA of a sign and travelling in the general direction of the sign, there is a 38% chance that they will detect the sign and a 97% probability that they will follow the signage information. In this scenario, due to the lower detection probability compared to Scenario 3, some agents originally located within catchment area 2 missed the emergency escape route signage chain and went to the main exit. For instance, an agent located in room 1 (circled red in Figure 5.30) left the room 1 and entered the corridor 1 but did not detect sign S4 and S5. This agent used the main exit to leave the structure. All the other agents located in catchment area 2 used the emergency escape route signage chain to find the emergency exit. All the agents in catchment area 1 used their knowledge of the main exit or the circulation signage chain to leave through the main exit (see Figure 5.30).

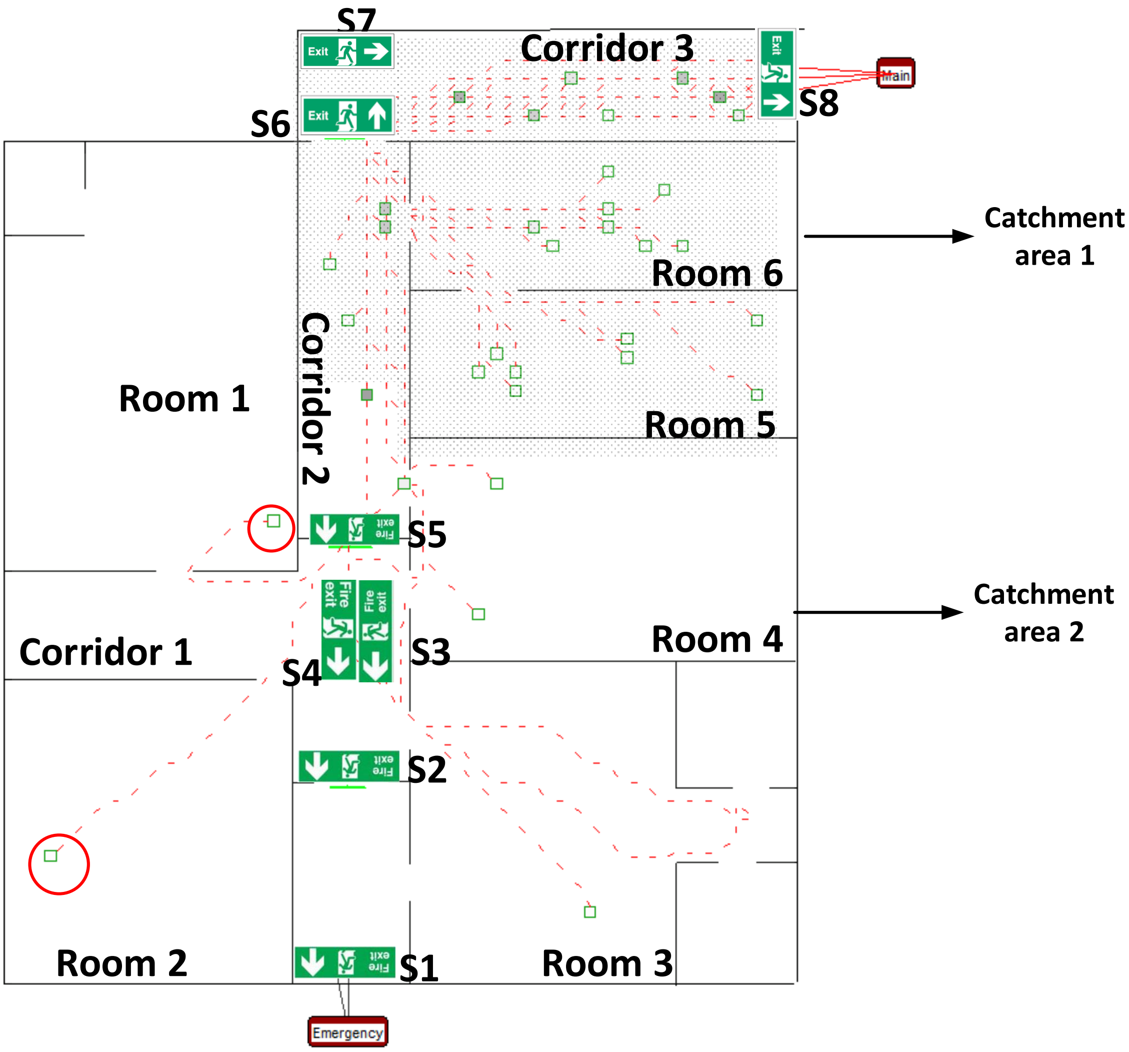


Figure 5.30: Travel path of agents in Scenario 3.

Due to the lower detection probability, the average usage of emergency exits is reduced to 34 which is 13% less than that of Scenario 3. The agent's average distance travelled is increased to 17.8 m which is 18% more than that of Scenario 2 and 3. The average total evacuation time is also increased to 55.5 s compared to 46.9 s in Scenario 3. In this scenario, the average total evacuation time is 53% less than Scenario 1.

The results from Scenario 3 and Scenario 4 demonstrate that signage system can be very useful in guiding the agents who are not familiar with the interior layout of the structure to emergency exits. Using signage system in a structure improves the evacuation performance. Scenario 3 is an ideal scenario based on an assumption in the interaction with signage. In this scenario, the signage detection probability and compliance probability are set to be 100%. Scenario 3 demonstrates that using the signage system, the total evacuation time and average distance travelled can be reduced to the same level as the most optimal evacuation solution, i.e. Scenario 2. Scenario 4 is similar to Scenario 3. The difference is that Scenario 4 uses the empirical data for the signage detection and compliance probabilities. According to this data, 38% of the occupants would detect a sign within visible range and 97% of those who detect the sign follow the sign. The lower detection probability (38%) results in slightly less optimal evacuation performance compared to that achieved in Scenario 3.

Lastly, qualitative validation demonstrates the comparison of predicted human behaviour with informed expectations and it signifies whether the model is able to produce realistic behaviours. In Scenario 1, the entire population used only the main exit to leave the structure. It was expected from this scenario to produce the worst total evacuation time. Scenario 2 is an idealistic but unrealistic scenario where all agents used all the available exits in the structure. The expectation from Scenario 2 was to produce the most optimal evacuation result. Both cases generated the broad scale of possible total evacuation times. The aim of introducing signage in Scenario 3 was to achieve the evacuation results of Scenario 2. This scenario was hypothetical as it considered the idealistic 100% detection probability and compliance probability. Due to the high value of detection probability, it was expected from this scenario to achieve the evacuation performance comparable to Scenario 2. Lastly, Scenario 4 is a more realistic scenario as it included the empirical data in the setting of the signage detection probability and compliance probability. It was expected from this scenario to produce the results which fall between Scenario 1 and Scenario 2/3. Finally, the results achieved in each scenario agreed with the informed expectations and produced realistic behaviour. Hence, the new signage-based navigation model can be used with confidence as it is validated against the demonstration case of BS 5499-4:2013.

5.5 Summary

This chapter started with a brief discussion on the significance of verification and validation. The verification is a process to verify that the implemented model is working as it is designed. The validation involves systematical comparison of the model predictions with informed information. The process of validation consists of component testing, functional validation, qualitative validation and quantitative validation.

Validating an evacuation model is a challenging task as no measure of successful validation will prove their correctness. Therefore, the credibility of the implementation is established through validating the model frequently in the diverse range of cases. Currently, there is a lack of quantitative validation data for evacuation models as a substantial number of evacuation trials are not conducted for the validation purposes.

The new signage-based navigation model was first verified through individual component tests and then validated as whole. In the component tests, all the major modules of the model were tested. In total, there were five component tests performed which are:

- Navigation Strategy 1 (NS1): Agent navigation with full or partial familiarity
- Navigation Strategy 2 (NS2): Agent following the signs along the escape route
- Navigation Strategy 3 (NS3): Agent with no previous or invalidated familiarity or exit knowledge
- Agent's following the signage direction
- Adaptive navigation behaviour using memory

The new signage-based navigation model passed all verification tests.

Lastly, the new signage-based navigation model was validated as a whole against one of the BS 5499-4:2013 demonstration cases. Qualitative validation demonstrates the comparison of predicted human behaviour with informed expectations.

For validation of the new model, four distinct scenarios were designed.

- In Scenario 1, no signage information was used. The entire population using their previous knowledge of the main exit utilised the main exit only in the simulation.

- In Scenario 2, it was assumed that all agents are aware of all exits. Hence, all the agents used the nearest available exit from their starting location. This scenario produced the most optimal evacuation results.

- In reality, it would be unlikely that the entire population is familiar with the structure like Scenario 2. Hence, to provide the knowledge of an exit/nearest emergency exit, a signage system is introduced in Scenario 3. The aim is to achieve the same optimal results as in Scenario 2. In this scenario it is assumed that agents will sees and follow the signs if they are within visible range, i.e. a 100% signage detection probability and a 100% signage compliance probability are assumed.

- Scenario 4 is a more realistic scenario which uses the empirical data for the signage detection and compliance probabilities [Xie *et al.*, 2012] compared with Scenario 3. This means even when an agent is within the VCA of a sign and travelling in the general direction of the sign he has a 38% chance of detecting the sign and if detected, a 97% chance of complying with the signage information.

The results from Scenario 3 and Scenario 4 demonstrated that the correct use of escape route signage system based on BS 5499-4:2013 to guide occupant in an evacuation can effectively reduce the total evacuation time. When compared to Scenario 2, the results of Scenario 3 demonstrated that total evacuation time can be reduced to a level which can be compared to a situation where the entire population have perfect knowledge of the structure (Scenario 2). However, in a more realistic situation as demonstrated through Scenario 4 in which a lower signage detection probability was used, an increase in total evacuation time and a reduced usage of emergency exits were noticed. Lastly, the results achieved in each scenario agreed with the informed expectations and produced realistic behaviour.

Chapter 6 The Demonstration Case

6.1 Introduction

In Chapter 5, the new signage-based navigation was verified through a series of component tests and qualitative validation. The verification and validation established the confidence in the new model to simulate the agents' wayfinding behaviour with/without using the chain of signs in a built environment. In this chapter, the new model is further examined through a large evacuation case using a hypothetical day care centre geometry. The aim of implementing this case is to demonstrate the capability of the model in simulating a full-scale evacuation from a more complex built environment.

The new model improved the representation of the interaction between agents and signage, especially the behaviour of following the signs along the escape routes. Hence, in order to demonstrate the improvement of the new model in simulating the impact of signage system on agent wayfinding during an evacuation in a complex built environment, a structure with multiple escape routes was required. In Section 6.2, the structure used for the demonstration case is discussed. The demonstration case is a hypothetical single floor structure containing a number of rooms, corridors, one main exit and several emergency exits. In this section, the way of populating the structure with agents is also explained. A total of 283 agents are used in the simulations to represent a general population. The identification of the escape routes and the subsequent planning of the signage system are explained in Section 6.3. In Section 6.4, four simulation scenarios designed are discusses. An overview of these four scenarios are as follows:

1. **Main exit usage:** In this scenario, no signage information is included. The entire population are familiar with the main exit only. Hence, all agents will use the main exit to evacuate.

2. **All exits usage:** Like the first scenario, this scenario also does not represent the interaction between the agents and signage. It is assumed that the entire population have full knowledge of all the exits. Hence, all agents will use the nearest available exit to evacuate.

3. **Introduction of signage in the demonstration case:** In this scenario, all agents have the partial familiarity with the main exit in the structure. However, the agents can now use the signage information to find an available exit.

4. **No previous familiarity or invalid exit knowledge:** All the agents have no previous familiarity with any exits. Hence, to find an exit, the agents execute their searching behaviour until they find an exit/sign.

Lastly, the results of running the simulations using the new model and buildingEXODUS for the above four scenarios are compared and discussed in Section 6.5.

6.2 Geometry and population

Figure 6.1 shows the geometry which is based on a hypothetical single floor building. It contains 29 rooms, 2 halls and 6 corridors. There are 6 exits, one main exit situated in the middle and 5 emergency exits located at three ends of the building. The total area of the geometry is 1308 m^2.

An arbitrary 283 agents are used in the demonstration case to represent a general population. These agents are randomly generated and distributed throughout the geometry using the buildingEXODUS feature called panel populate with default travel speed ranging from 1.2 m/s to 1.5 m/s. It is also assumed that all occupants are fit with full mobility (no movement disabilities) and they require between 0 to 30 seconds to respond to an evacuation alarm. The average height of the occupants is assumed to be 1.75m when calculating the extent of the VCAs of the signs.

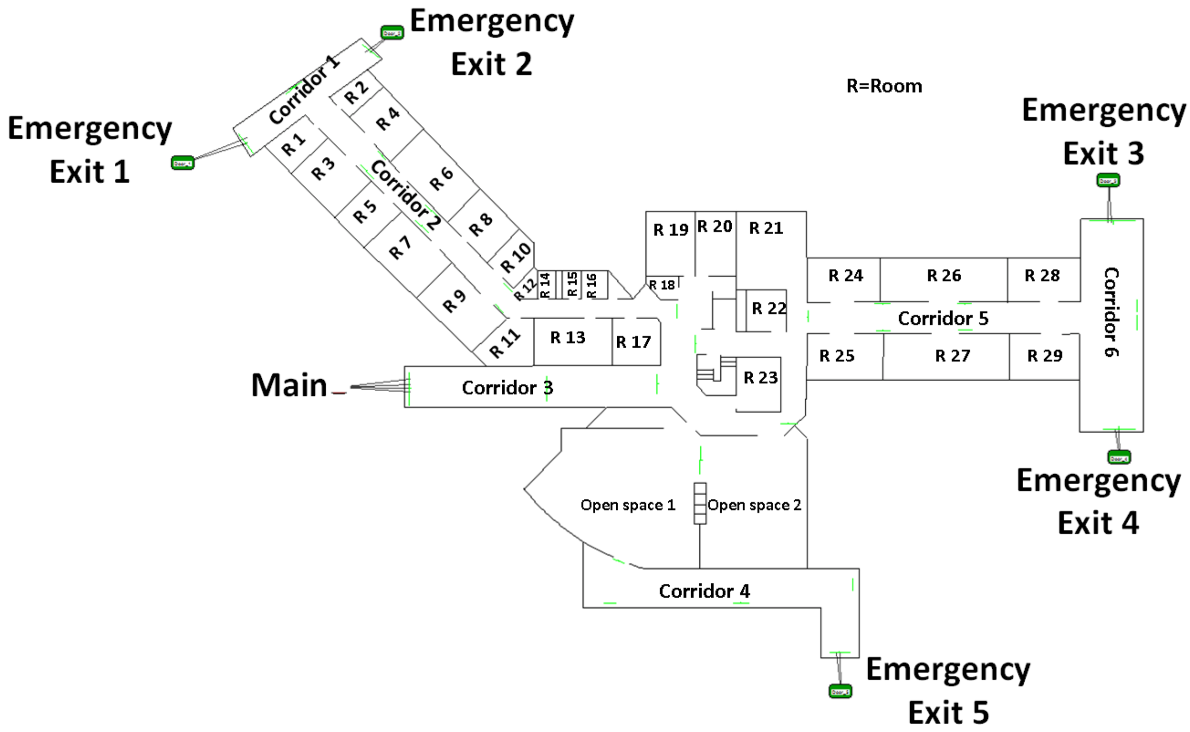


Figure 6.1: The geometry used for the demonstration case.

Lastly, the generated navigation graph for the above structure is depicted in Figure 6.2.

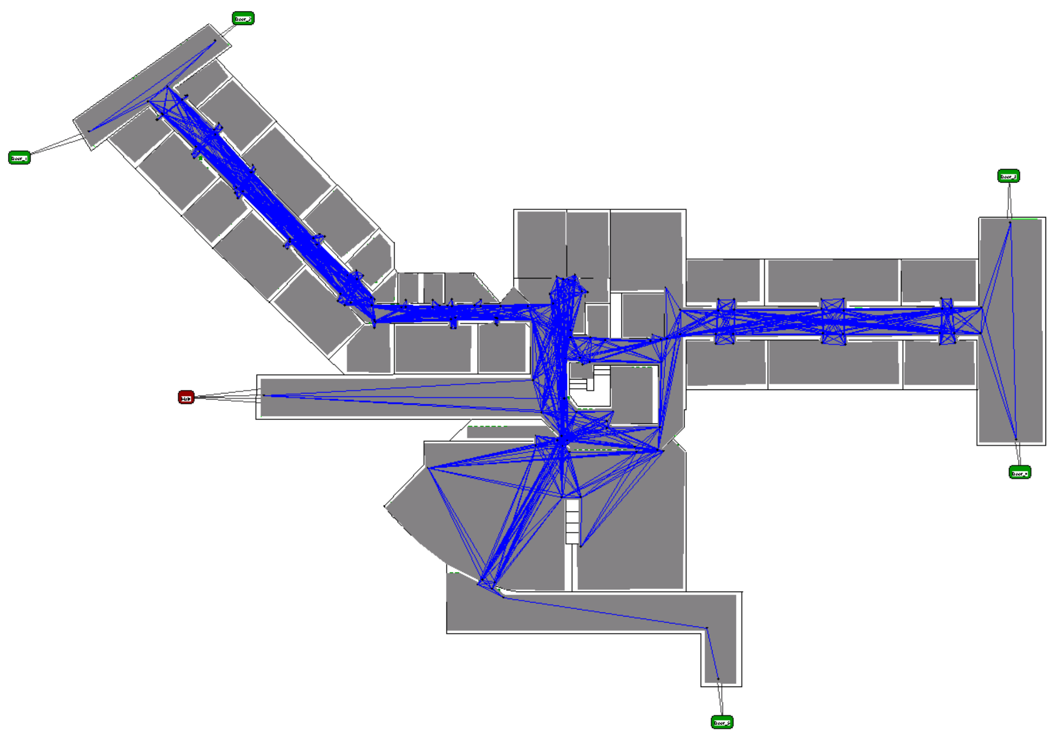


Figure 6.2: The generated navigational graph for the demonstration case.

6.3 Identify escape routes and plan signage system

According to the UK signage standards [BS 5499-4, BS 5499-10] and international standards [BS ISO 3864-1, BS EN ISO 7010], first and foremost, the escape routes must be identified before planning a signage system for a structure. According to BS 5499-4:2013, an escape route provides a means of escape from any place within a premise to an exit or a place of safety. In general, there are multiple escape routes in a built structure due to the complex layout and the requirement for additional exit capacity through providing multiple exits (such as emergency exits). This will also help the occupants select alternative escape route in case of losing any part of the escape routes due to structural collapse, fire or smoke. Furthermore, any escape route within the premises should normally have the shortest travel distance to a place of safety.

buildingEXODUS allows the model user to view the catchment area of each exit which represents the particular region within which the agents should use the corresponding nearest exit. The catchment areas of the six exits are shown in Figure 6.3. Catchment area 1 is associated with emergency exit 1 and 2. This implies that emergency exit 1 and 2 are the nearest exit for all agents located in catchment area 1. Furthermore, an agent located in catchment area 2 will attempt to leave the structure using the main exit.

It should be noted that due to the layout of the geometry, both emergency exit 1 and 2 are associated with catchment area 1. Emergency exit 3 and 4 are associated with catchment area 4. Hence, in the analysis of simulation results, the usage of the emergency exit 1 and 2 will not be examined separately. This means the usage of emergency exit 1 and 2 will be considered together. Similarly, the usage of emergency exit 3 and 4 will also be considered together.

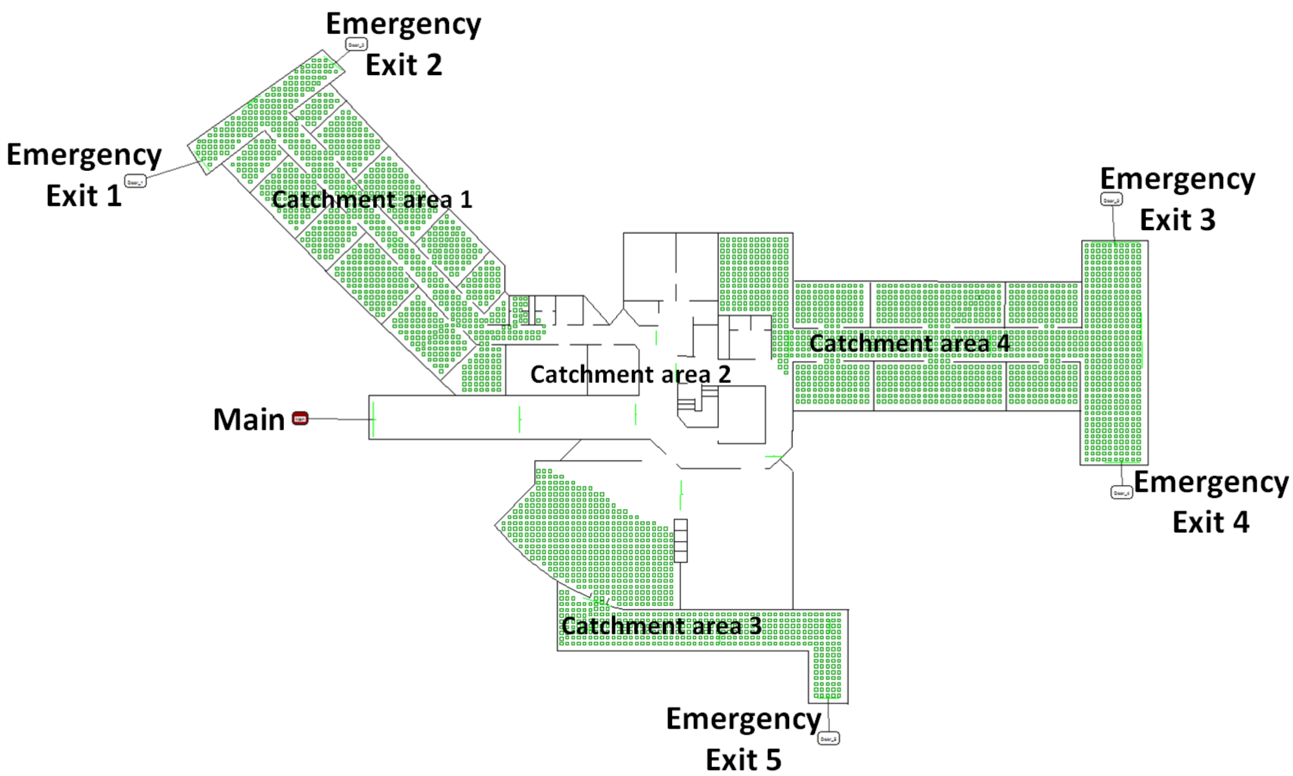


Figure 6.3: Generated catchment areas for the main exit and emergency exits using buildingEXODUS.

Table 6.1 shows each catchment area, the associated exit and the number of agents initially located within each catchment area.

Table 6.1: Catchment areas and associated exits.

Catchment area	Associated exit	Number of agents in each catchment area
Catchment area 1	Exit 1 and Exit 2	59
Catchment area 2	Main exit	94
Catchment area 3	Exit 5	46
Catchment area 4	Exit 3 and Exit 4	84

As previously discussed in the literature review (Chapter 2, Section 2.4), due to the complex internal layout of the building the exits may not be directly visible from most of the places within the premises and the escape routes leading to the exits may not be easily recognizable, especially those escape routes designed for emergency evacuation. This wayfinding problem is commonly addressed by providing escape route signing system which indicates the directions of the means of escape to allow occupants to escape without assistance [BS 5499-4:2013, BS EN ISO 7010]. The UK standards [BS 5499-4, BS 5499-10] and international standards [BS ISO 3864-1, BS EN ISO 7010] provide guidelines for planning and implementing escape route signage system.

Here the British signage standard BS 5499-4:2013 is used to guide the designing of the signage system for the geometry used in the demonstrate case. In each catchment area, a series of signs should be placed to guide the agents towards the exit(s) associated with each catchment area. For instance, in catchment area 1, the signs should be installed along escape route to guide the agents towards emergency exit 1 and 2, so do the signs in the other region of the geometry. The planning of the signage system for the four catchment areas according to BS 5499-4:2013 is now discussed.

Catchment area 1 includes two corridors that forms a T-junction and several rooms around the T-junction (see Figure 6.3). BS 5499-4:2013 provided 22 cases in Annex A to illustrate the correct use of escape route signs in various typical situations. The 19th case shows a T-junction corridor in a building offering alternative equidistant paths (see Figure 6.4). In this case, four signs are required to indicate the two routes. Sign 1 and 2 indicate the change in direction and sign 3 positioned above the doors indicated the final exits. Catchment area 1 includes the same type of T-junction corridor (see Figure 6.5). Hence, a similar signage configuration is adopted. Sign S7 and S8 are added to indicate the change in travel direction. Sign S9 and S10 are positioned above emergency exit 1 and 2 respectively.

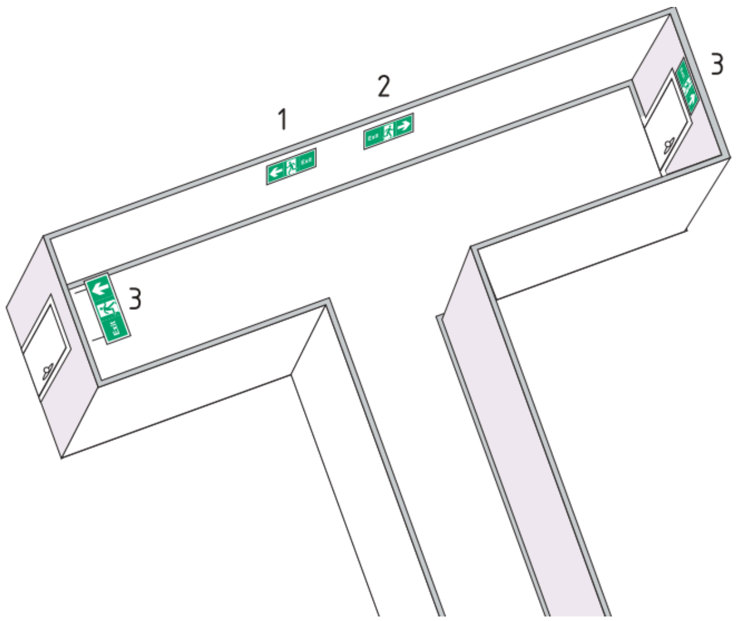


Figure 6.4: BS 5499-4:2013 case number 19 showing T-junction corridor with four signs.

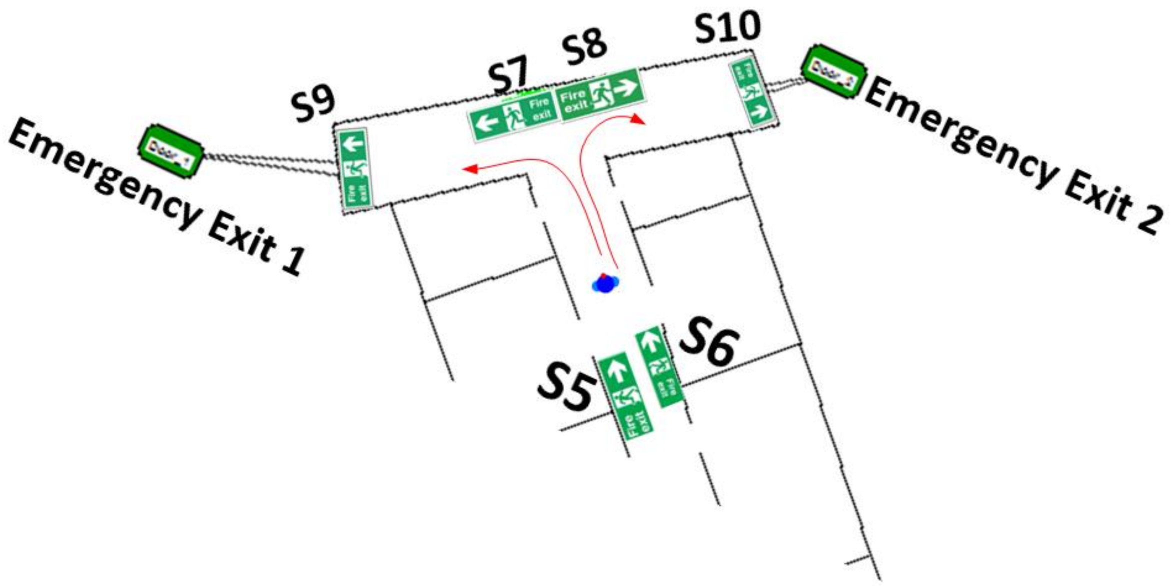


Figure 6.5: The T-junction in catchment area 1 and the signs installed.

The fourth case in BS 5499-4:2013 shows two exit signs positioned on the wall to indicate the escape direction of progressing forward towards the end of the stairway (see Figure 6.6). Similarly, in order to indicate the direction of progressing forward towards the end of the corridor in catchment area 1, three pairs of escape route signs, S1/S2, S3/S4 and S5/S6 are installed on the wall along the corridor towards the T-junction (see Table 6.2 signage in catchment area 1).

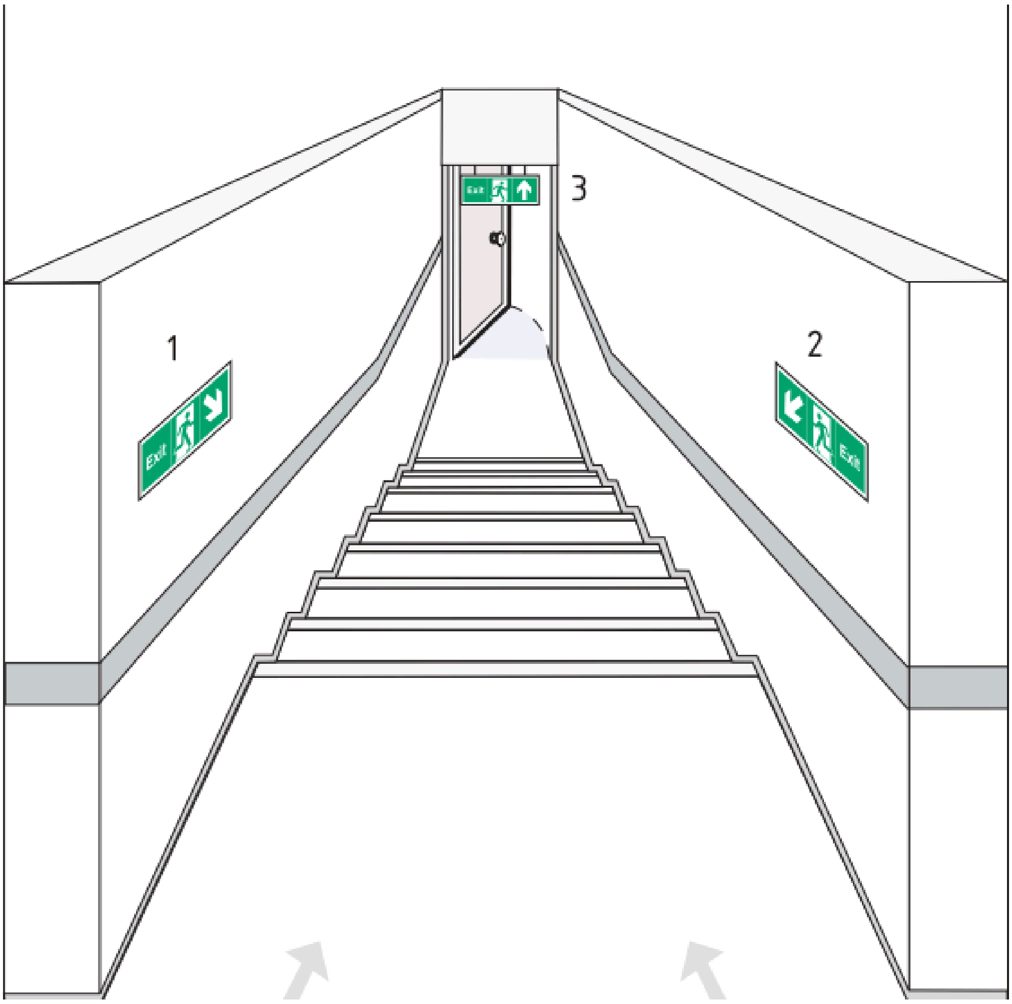


Figure 6.6: BS 5499-4:2013 case number 4 with two signs on the wall indicating the direction of progressing forward.

Catchment area 2 includes a long entrance corridor, the circulation area in the middle of the geometry, several rooms and a hall at the bottom right corner (see Figure 6.3). The main exit is the only exit associated with catchment area 2, i.e. the main exit is the nearest exit for anyone located within this region. Therefore, the exit signs within catchment area 2 should indicate the route towards the main exit. The main exit is mainly used for normal circulation; hence, a series of non-emergency exit signs are installed in this area. The 10th case in BS 5499-4:2013 demonstrates a corridor with an exit at the end of the corridor (see Figure 6.7). This case advises installing the signs suspended in the corridor pointing at the door. Hence, in catchment area 2, sign S15 is installed over the exit main. Sign S13 and S14 hanging in the corridor indicate the non-emergency route via the main exit (see Table 6.2 signage in catchment area 2).

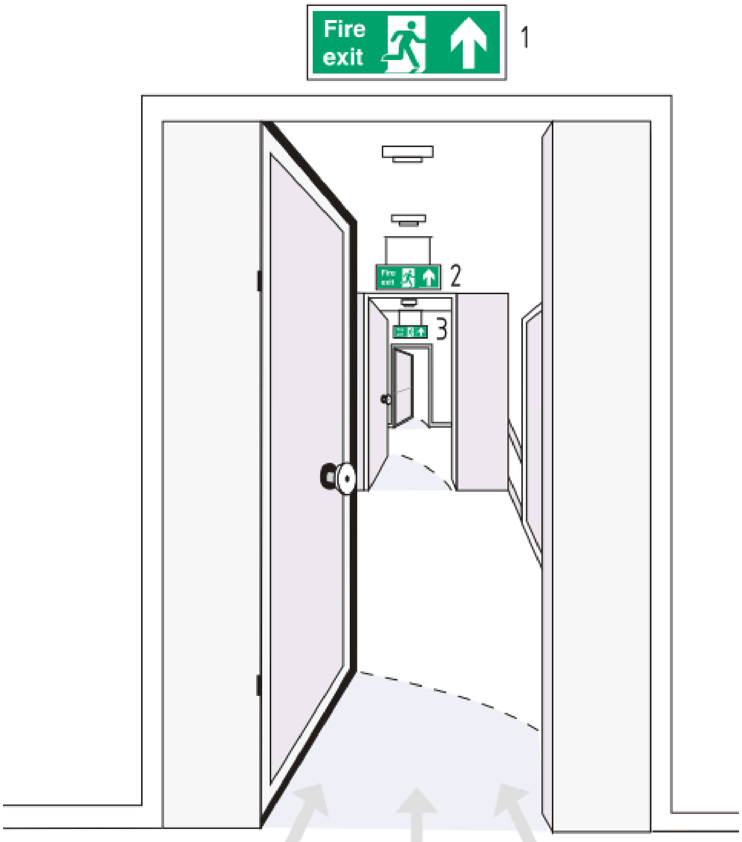


Figure 6.7: Case number 10 in BS 5499-4:2013.

BS 5499-4:2013 advises to suspend signs in a corridor where a change of direction is required. The 12th case shows a corridor where a change of direction is required at the end of the corridor (see Figure 6.8). In catchment area 2, sign S11, S12 and S16 hanging in the corridor are added to indicate the change in direction (see Table 6.2 signage in catchment area 2).

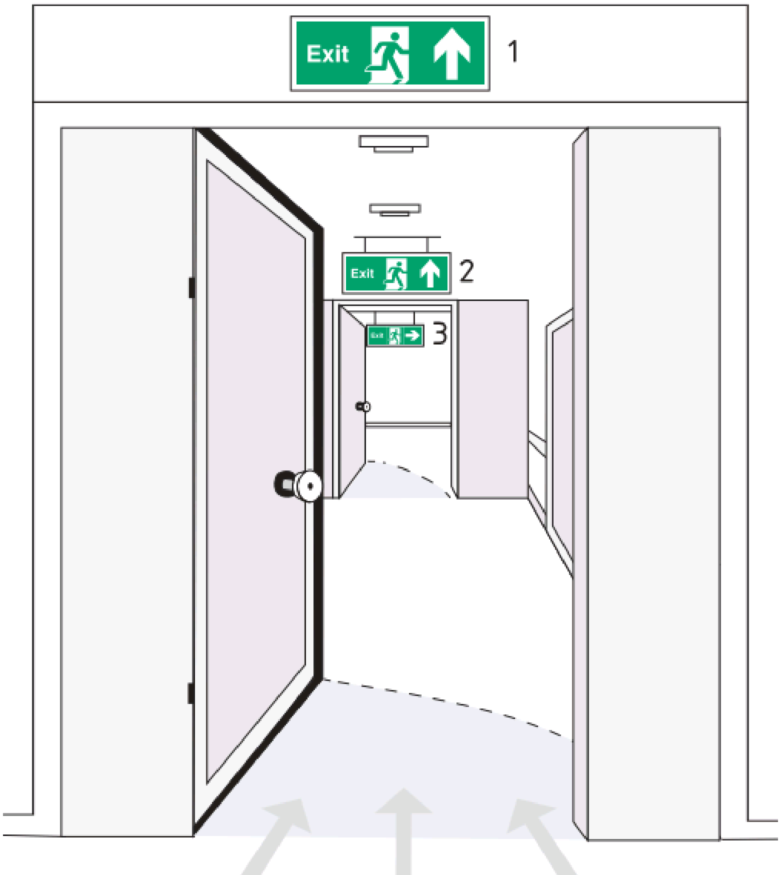


Figure 6.8: Case number 13 in BS 5499-4:2013. Sign 3 indicates a change of direction.

BS 5499-4:2013 advises suspending a sign in an open space. The 17th case shows an open space with a sign hanging from the celling indicating to move forward and across to the right to find an exit (see Figure 6.9). Catchment area 2 also includes an open space (the hall at the bottom right corner). Hence, sign S17 is added to direct the agents to move from the open space towards sign S13 and eventually towards the main exit (see Table 6.2 signage in catchment area 2).

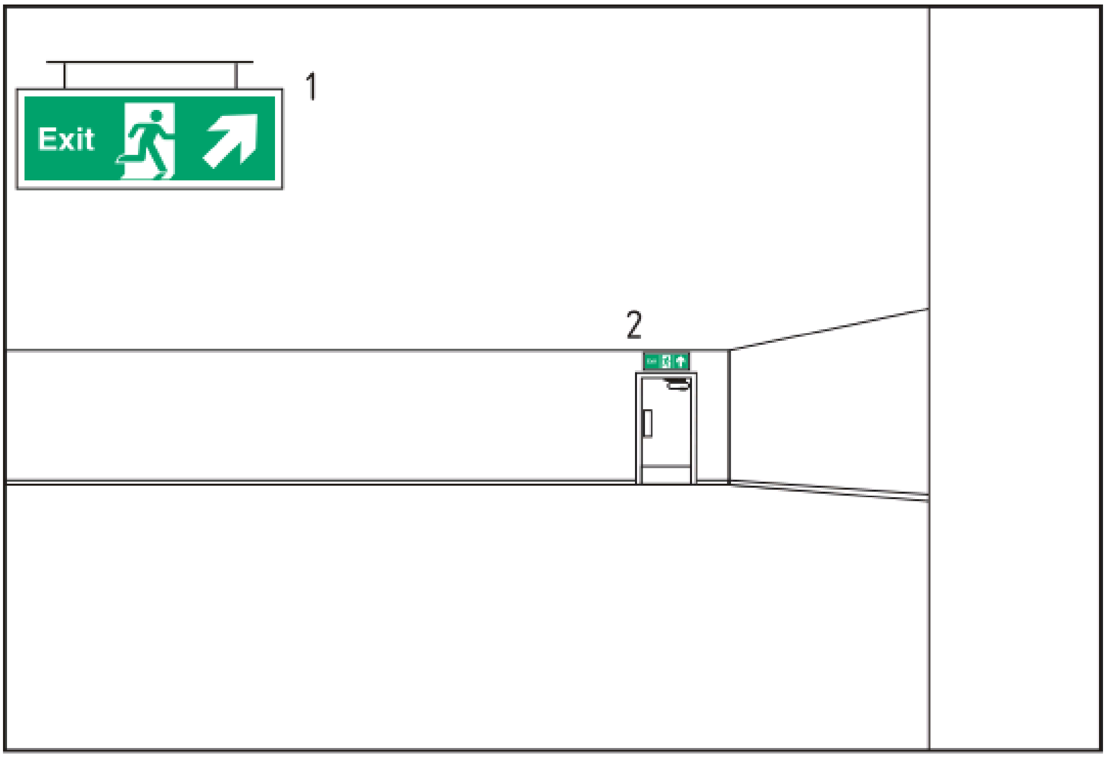


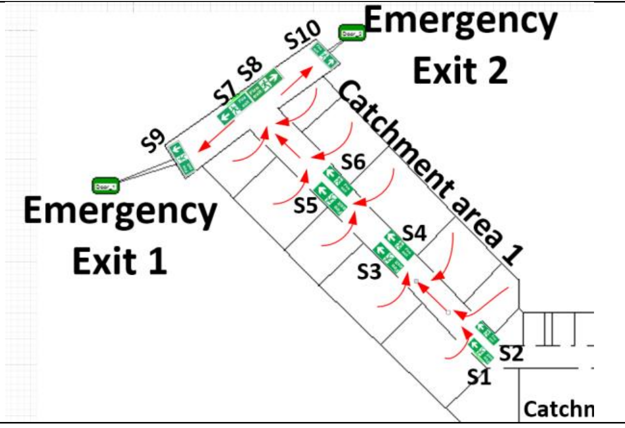
Figure 6.9: Case number 17 in BS 5499-4:2013 with hanging Sign 1.

Catchment area 3 includes an ‘L’ shape corridor and a hall at the bottom left corner of the geometry (see Figure 6.3). A series of escape route signs are installed in this catchment area which is associated with emergency exit 5. Sign S23 is positioned above emergency exit 5. To reach the emergency exit 5, a change in direction is required in the ‘L’ corridor. Hence, sign S22, S21 and S20 are placed in the corridor to indicate the escape route via exit 5. Catchment area 3 also includes an open space (i.e. the hall). Sign S18 and S19 are added to guide the agents towards the corridor (see Table 6.2 signage in catchment area 3).

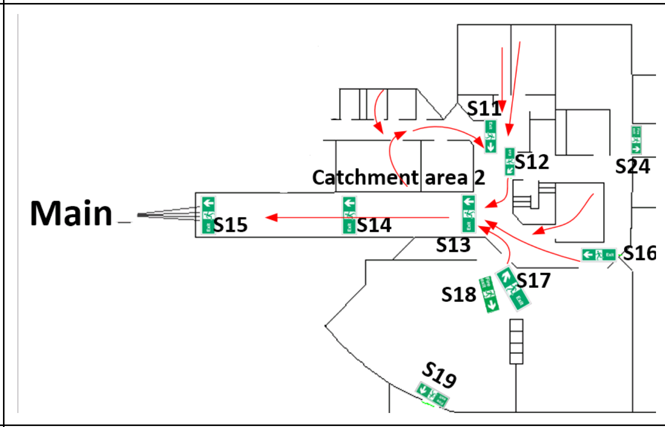
Lastly, catchment area 4 which has a similar layout as catchment area 1, includes a T-junction, a number of rooms and part of the circulation space in the model of the geometry. Escape route signs are installed for catchment area 4 associated with emergency exit 3 and 4. In this area, corridor 6 is a T-junction corridor. Hence, similar to the 19th case of BS 5499-4:2013 (see Figure 6.4), sign S31 and S32 are positioned above emergency exit 3 and 4 respectively, while sign S29 and S30 are added to indicate the change in travel direction. Similar to the 4th case in BS 5499-4:2013 five escape route signs, S24, S25/S26 and S27/S28 are installed in the corridor to indicate the escape route via emergency exit 3 and 4 (see Table 6.2, signage in catchment area 4). Table 6.2 shows the exit signs planned for each catchment area.

Table 6.2: Signage planned in each catchment area.

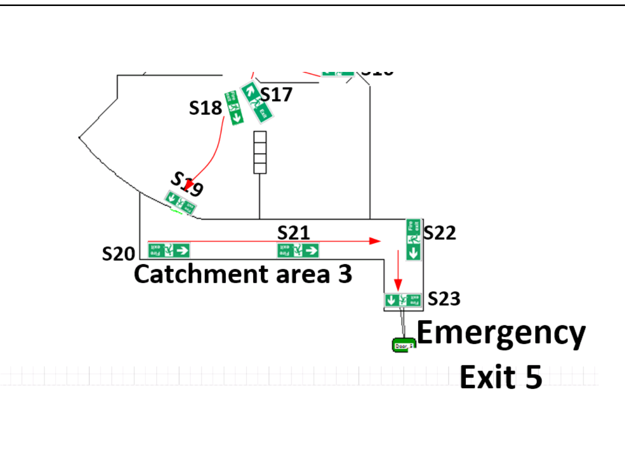
Signage in Catchment area 1



Signage in Catchment area 2



Signage in Catchment area 3



Signage in Catchment area 4

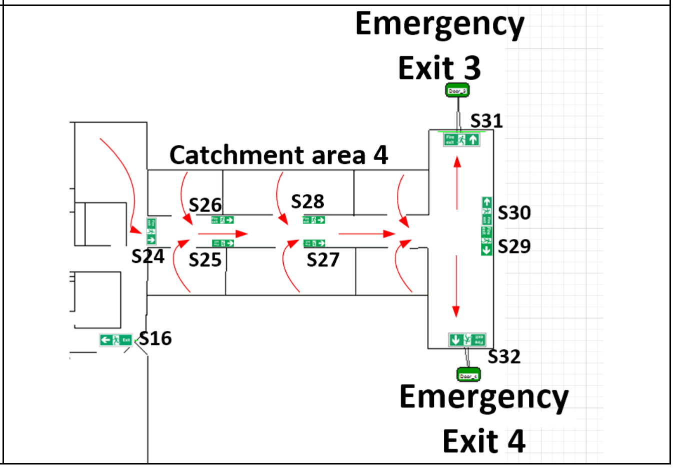


Table 6.3 lists the signs in each catchment area.

Table 6.3: Chain of signs in each catchment area.

Catchment area	Associated exit	Signs	Type of sign
Catchment area 1	Emergency exit 1	S1, S3, S5, S7, S9	Escape route signs
	Emergency exit 2	S2, S4, S6, S8, S10	Escape route signs
Catchment area 2	Main exit	S11, S12, S13, S14, S15 S16, S17, S13, S14, S15 S17, S13, S14, S15	Non-emergency signs
Catchment area 3	Emergency exit 5	S18, S19, S20, S21, S22, S23	Escape route signs
Catchment area 4	Emergency exit 3	S24, S26, S28, S30, S31	Escape route signs
	Emergency exit 4	S24, S25, S27, S29, S32	Escape route signs

The complete signage network of the demonstration case is shown in Figure 6.10.

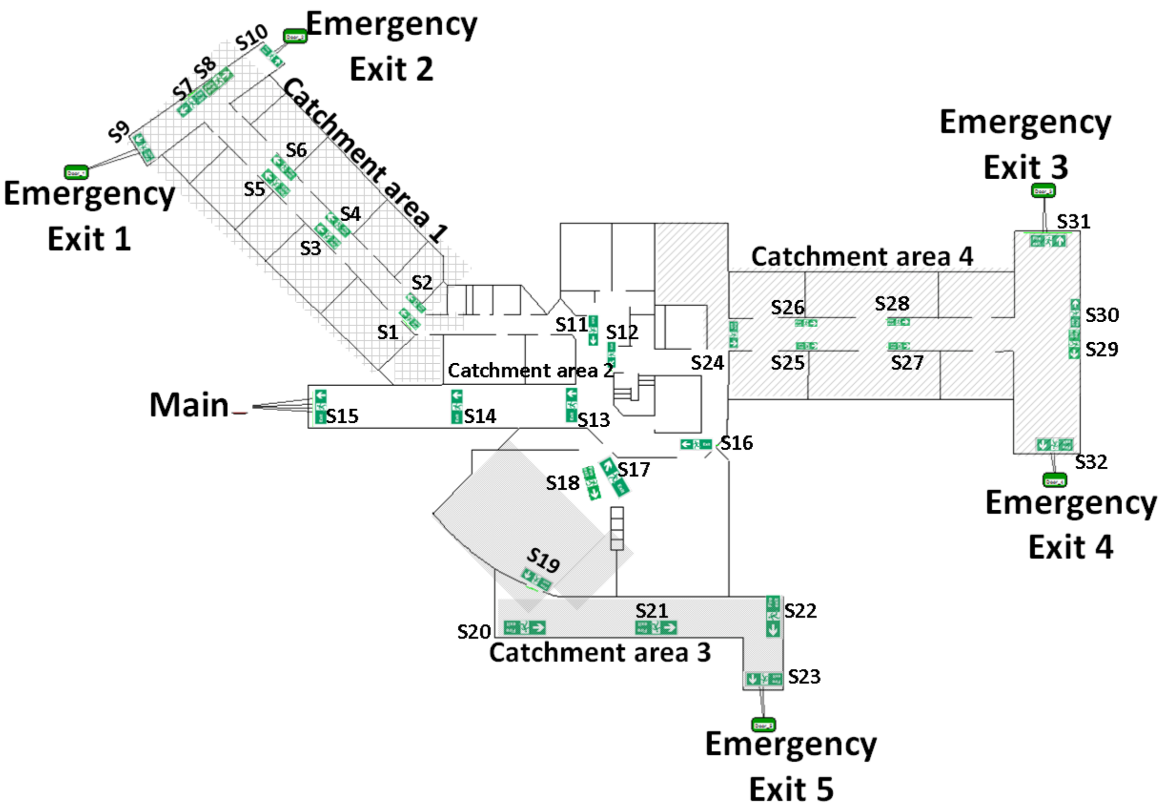


Figure 6.10: Complete signage network in the demonstration case.

Lastly, all of the installed signs are externally illuminated with a vertical illuminance of 100lux [BS 5499-4:2013]. The signs are installed 2.2 m high above the floor. The graphical symbol on each sign is 75 mm in height. Hence, each sign installed in the geometry produces a maximum Visibility Catchment Area (VCA) of approximately 13 m^2 [BS 5499-4:2013]. Figure 6.11 shows the VCA coverage of all escape route signs and non-emergency signs cover 756.2 m^2 of floor space and so the main exit or emergency exit can be seen from 43.5% of the floor space.

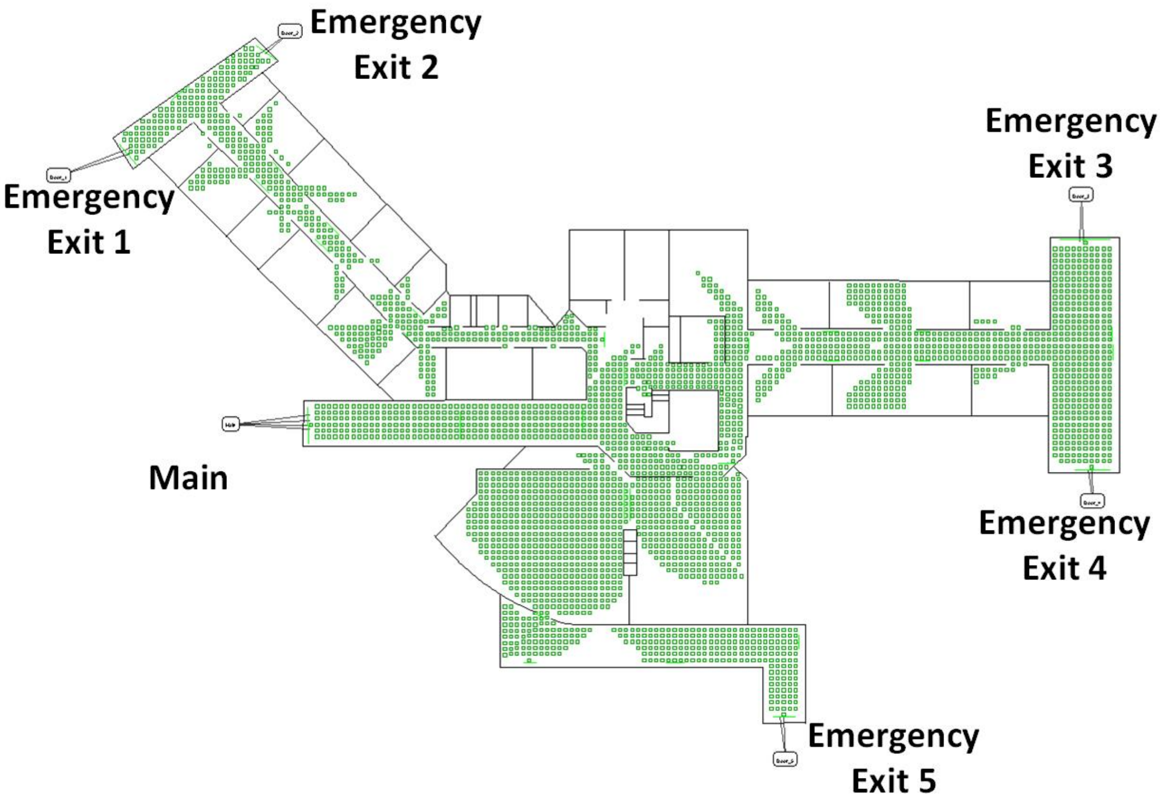


Figure 6.11: The VCA coverage of the escape route signage system in the geometry.

6.4 Simulation scenarios

The new signage-based navigation model is examined through a large hypothetical day care centre geometry. The aim of implementing this case is to demonstrate the capability of the model in simulating a full-scale evacuation from a more complex built environment. Ten simulations are conducted for each case so that statistics can discriminate any differences if they exist. Each repeat simulation involved the same agents located within the same starting locations. The following four scenarios are examined:

Scenario 1: Main exit usage

In this scenario, the entire population are aware of the main exit. Hence, all the agents use the main exit to evacuate the structure and ignore signage information to find available emergency exits. This depicts a scenario where all occupants are familiar with the main exit that is in normal daily use. This scenario is simulated using both the new signage-based navigation model (Scenario 1a) and buildingEXODUS (Scenario 1b).

Scenario 2: All exits usage

In this scenario, it is assumed that the entire population have knowledge of all the exits and hence, they can use their nearest available exit to evacuate the structure. It should be noted that this is an ideal, however, unrealistic scenario which produces the most optimal egress results. Like Scenario 1, this scenario is simulated using the new signage-based navigation model (Scenario 2a) and buildingEXODUS (Scenario 2b). The results produced by the two models are compared with each other to show the similarity in evacuation performance.

Scenario 3: Introduction of signage in the demonstration case

In this scenario, it is assumed that the entire population are familiar only with the main exit. However, during the evacuation, they can use signage to find the emergency exits. In the scenario, the signs are installed in the structure according to BS 5499:4-2013 (see Section 6.3) and the empirical data is used to set the signage detection and compliance probabilities [Xie *et al.*, 2012]. This means when an agent is located within the VCA of a sign, the agent has a 38% chance of detecting the sign and if detected, a 97% chance of complying with the signage information. This scenario is simulated using both the new signage-based navigation model (Scenario 3a) and buildingEXODUS (Scenario 3b).

Scenario 4: No previous or invalidated familiarity or exit knowledge

This scenario is simulated using the new signage-based navigation model. In this scenario, the entire population have no previous familiarity with the exits. Hence, the occupants have to perform search for exit and signage. This scenario has three variations.

Scenario 4a: This is a hypothetical scenario where no signage information is available for the agents. Hence, to find an exit, agents rely purely on their searching behaviour (Chapter 4, Section 4.5.3.1).

Scenario 4b: In a built environment, signage system is commonly used to provide the information indicating the direction and location of escape routes and exits. BS 5499:4-2013 provides the guidelines for the design and plan of escape route signage system. In this scenario, the signage system planned for this geometry in Section 6.3 is used in the simulation to examine the efficiency of the system in a scenario where the agents have no prior exit knowledge. The signage detection probability and compliance probability are set to 100% in the simulation. This represents an ideal application of the signage system that any agents will follow the direction of a sign provided they can physically see the sign.

Scenario 4c: This is similar to Scenario 4b. The only difference is that the empirical data is used for demonstrating the real-world signage detection and compliance probability [Xie *et al.*, 2012]. This means when an agent is within the VCA of a sign, he has a 38% chance of detecting the sign and if detected, a 97% chance of complying with the signage information.

The summary of all four scenarios is presented in Table 6.4.

Table 6.4: Summary of scenarios modelled.

Scenario		**Navigation model**	**Exit knowledge**	**Use of signage**	**Detection probability**	**Compliance probability**
1	1a	New model	Main exit	No	-	-
	1b	buildingEXODUS				-
2	2a	New model	All exits	No	-	-
	2b	buildingEXODUS				-
3	3a	New model	Main exit	Yes	38%	100%
	3b	buildingEXODUS			38%	100%
4	4a	New model	No	No	-	-
	4b	New model		Yes	100%	100%
	4c	New model		Yes	38%	100%

6.5 Simulation results and discussion

Each scenario was run 10 times to produce a range of results. In each case, agents' starting locations were kept constant. Table 6.5 lists the average values with two standard deviations for a few key parameters from the simulations.

Table 6.5: Average evacuation performance of four scenarios.

Scenarios		Navigation model	Total evacuation time (s)	Average congestion time (s)	Average distance travelled (m)	Average individual evacuation time (s)	Average number of agents using emergency exits
1	1a	New model	145.3±1.1	26.3 ± 0.6	52.9 ± 0.2	83.5 ± 0.7	0
	1b	buildingEXODUS	144.6 ± 1.1	27.6 ± 0.7	51.3 ± 0.1	82.8 ± 0.8	0
2	2a	New model	74.5±1.3	4.5 ± 0.3	26.8 ± 0.7	41.3 ± 0.3	191±0
	2b	buildingEXODUS	76.6 ±1.05	4.8 ± 0.1	26.5 ± 0.06	41.5 ± 0.1	191± 0.5
3	3a	New model	112.2 ± 8.4	2.3 ± 0.3	33.4 ± 0.7	44.2 ± 0.7	175± 0.7
	3b	buildingEXODUS	93.9 ± 13.7	2.9±0.3	29.2±0.3	41.7±0.4	195±1.5
4	4a	New model	105.5 ± 3.3	3.3 ± 0.3	40.2 ± 0.8	50.5 ± 0.9	165± 4.3
	4b	New model	78.9 ± 1.7	4.3 ± 0.3	27.8 ± 0.1	41.9 ± 0.4	220±1.1
	4c	New model	105.7±10.0	1.7 ± 0.3	32.3±0.5	42.8 ± 0.5	205±5.8

6.5.1 Scenario 1a and 1b results

Scenario 1a is modelled using the new signage-based navigation model. The entire population evacuated from the structure using the main exit located in the middle of the building. In the early stage of the evacuation, a large number of arrivals at the main exit surpassed the exit flow capacity which led to the congestion around the main exit. In this scenario, on average the agents spent 26.3 s in congestion which accounts for 32% of their average individual evacuation time (83.5 s). The average distance travelled is 52.9 m.

Scenario 1b is modelled using buildingEXODUS. Like Scenario 1a, all the agents evacuated through the main exit. This led to the congestion around the main exit. On average the agents spent 27.6 s in congestion which accounts for 33% of their average individual evacuation time (82.8 s). The average distance travelled is 51.3 m. Figure 6.12 and Figure 6.13 present the mean values.

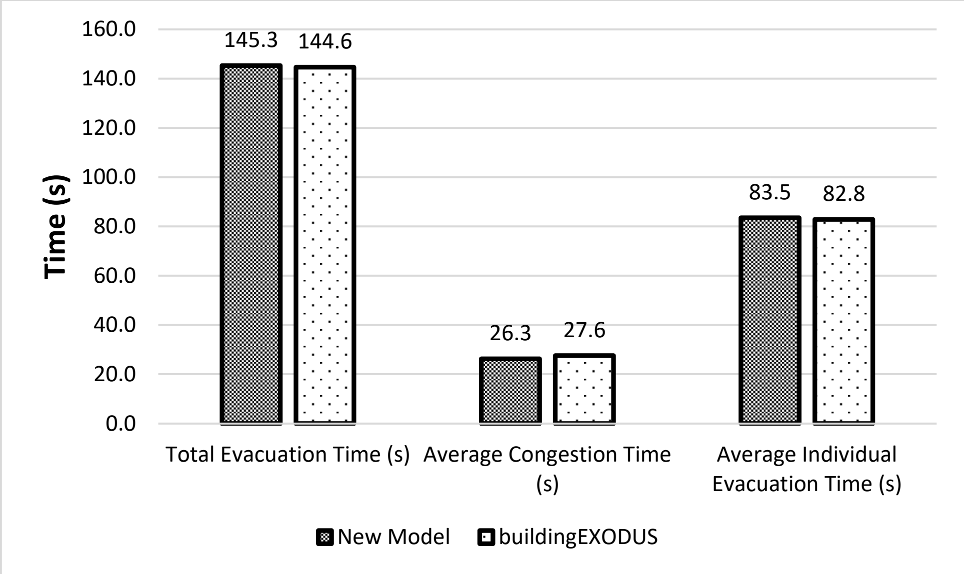


Figure 6.12: Average total evacuation time, average congestion time and average individual evacuation time of Scenarios 1a and 1b.

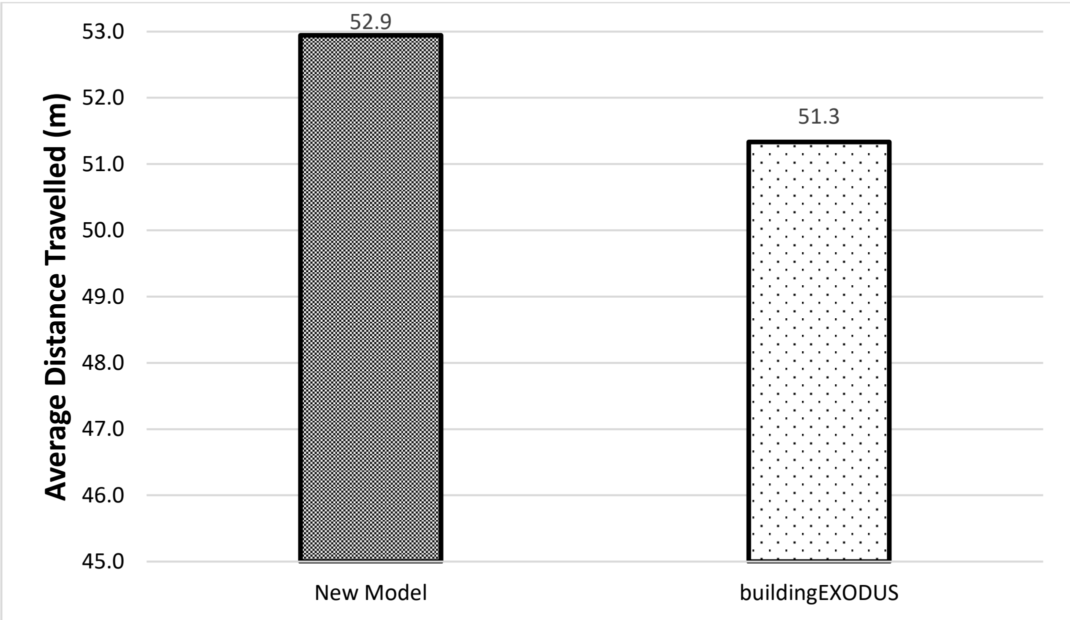


Figure 6.13: Average distance travelled by the agents in Scenario 1a and 1b.

In Scenario 1a and 1b, the new model and buildingEXODUS produced very close results (see Figure 6.12 and Figure 6.13). This is further examined using the Mann–Whitney U statistical test. The test was performed for the average congestion time, the average distance travelled and the average personal evacuation time.

The test results show that the difference in the average congestion time generated by buildingEXODUS and the new model is not statistically significant (Mann– Whitney U=37579, n1=10, n2=10, P=0.23>0.05, two-tailed). The results showed that the difference in the distance travelled between generated by buildingEXODUS and the new model is not statistically significant (Mann– Whitney U=37843.5, n1=10, n2=10, P=0.28>0.05, two-tailed). Finally, the difference in the agents' personal evacuation time generated by buildingEXODUS and the new model is also not statistically significant (Mann– Whitney U=39622, n1=10, n2=10, P=0.88>0.05, two-tailed). The comparison of the evacuation performance produced by buildingEXODUS and the new model demonstrated that both models produced similar and closer results.

6.5.2 Scenario 2a and 2b results

Scenario 2a and 2b are modelled using the new signage-based navigation model and buildingEXODUS respectively. In both scenarios, it is assumed that all the agents know the internal layout of the structure and location of all exits. Hence, the agents will use the nearest available exit from their starting location to evacuate.

As discussed in Section 6.3, buildingEXODUS allows the model user to view the catchment area of each exit which represents the particular region within which the agents should use the corresponding nearest exit. In Figure 6.3, the catchment area generated by each exit in the geometry is shown.

In Scenario 2a, the average travel distance was significantly reduced to 26.8 m compared 52.9 m in Scenario 1a demonstrating the significant difference between the behaviour of using the main exit only and the behaviour of using the nearest available exit from their starting locations. The total evacuation time was also reduced to 74.5 s by nearly a half of that for Scenario 1a. The average time spent by agents in congestion also significantly decreased to 4.5 s which accounts for 11% of their average individual evacuation time (41.3 s).

Scenario 2b is simulated using buildingEXODUS which generated very similar results to Scenario 2a. In Scenario 2b, the average travel distance was 26.5 m compared to 26.8 m in Scenario 2a. The total evacuation time was reduced to 76.6 s compared to 74.5 s in Scenario 2a. The average time spent by the agents in congestion was also similar between Scenario 2a and 2b (4.5 s and 4.8 s respectively). In both scenarios (2a and 2b), 191 agents used the emergency exits to evacuate the structure. The average values of the key evacuation parameters in Scenarios 2a and 2b are shown in Figure 6.14, Figure 6.15 and Figure 6.16.

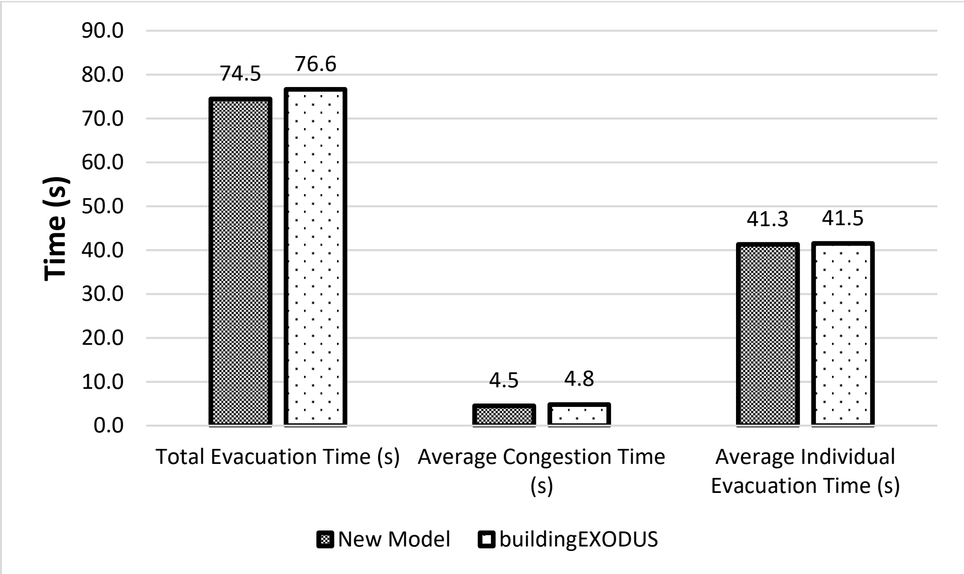


Figure 6.14: Average total evacuation time, average congestion time and average individual evacuation time of Scenarios 2a and 2b.

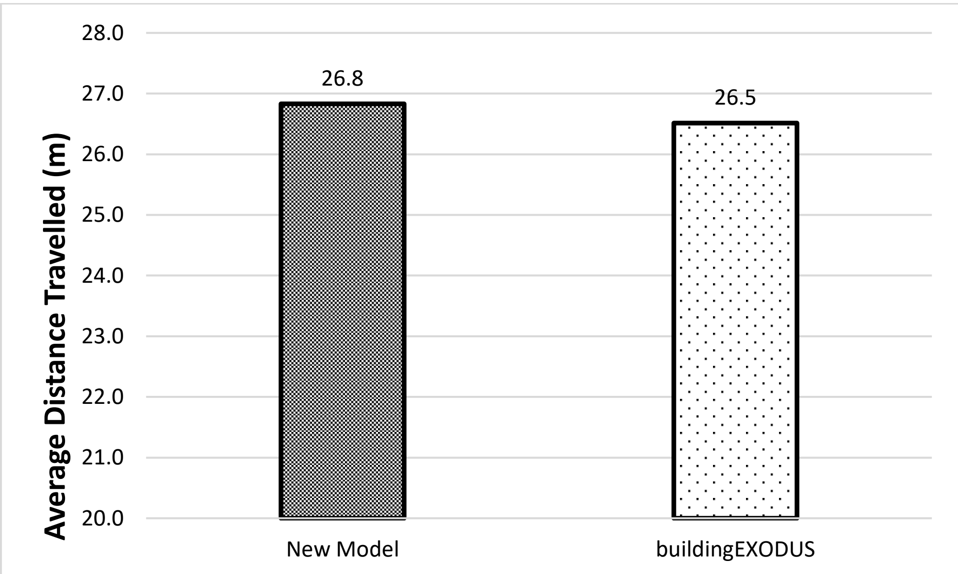


Figure 6.15: Average distance travelled by the agents in Scenario 2a and 2b.

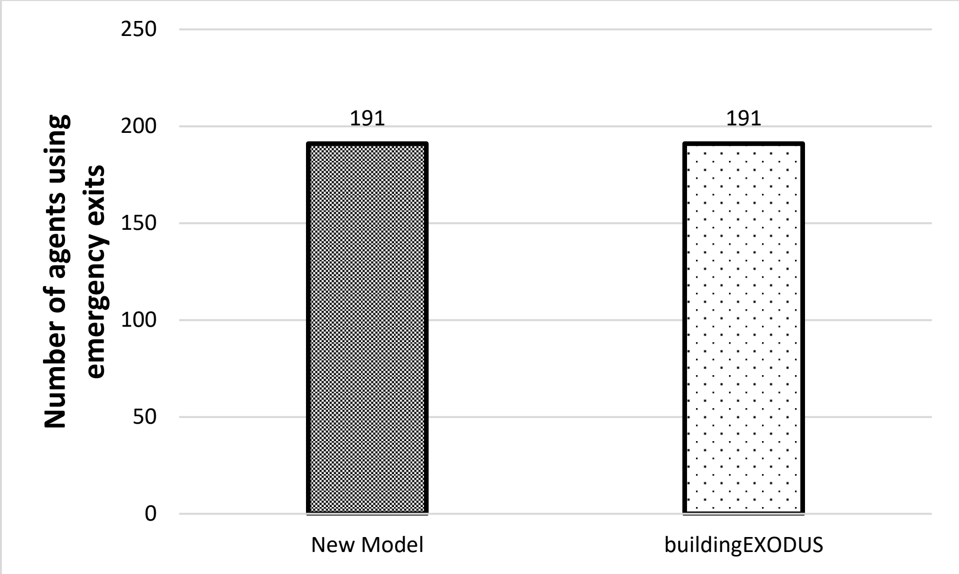


Figure 6.16: Average number of agents using emergency exits in Scenario 2a and 2b.

In Scenario 2a and 2b, the new model and buildingEXODUS produced very close results. This is further analysed using the Mann– Whitney U statistical test. The test focusses on the average congestion time, the average distance travelled and the average personal evacuation time.

The test results show that the difference in the average congestion time generated by buildingEXODUS and the new model is not statistically significant (Mann– Whitney U=38516, n1=10, n2=10, P=0.52>0.05, two-tailed). The results show that the difference in the average distance travelled generated by buildingEXODUS and the new model is not statistically significant (Mann– Whitney U=39407.5, n1=10, n2=10, P=0.85>0.05, two-tailed). Similarly, the difference in the agents' personal evacuation time generated by buildingEXODUS and the new model is also not statistically significant (Mann– Whitney U=39533.5, n1=10, n2=10, P=0.90>0.05, two-tailed). The comparison of the evacuation performance produced by buildingEXODUS and the new model demonstrated that both models produced similar and closer results.

6.5.3 Scenario 3a and 3b results

In an evacuation setting, Scenario 1a/1b and 2a/2b demonstrated two extreme situations in terms of agents' exit knowledge. In Scenario 1a and 1b, the agents were aware of only main exit hence, all the agents used the main exit to evacuate the structure. Whereas in Scenario 2a and 2b, it was assumed that the entire population were familiar with all the exits hence, all the agents used the nearest exit from their starting location. Due to the use of the nearest exit, Scenario 2a/2b produced the most optimal evacuation results.

In the real world, Scenario 2a/2b are unrealistic because it would be unlikely that the entire population in a structure are familiar with the internal layout of the building. The building occupants who are familiar with the structure may wayfind to the nearest available exit during an evacuation. However, there may be some others who are less familiar with the structure. Escape route signs provided a means of guiding occupants to an exit or a place of safety. The new signage-based navigation model is capable of simulating the agents' wayfinding behaviour using the series of signs. Hence, the interaction between agents and signage system is enabled in Scenario 3.

Scenario 3 has two variations. Scenario 3a is modelled using the new signage-based navigation model and Scenario 3b is modelled using buildingEXODUS. In both Scenarios (3a and 3b), the empirical data is used for demonstrating the real-world signage detection and compliance probabilities [Xie *et al.,* 2012]. The results of Scenario 3a are compared with the results of Scenario 3b to demonstrate the similarities and differences between the two approaches of modelling the interaction with signage.

Prior to running the simulations, it was vital to ensure that the comparison of new signage-based navigation model and buildingEXODUS can perform on the same basis. In buildingEXODUS, an agent can detect a sign provided that the agent is in the Visibility Catchment Area (VCA) of the sign and the relative orientation between the agent's travel direction and the sign is examined to determine whether they can discern the sign [Filippidis *et al.,* 2001, 2003, 2006]. The impact of the relative orientation between the agent's travel direction and the sign on the perception of the sign is simulated through an arbitrary sigmoid function [Filippidis *et al.,* 2001, 2003, 2006, 2008]. The sigmoid function provides an estimation of the difficulty of an agent seeing a sign based on the agent's angle of approach relative to the sign. The mode user can the disable the sigmoid function or enter an arbitrary detection probability between 0% and 100%.

As previously discussed in Chapter 4 (Section 4.5.2.1), in the new model the relative orientation between the agent and the sign has not been implemented. This is considered as future work. Hence, in buildingEXODUS, the sigmoid function was disabled, instead a 100% detection probability was used. This step ensures that the comparison of the new model and buildingEXODUS can be performed on the same basis.

The average values of the key evacuation parameters of Scenarios 3a and 3b are shown in Figure 6.17, Figure 6.18 and Figure 6.19. By and large, both models produced similar results. In Scenario 3a, on average time the agents spent 2.3 s in congestion which accounts for 5% of their average individual evacuation time (44.2 s). The average distance travelled is 33.4 m. On average, 175 agents used the emergency exits. In Scenario 3b, the average travel distance was reduced to 29.2 m demonstrating that a few more agents may have uses the nearest available exit from their starting locations compared with Scenario 3a. Indeed, on average 195 agents used the emergency exits and the total evacuation time was also reduced to 93.9 s compared with 112.2 s in Scenario 3a.

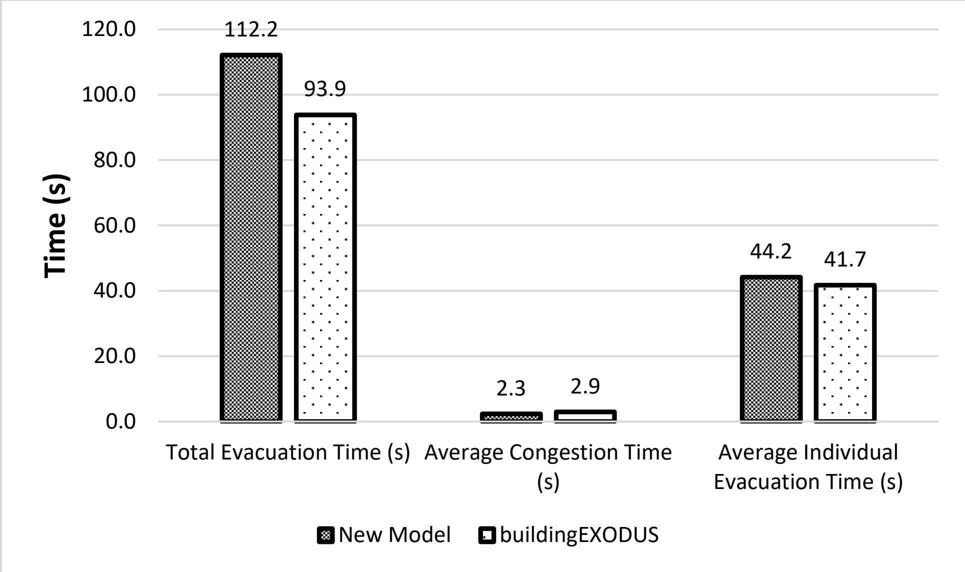


Figure 6.17: Average total evacuation time, average congestion time and average individual evacuation time of Scenarios 3a and 3b.

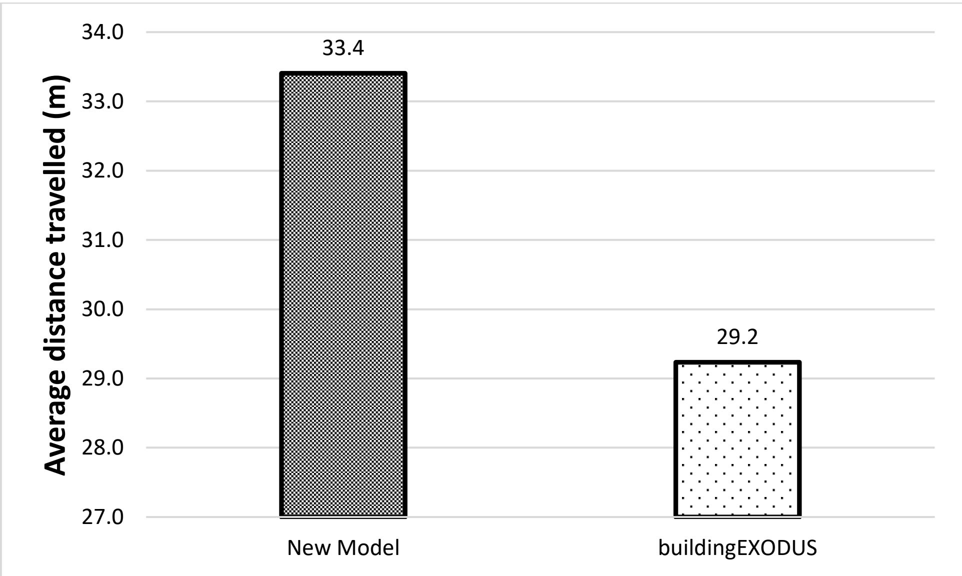


Figure 6.18: Average distance travelled by the agents in Scenario 3a and 3b.

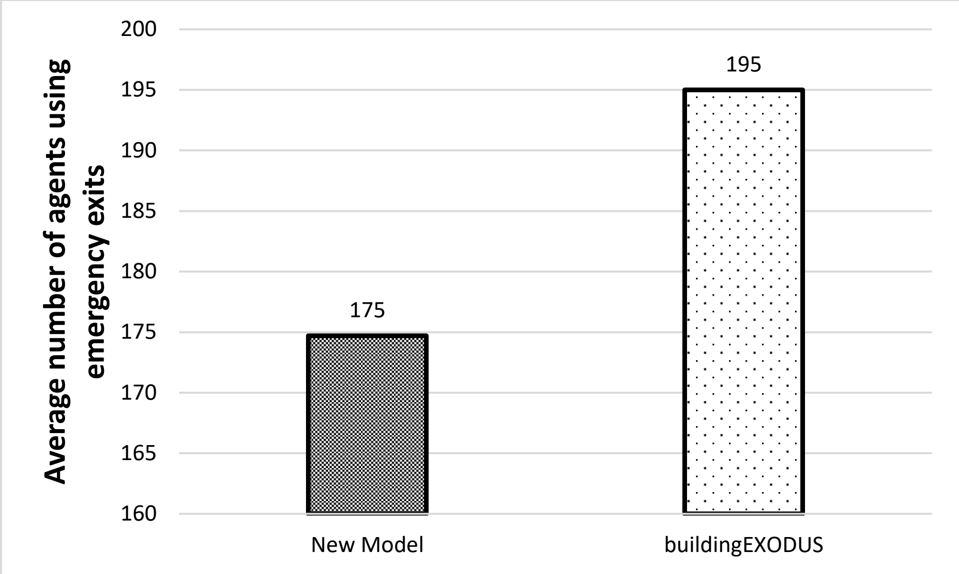


Figure 6.19: Average number of agents using emergency exits in Scenario 3a and 3b

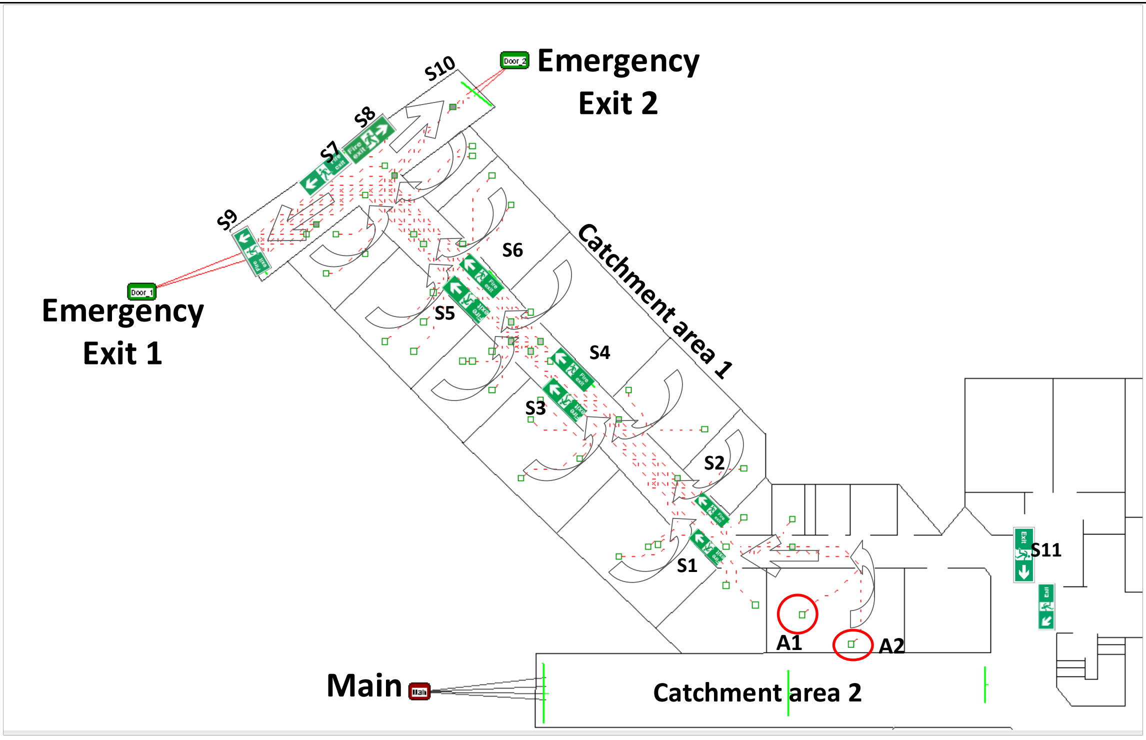
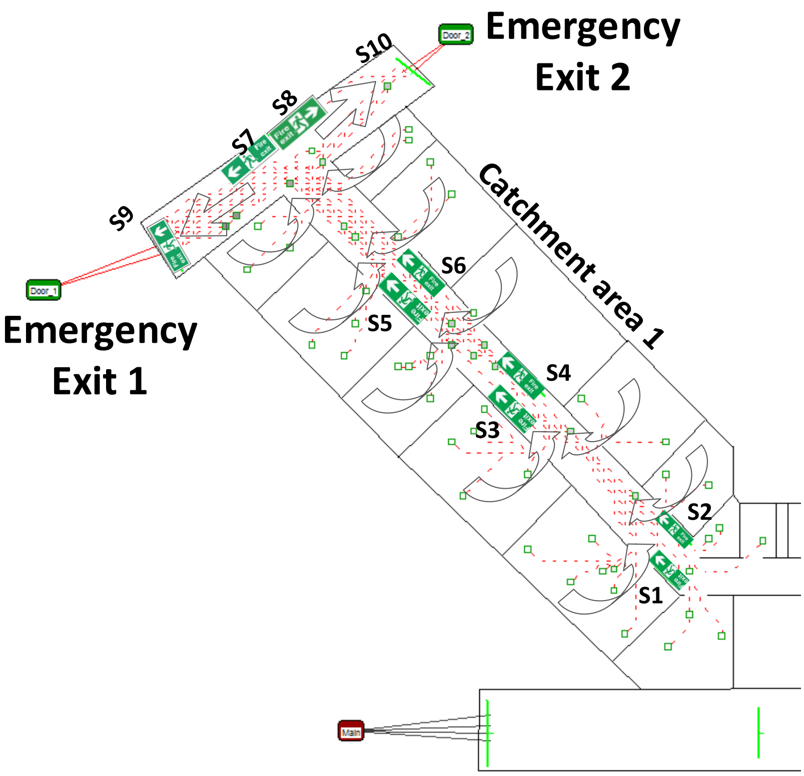
From Figure 6.17, Figure 6.18 and Figure 6.19, in the new model slightly longer average distance travelled and less usage of emergency exits can be observed. This can be explained by comparing the agent's travel path in both models. Table 6.6 shows the travel paths of the agents who used signage to wayfind to the emergency exits in catchment area 1 produced by the new model and buildingEXODUS.

From observing the generated travel paths by both models, it can be seen that the majority of the agents used signage according to the planned escape route in catchment area 1. However, in the new model, two agents, A1 and A2 (both circled red) who were originally located in catchment area 2 and should use the main exit went to emergency exit 1. When they left their starting room and entered the corridor, they missed sign S11 which directs them to the route leading to the main exit but then detected sign S1 at the opposite direction and started following sign S1. Agent A1 and A2 eventually used the emergency exit 1 which are located further away than the main exit to them to leave the building. This shows a typical behaviour that occupants may select a longer route if the zone of influence of two signs indicating two different routes overlap with each other.

The travel paths of agents using buildingEXODUS in catchment area 1 show that the majority of the agents located in catchment area 1 used emergency exit 1 and 2. In buildingEXODUS, the agents do not explicitly follow the direction of the signs. Instead, they travel between the redirection nodes which link the signs in the signage chain along the intended escape route. This modelling approach reduces the chance of agent missing the next sign along the signage chain as the agents are always 'correctly' directed to the location where the next sign is. It should be note that although the detection probability of each sign is very low (38%) in scenario 3b, with the influence of multiple signs on their path, the majority of the agents in catchment area 1 still detected one or more exit signs and chose to evacuate via emergency exit 1 or 2 in the buildingEXODUS simulations.

On the contrary, in the new model, the agents who detect a sign move according to the direction indicated by the sign. Compared with buildingEXODUS, this modelling approach produces a slightly higher chance of agent missing the next sign along the signage chain when following a signage direction, as the sign indicates the direction of escape route rather than the precise location of next sign along the signage chain. Although there are two agents who started in catchment area 2 were directed to emergency exit 1 in scenario 3a, a few more agents who started in catchment area 1 missed following the signage chain and eventually went to the main exit. This is more evident when examining the usage of the main exit.

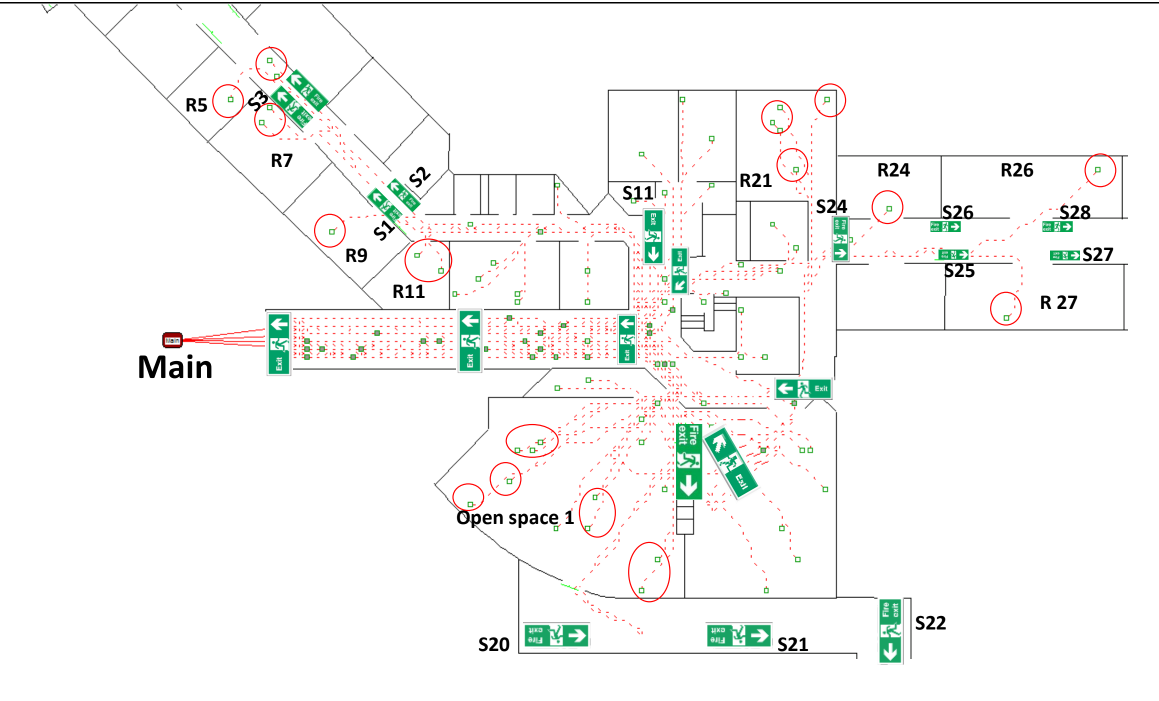
Table 6.6: Travel paths of the agents following signage in catchment area 1.

<table>
<tr><th>New signage-based navigation model</th></tr>
<tr><td>
</td></tr>
<tr><th>buildingEXODUS</th></tr>
<tr><td>
</td></tr>
</table>

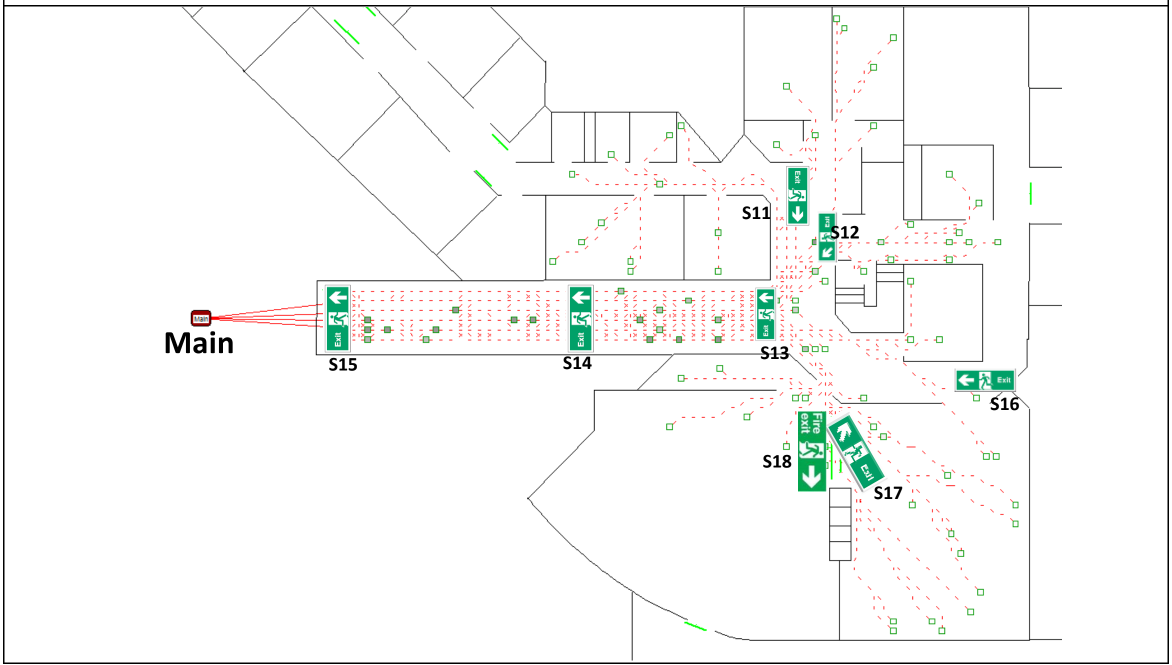
The main exit is associated with the catchment area 2 (see Table 6.1). Table 6.7 shows the travel paths of the agents produced by the new model and buildingEXODUS. In the new model, 7 agents (see Table 6.7, circled red) from catchment area 1 used the main exit. The agents located in room R5, R7, R9 and R11 missed detecting the sign S1, S2, S3 and S4. These agents then used their knowledge of the main exit to leave the building. Catchment area 3 includes open space 1. 8 agents (see Table 6.7, circled red) from open space 1 missed detecting sign S18 and S19. These eight agents then used their knowledge of the main exit to escape the building. Lastly, 10 agents from catchment area 4 also used the main exit to leave the structure.

Table 6.7: Travel paths of the agents following signage in catchment area 2.

New signage-based navigation model



buildingEXODUS

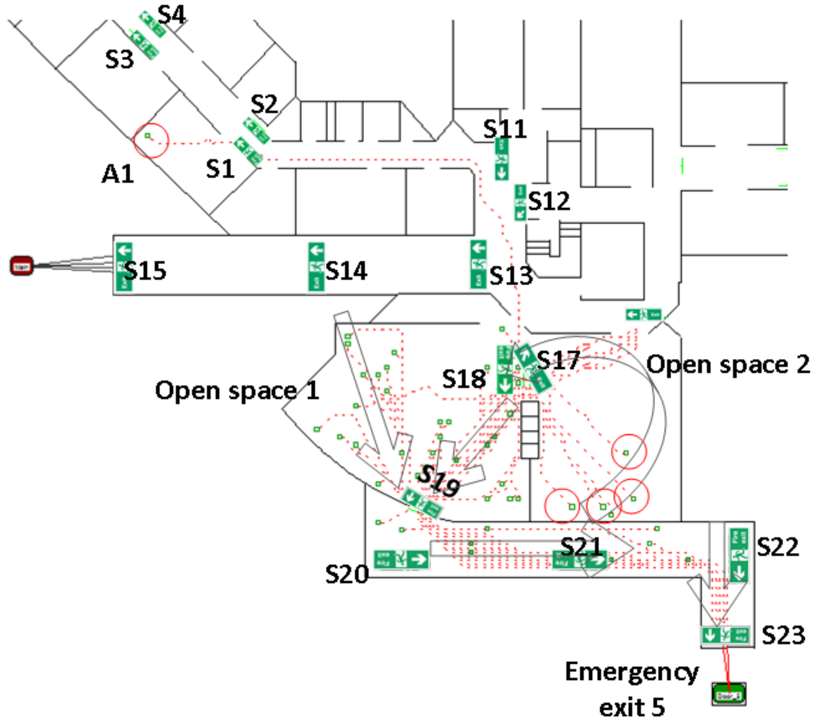
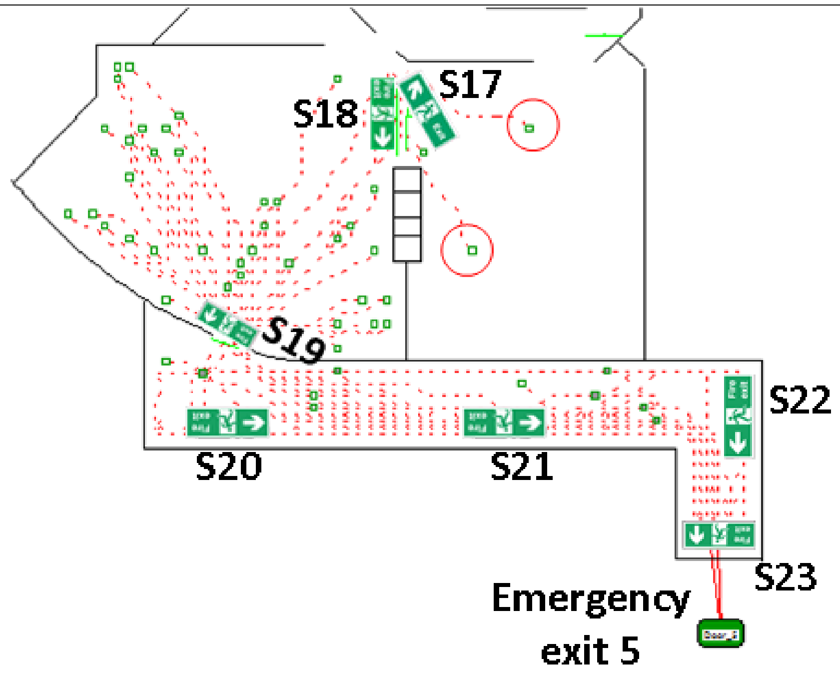


Emergency exit 5 is associated with catchment area 3 (see Table 6.1). Table 6.8 shows the travel paths of the agents in the new model and buildingEXODUS which show that most of the agents utilised the signs installed in catchment area 3. In the new model, five agents (see Table

6.8, circled red) who were originally located in the open space 2 of catchment area 2 and one agent from catchment area 1 used emergency exit 5 (see Table 6.8, circled red). The agents located in open space 2 detected the sign S17 indicating the route to the main exit. However, when they were heading to the main exit, some of them also detected sign S19 indicating the route leading to emergency exit 5. This is why these agents changed their travel direction towards the sign S19 and then followed the route indicated by sign S20, S21, S22 and S23 to leave the structure via emergency exit 5. The agent A1 located in catchment area 1 missed the signs in that area and was heading to the main exit. The agent A1 then detected and started following the direction of sign S11. The sign S11 provided the direction towards the sign S13. However, the agent missed sign S13 and entered the open space 1 where the agent detected sign S18. Using this sign, the agent then followed the route indicated by sign S19, S20, S21, S22 and S23 to use emergency exit 5.

The travel paths of the agents produced by buildingEXODUS in catchment area 3 shows that most of all the agents located in this catchment area used emergency exit 5 to leave the building. Two agents who were originally located in catchment area 2 (see Table 6.8, circled red) detected the sign S17 but also detected sign S18 and leave the building via emergency exit 5.

Table 6.8: Travel paths of the agents following signage in catchment area 3.

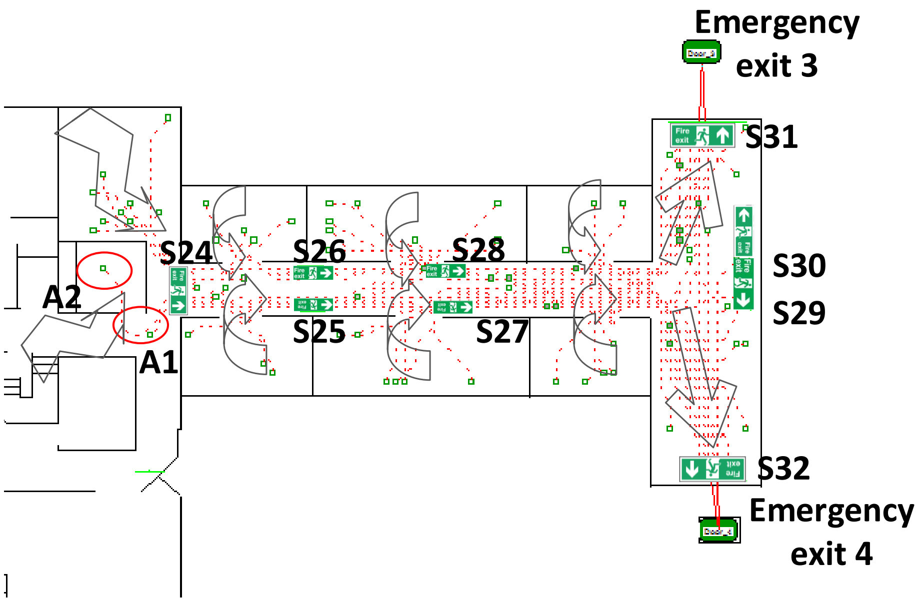
New signage-based navigation model

buildingEXODUS


Emergency exit 3 and 4 are associated with catchment area 4 (see Table 6.1). Table 6.9 shows the travel paths of the agents produced by the new model and buildingEXODUS. In the new model, most of the agents located in catchment area 4 used emergency exit 3 and 4. In addition, two agents (see Table 6.9, circled red) who were originally located in the catchment area 2 used emergency exit 3 (see Table 6.9, circled red). These two agents, A1 and A2, were located near to sign S24. Hence, agent A1 and A2 detected the sign S24 and followed the chain of signs in catchment area 4.

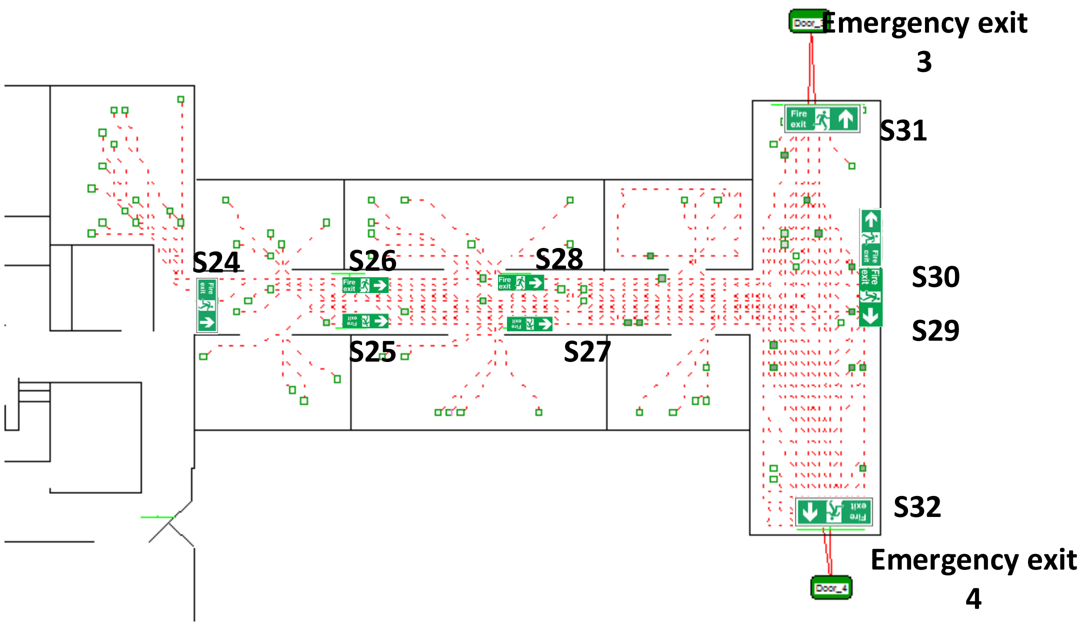
The travel paths of the agents using buildingEXODUS in catchment area 4 show that most of the agents located in this catchment area used emergency exit 3 and 4 to leave the model.

Table 6.9: Travel paths of the agents following signage in catchment area 4.

New signage-based navigation model



buildingEXODUS



The comparison of the new signage-based navigation model and buildingEXODUS results demonstrated that both models produced similar results. The analysis of travel paths of the agents produced by the new model and buildingEXODUS highlighted the limitations of the existing approach in modelling the interaction between the agent and signage. These limitations were discussed in Chapter 4 (Section 4.2). A major limitation of buildingEXODUS is agent's inability to understand the direction of the sign. Due to this limitation, a model user has to manually connect the signs with each other to signify a chain of signs. This neglects the potential 'human errors' in both occupant behaviour of following a signage direction and in signage configuration (for instance, an agent can still correctly identify the location of connected signs, even they are not visible to each other). The new model simulates the agent behaviour of following the direction of the sign. This approach does allow the 'human errors' to happen during their movement of following a signage direction. Besides, it could pick up signage configuration errors if the signs are not properly positioned (e.g. pointing to wrong direction or too far apart). In the real world, when occupants see a sign, they only get the direction on the sign and it is expected that they would follow the direction of the sign along the escape route [BS5499-4:2013; Xie *et al.,* (2011), Xie (2012)]. Hence, the interaction with signage simulated by the new model is a better approximation of the real-world behaviour than the existing approach in buildingEXODUS.

Examine the impact of signage on agent wayfinding behaviour in Scenarios 1a and 2a

To examine the impact of the signage system on agents' wayfinding behaviour, Scenario 3a results are compared with Scenario 1a (agents use the main exit only) and Scenario 2a (agents use all the exits). Figure 6.20, Figure 6.21 and Figure 6.22 shows the comparison of the average evacuation parameters for Scenario 1a, 2a and 3a.

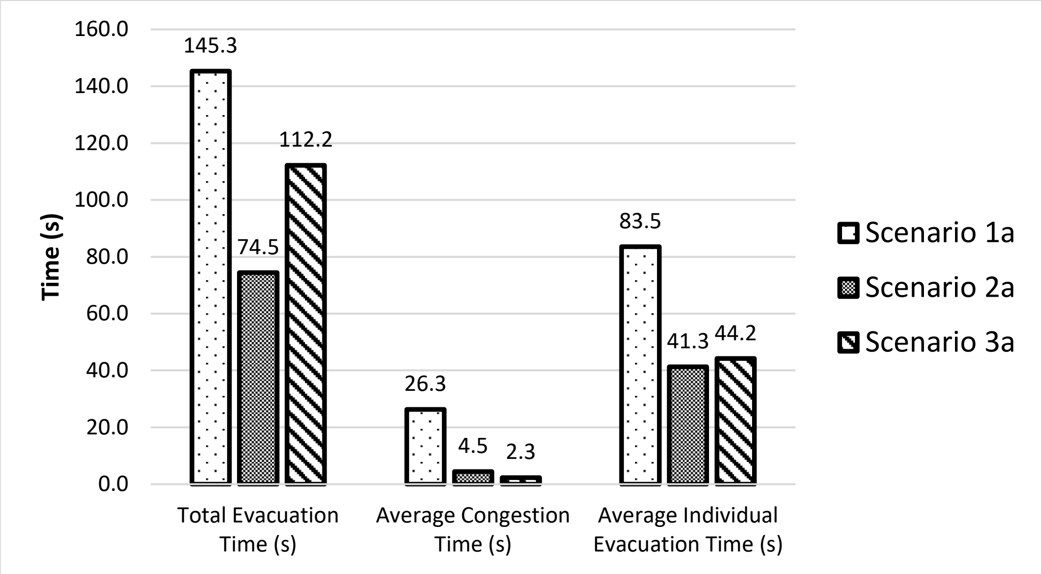


Figure 6.20: Average total evacuation time, average congestion time and average individual evacuation times of Scenarios 1a, 2a and 3a.

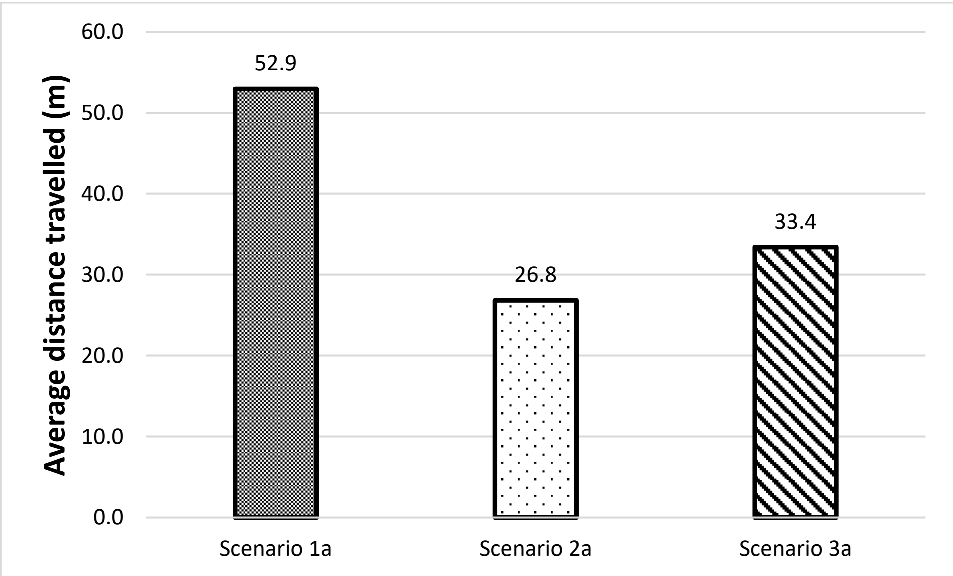


Figure 6.21: Average distance travelled by the agents in Scenarios 1a, 2a and 3.

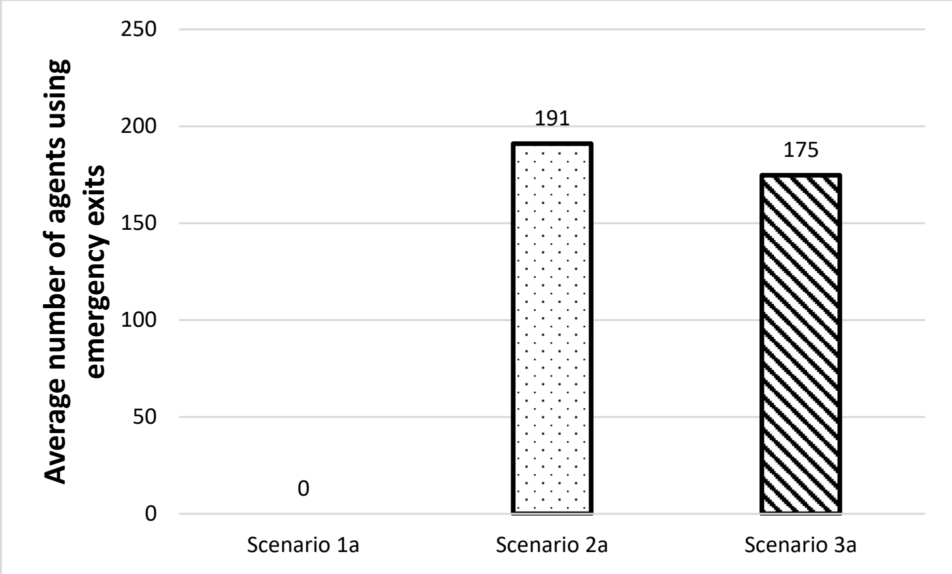


Figure 6.22: Average number of the agents using emergency exits in Scenarios 1a, 2a and 3.

In Scenario 1a, the entire population used the main exit and ignored all the emergency exits. The higher travel distance travelled by agents was expected in this scenario. Scenario 2a produced the most optimal results by allowing the agents to use the nearest available exit from their starting location. Hence, 191 agents used the emergency exits, a significant improvement from Scenario 1a. The average travel distance is also significantly reduced to 26.8 m compared to Scenario 1a. Scenario 3a is a more realistic scenario in which the agents' level of familiarity is same as Scenario 1a at the beginning of the simulation. In order to achieve the optimal results of Scenario 2a, i.e. providing the agents with necessary wayfinding information, the signage system is used in Scenario 3a which uses the empirical data for detection and compliance probability [Xie *et al.*, 2012]. In Scenario 3a, the average travel distance covered by the agents was 33.4 m which are 58% less than the result of Scenario 1a.

Using the signs in Scenario 3a, the total evacuation time is reduced to 112.2 s which is 29% less than Scenario 1a (agents use the main exit only) and 33% more than the evacuation time in Scenario 2a (agents use all exits). In Scenario 3a, the average time spent in congestion is also reduced to 2.3 s from 26.3 s in Scenario 1a which accounts for 5% of their average individual evacuation time (44.4 s).

From analysing the simulation results of Scenario 1a, 2a and 3a, it shows that the escape route signage system can be useful in guiding the agents who are not familiar with the internal layout of a structure to emergency exit. Furthermore, the escape route signage system in a structure also allowed to improve the evacuation performance such as the total evacuation time against Scenario 1a. Scenario 2a is an ideal but unrealistic scenario in which all agents are well familiar with the building layout and used all the available exits based on the shortest distance to an exit. It was expected that Scenario 2a produces the most optimal evacuation result. Scenario 1a and 2a generated the wide range of possible total evacuation times. Lastly, Scenario 3a allows the interaction between the agent and signage. This scenario demonstrated that the correct implementation of a signage system according to BS5499-4:2013 can improve the evacuation performance. For instance, the total evacuation time and the average distance travelled can be reduced to a level that is comparable with the most optimal evacuation solution (Scenario 2a).

6.5.4 Scenario 4a, 4b and 4c results

In Scenario 4, the agents have no previous familiarity with any exits. To find an exit, the agents will use their searching behaviour described in Chapter 4 (Section 4.5.3.1). In order to compare the difference in agents' wayfinding behaviour with and without the chain of signs, Scenario 4 has three variations.

- In Scenario 4a, no signage information is included, and the agents purely rely on their searching behaviour to find an exit.

- Scenario 4b introduced the signage system implemented according to the BS 5499:4-2013. The signage detection and compliance probabilities are set to 100%.

- Lastly, in Scenario 4c, the empirical data is used for demonstrating the real-world detection and compliance probability [Xie *et al.*, 2012] i.e., when an agent is within the VCA of a sign, they have a 38% chance of detecting the sign and if detected, a 97% chance of complying with the signage information.

Figure 6.23, Figure 6.24 and Figure 6.25 present the average values for some key evacuation parameters generated by the simulations using the new signage-based navigation model.

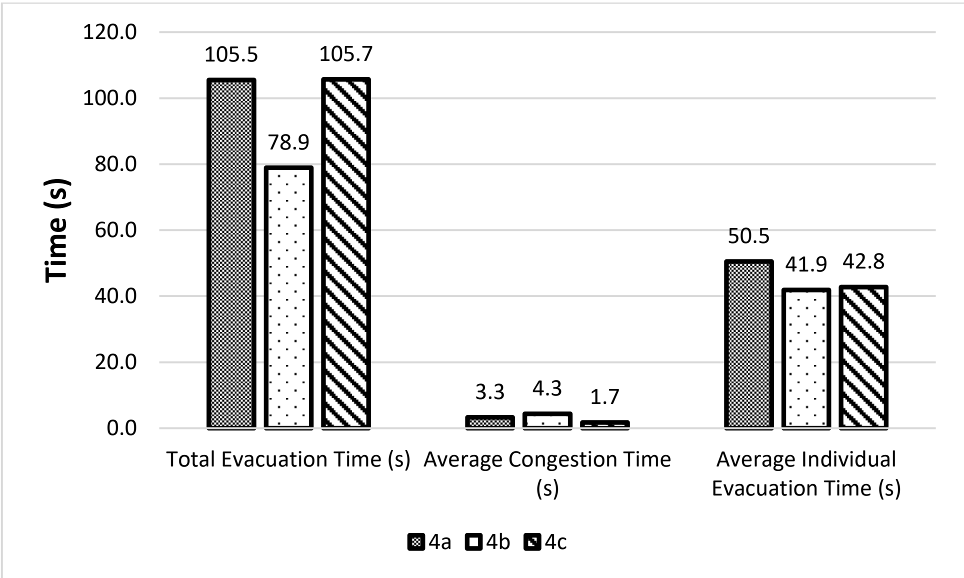


Figure 6.23: Average individual evacuation times, average congestion time and average individual evacuation time of the modelled Scenarios 4a, 4b and 4c.

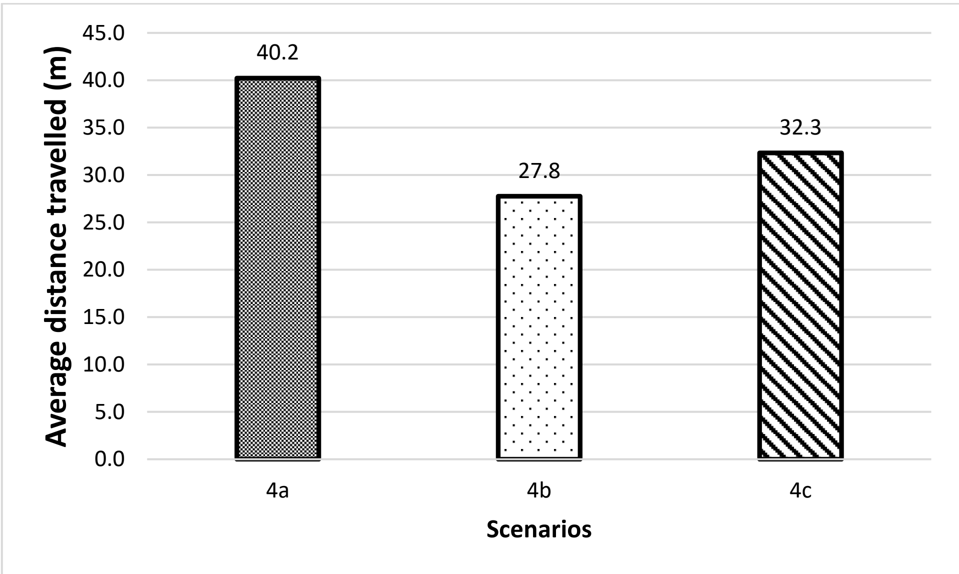


Figure 6.24: Average individual travel distance of the modelled Scenarios 4a, 4b and 4c

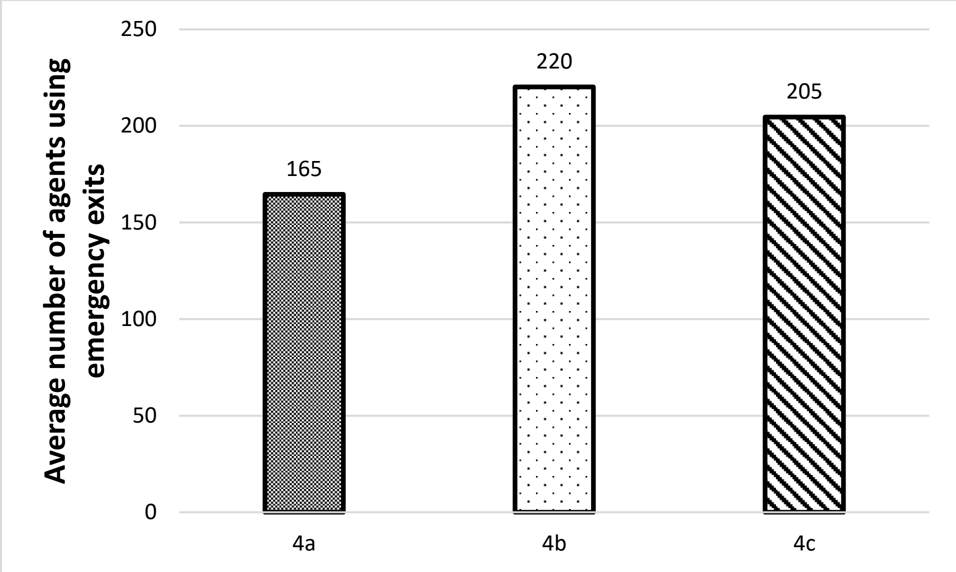


Figure 6.25: Average numbers of agents using emergency exits in Scenarios 4a, 4b and 4c.

In Scenario 4a, since the signage system was not used, the agents performed searching to find an exit. In this scenario, on average the agents spent 3.3 s in congestion which accounts for 6% of their average individual evacuation time (50.5 s) while the average distance travelled is 40.2 m.

As previously discussed in Chapter 4 (Section 4.5.3.1), the agents' searching behaviour was implemented based on the Breadth First Search (BFS) algorithm. The agents started searching from the nearest unvisited waypoint from the agent's starting location. The agents continued to perform BFS until they find an exit/sign. The signal approach of representing the search behaviour in the model, i.e. BFS makes the searching behaviour deterministic in nature. Figure 6.26 shows the travel paths of all the agents who used the exit 1 and exit 2 to evacuate the structure. For instance, started from the nearest unvisited waypoint agent A1 performed BFS until the agent found exit 1.

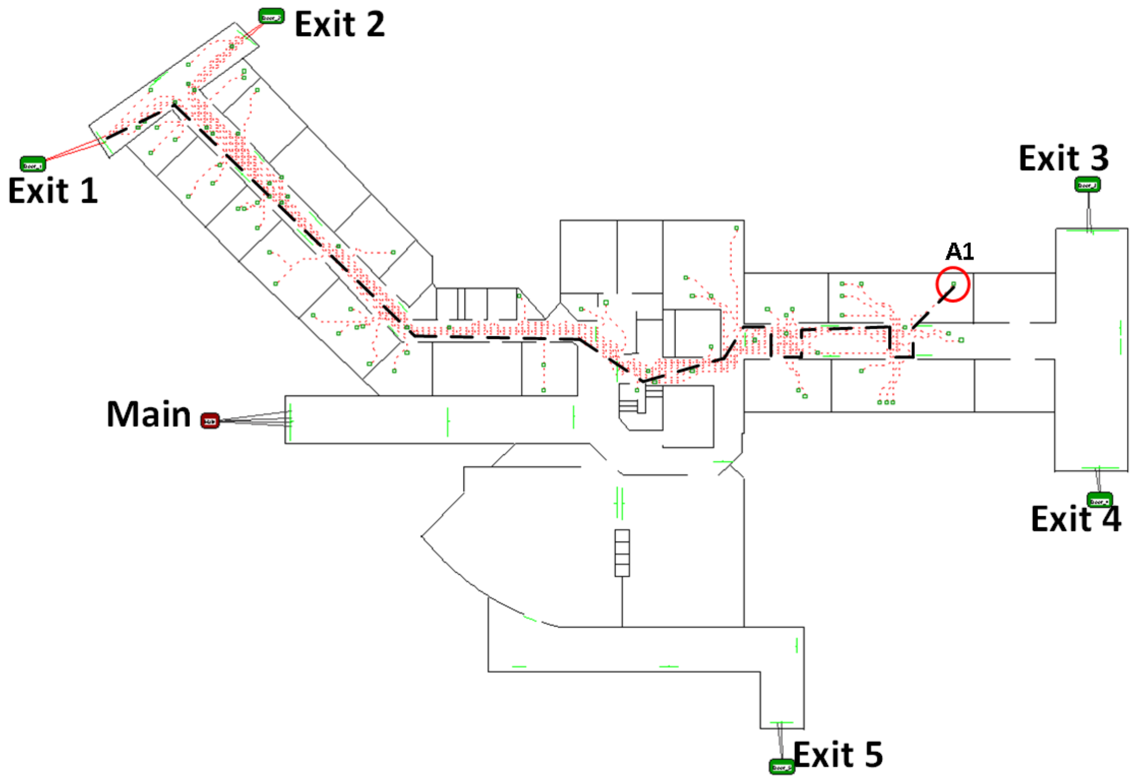


Figure 6.26: Agent A1 travel path in Scenario 4a.

The searching behaviour without external source of wayfinding formation resulted in the highest average travel distance recorded in Scenario 4a compared to 4b (27.8 m) and 4c (32.3 m). In this scenario, the average number of agents using each exit is shown in Table 6.10.

Table 6.10: Average number of agents using each exit in Scenario 4a.

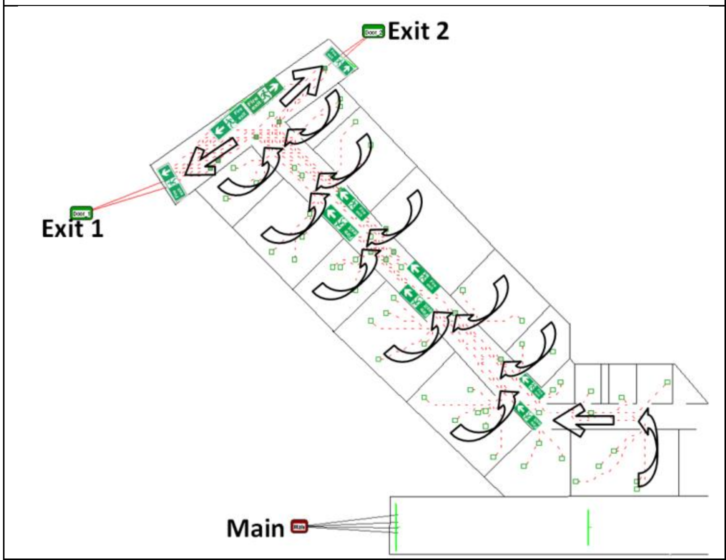
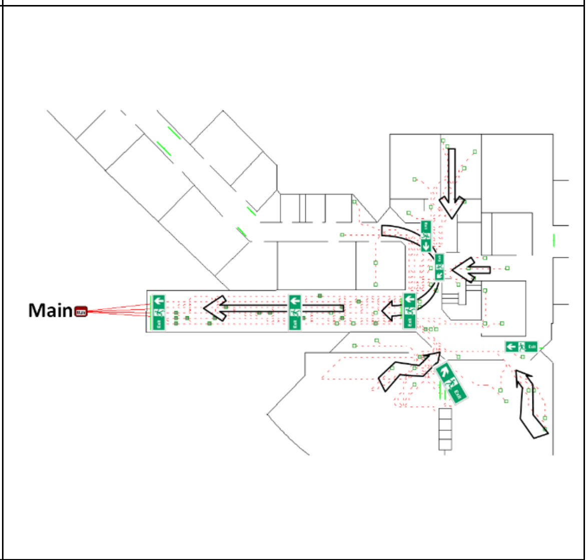
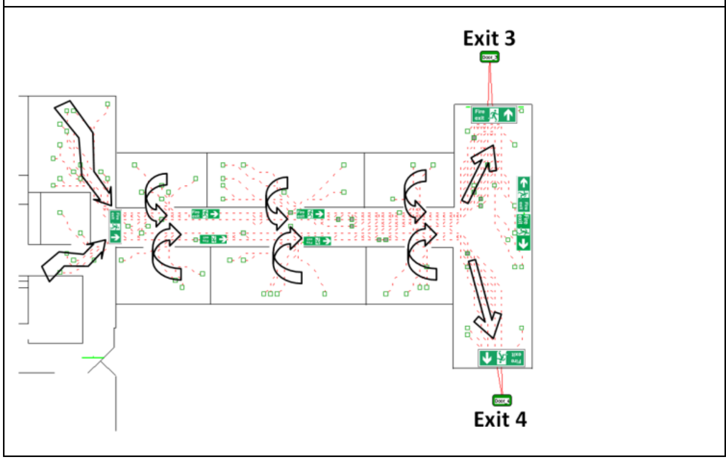
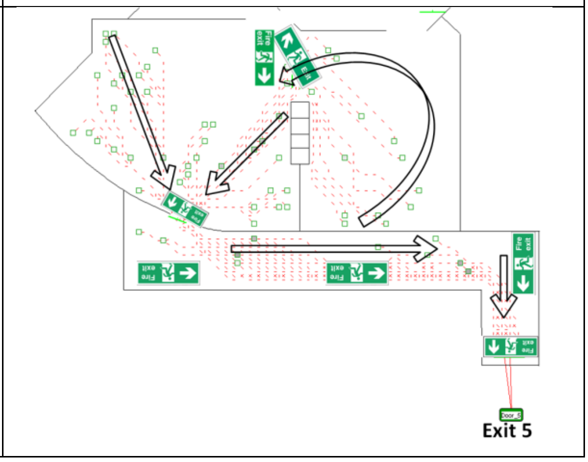
Emergency Exit 1+ Emergency Exit 2	Main exit	Emergency Exit 3+ Emergency Exit 4	Emergency Exit 5
73	118	74	18

In the real world, the knowledge of nearest exit/emergency exit in the structure is conveyed to the building occupants through signage. The signage information was included in Scenario 4b exit with the signage detection and compliance probabilities being set to 100%. This scenario allows the agents to find an available exit using the signage.

In Scenario 4b, the average travel distance was reduced to 27.8 m compared 40.2 m in Scenario 4a demonstrating the effect of agents using the signage system to find an available exit. Due to the high detection probability and compliance probability, a higher number of agents found and used the emergency exits; 220 agents used the emergency exits compared to 165 agents in Scenario 4a. Lastly, the total evacuation time was reduced to 105.5 s compared with 78.9 s in Scenario 4a.

Using the high detection probability, the agents located in each catchment area (see Figure 6.3), used the signage installed in their individual catchment area. The travel paths of all the agents in Scenario 4b are shown in Table 6.11.

Table 6.11: Travel paths taken by the agents in Scenario 4b.

<table>
<tr><th>Exit 1 and Exit 2</th><th>Main Exit</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><th>Exit 3 and Exit 4</th><th>Exit 5</th></tr>
<tr><td>
</td><td>
</td></tr>
</table>

There are 15 agents (see Figure 6.27, circled) originally located in catchment area 2 who used exit 5 to evacuate the structure. These 15 agents detected the sign S17 and were moving towards the main exit. While following the sign S17, these agents entered the VCA of sign S19 located in catchment area 3. Hence, the agents started following the direction of sign S19 and eventually used exit 5 to leave the structure. In this particular situation, the overlapping of the VCAs of sign S17 and sign S19 redirected the agents to use the route defined in catchment area 3.

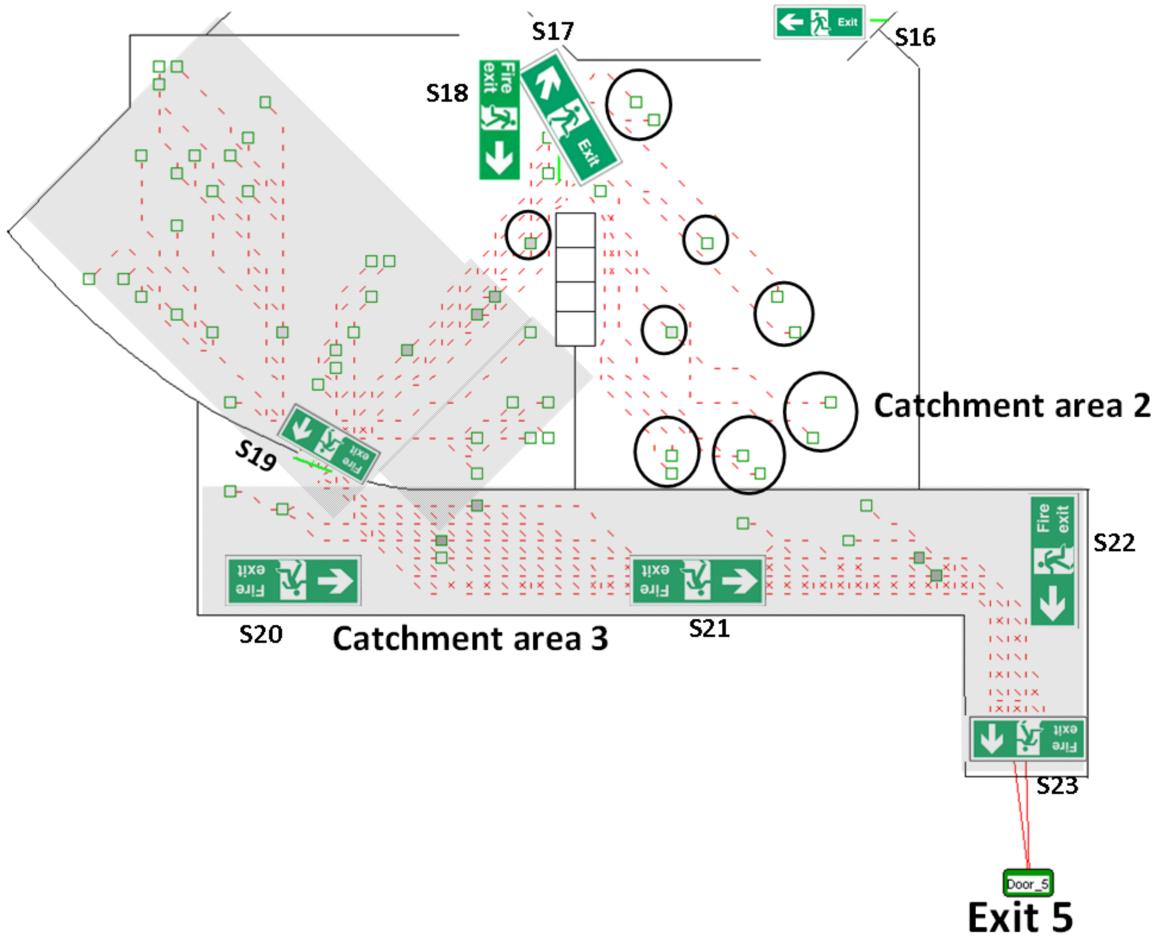


Figure 6.27: Agents of catchment area 2 using Exit 5.

As previously discussed in Section 6.3, the signage system in this demonstration case was planned according to the guidelines of BS5499-4:2013. The planning of the signage system involved the planning of the escape routes and deciding the location and direction of the signs along the intended route within the premises. However, due to the internal layout of the structure, the planned signage system may not always function as intended. In this particular case, in order to guide the agents in catchment area 2 to use the main exit, a series of non-emergency signs were installed. One of the signs, S17 was intended to indicate the escape direction towards sign S13. However, this route was also covered by the other signs indicating the emergency route leading to emergency exit 5. Therefore, 15 agents who were originally located in catchment area 2 (see Figure 6.27) and were following the direction of the sign S17 also detected sign S19 which then redirected them to use another escape route towards emergency exit 5. It should be noticed that this is a signage configuration problem, which may be addressed by relocating sign S17 to indicate the route via sign S16.

In Scenario 4b, the signage detection and compliance probabilities were set to 100%. This means when an agent enters the VCA of a sign, they have a 100% chance of detecting and following the information provided by the sign. Using such a high detection and compliance probability produced the most optimal results possible using the signage system.

Scenario 2a was idealistic as it was assumed that the entire population were aware of all exits. Hence, all the agents used the nearest available exit to leave the structure. Due to this assumption, this scenario also produced the most optimal results possible in an evacuation scenario without signage. On comparing the results of Scenario 2a with 4b, both scenarios produced largely similar results. The average values of the key evacuation parameters of Scenario 2a and 4b are shown in Figure 6.28, Figure 6.29 and Figure 6.30.

The comparison of the total evacuation time, the average time spent in congestion and the average individual evacuation time between the two scenarios shows almost identical results. This confirms that a properly planned signage system according to BS5499-4:2013 can achieve the same level of optimal evacuation performance as in Scenario 2a (where people have a good knowledge of all exits) provided that the signs are efficient in catching people’s attention.

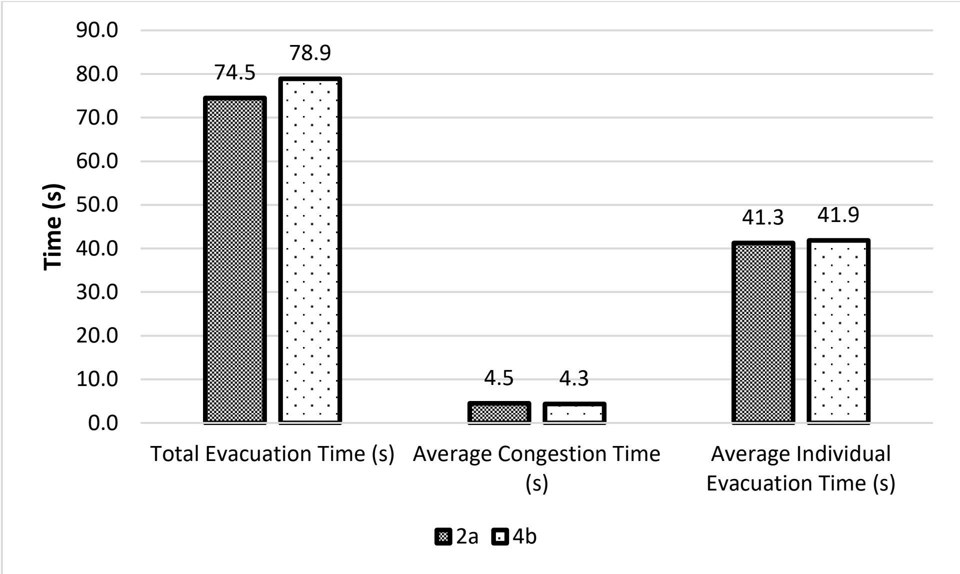


Figure 6.28: Average total evacuation time, average congestion time and average individual evacuation time of Scenario 2a and 4b.

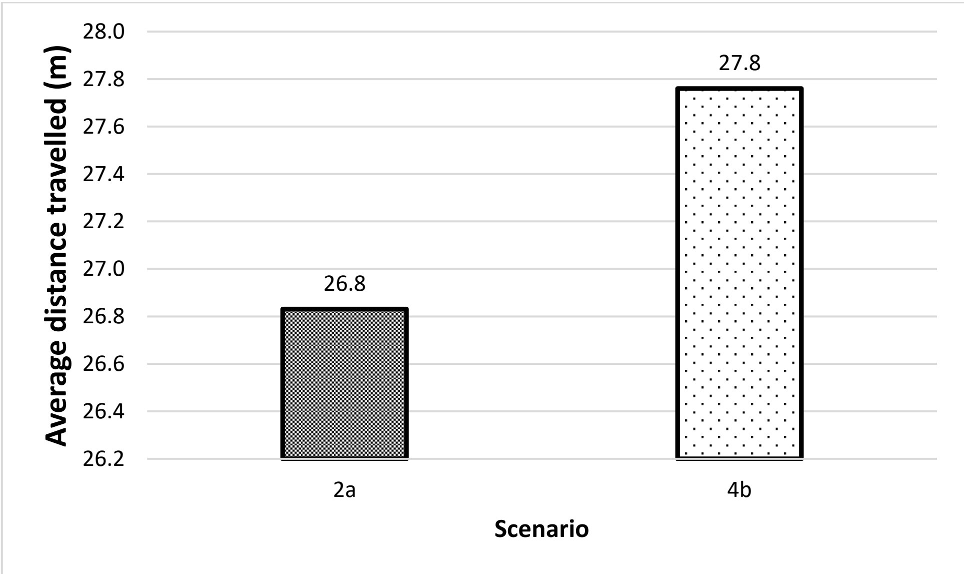


Figure 6.29: Average travel distance travelled by the agents in Scenario 2a and 4b

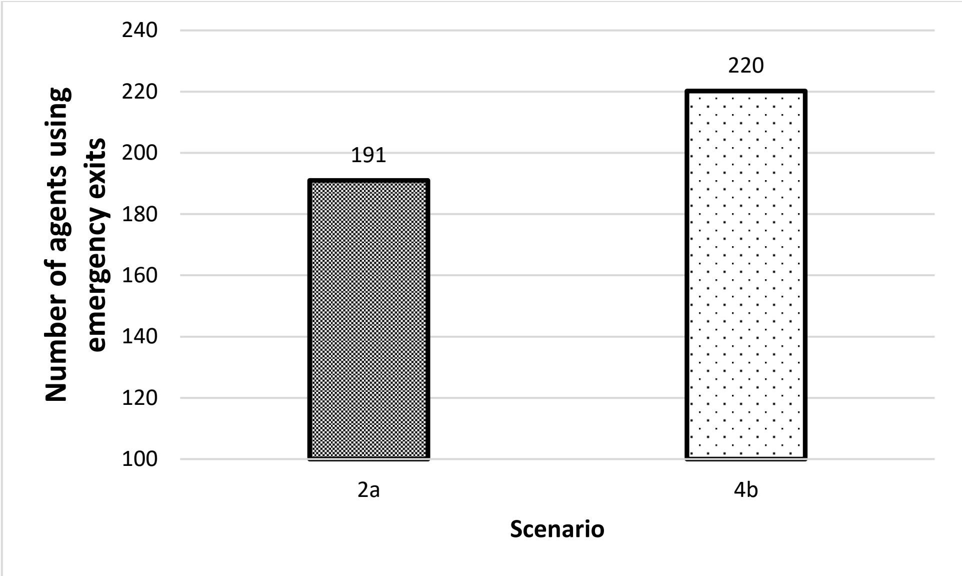
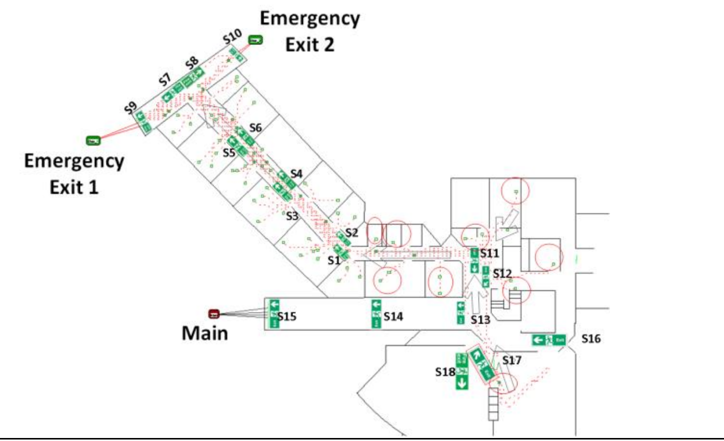
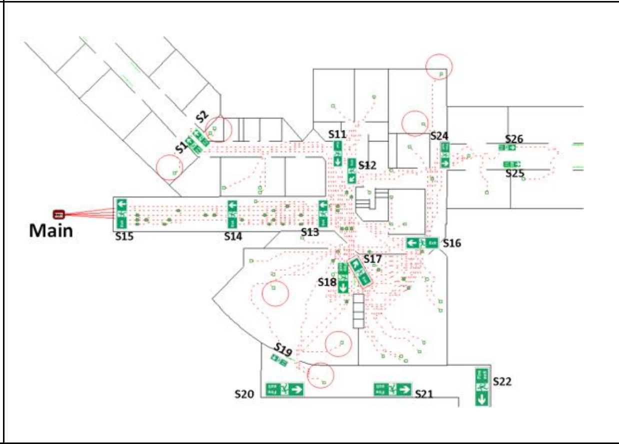
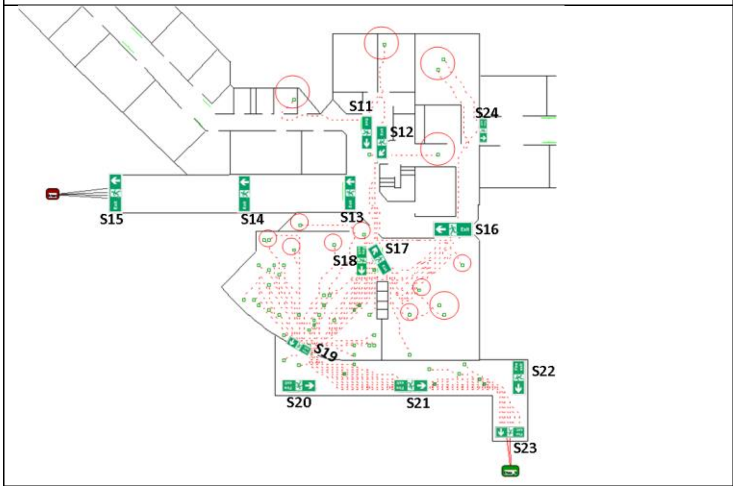
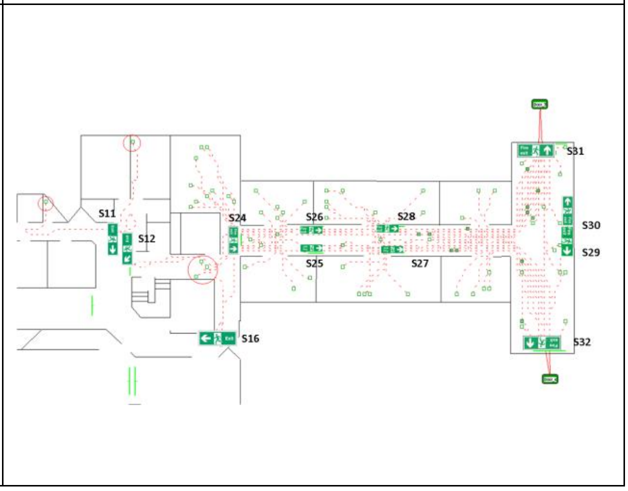


Figure 6.30: Average usage of emergency exits in Scenario 2a and 4b.

Scenario 4c is similar to Scenario 4b with the only difference in the use of empirical data for detection and compliance probabilities in Scenario 4c. The travel paths of all the agents in Scenario 4c are shown in the diagrams in Table 6.12.

Table 6.12: Travel paths taken by the agents in Scenario 4c.

<table>
<tr><th>Exit 1 and Exit 2 (Catchment area 1)</th><th>Main (Catchment area 2)</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><th>Exit 5 (Catchment area 3)</th><th>Exit 3 and Exit 4 (Catchment area 4)</th></tr>
<tr><td>
</td><td>
</td></tr>
</table>

In Scenario 4a, agents performed searching behaviour without any guidance to find an exit. Table 6.10 showed the number of agents using the exits in Scenario 4a. In Scenario 4c, agents can now use signage information during their search for an available exit. In this scenario, the average number of agents using each exit is shown in Table 6.13.

Table 6.13: Average number of agents using each exit in Scenario 4c.

Emergency Exit 1+ Emergency Exit 2	Main exit	Emergency Exit 3+ Emergency Exit 4	Emergency Exit 5
66	78	83	56

Figure 6.31 a comparison of the exit usage between Scenario 4c and Scenario 4a. In Scenario 4a, no signage information was included, and the agents purely relied on their searching behaviour to find an exit. In this scenario, a large proportion of the agent population used the main exit to leave the structure. In the meantime, a slightly under usage of the emergency exits is apparent. By enabling the interaction with signage during their search an exit in Scenario 4c, the simulations produced a more balanced use of all available exits. This results show that the signage system can help achieve more balance use of available exits when the occupant population lack the necessary knowledge of building layout.

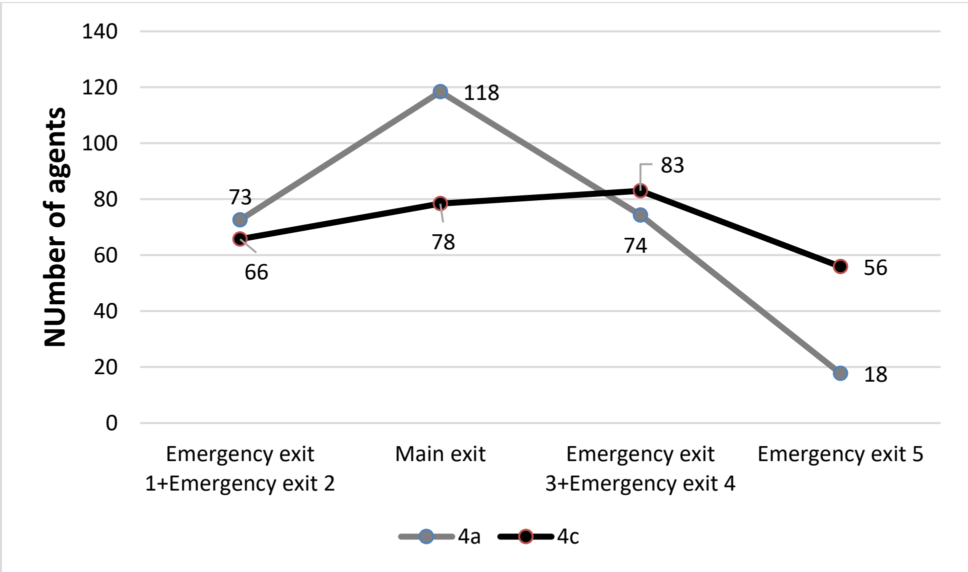


Figure 6.31: Number of agents using exits in Scenario 4a and 4c.

6.6 Summary

In this chapter, a complex demonstration case based on a hypothetical building structure was presented to show the new signage-based navigation model's capability to simulate the agents' wayfinding behaviour with/without a previous familiarity with the exits as well as with/without signage system. Another important objective of this demonstration case was to show the difference in the way of representing the interaction between the agent and the chain of signs between the new model and buildingEXODUS.

In the real world, when occupants see a sign, they will perceive the direction indicated by the sign and start following that direction [BS5499-4:2013]. To represent this behaviour, the current modelling approaches work on a prescriptive approach. In buildingEXODUS, when designing a signage system, a model user manually connects the signs by providing a target to visit to create a complete escape route [Filippidis *et al.*, 2001, 2003, 2006, 2008]. Each sign has an associated redirection node which connects to the next sign. When an agent starts following a sign, the location of the next redirection node is added to the agent's itinerary list. This implies that the agent implicitly knows the location of the next sign in the chain due to the redirection node being added to the itinerary list. Hence, the agents follow the signs deterministically with no sense of direction. On the contrary, in the new model, a user only need to provide the location and direction of the signs as it would be planning and positioning a signage system within a real built environment. The new model can then simulate agent's behaviour of understanding and following the direction of the signs.

To demonstrate the differences and similarities between the agents' wayfinding approaches and modelling chain signage, the demonstration case is modelled using the new signage-based navigation model and buildingEXODUS. Four scenarios were examined with different levels of exit knowledge. In Scenario 1, no signage information was included, and all the agents are familiar with the main exit only. In Scenario 2, no signage information was included, and all the agents had full knowledge of all exits. In Scenario 3, agents are familiar with the main exit only, but they can use signage to find an exit. Lastly, in Scenario 4, agents had no previous familiarity with the structure. Hence, their navigation relies on the searching behaviour and signage in the structure.

The comparison of the new signage-based navigation model and buildingEXODUS results demonstrated that both models produced largely the similar results when simulating the scenarios without signage. However, the analysis also showed the difference in the results while modelling the interaction between the agent and signage. The difference was due to the different ways of representing the interaction with signage between the two models. To represent a chain of signs in buildingEXODUS, all the signs had to be linked manually. Due to this prescriptive approach, the agents implicitly knew the location of the next sign and followed the signs almost deterministically. In the new signage-based navigation model, an agent can understand the direction of the sign and use their sense of direction based on the navigational graph to guide their movement into a particular direction. In this way, when an agent detects a sign, the agent starts following the direction of the sign. This is a more realistic representation of the behaviour of following the signs. In addition, this modelling approach allows to examine 'human errors' that could happen in using signage in wayfinding and planning a signage system, i.e. occupants could miss the next sign when following a signage direction and signage configuration errors can be identified.

Scenario 4 is a special scenario in which the agents had no previous familiarity with any exits. At present, all of the evacuation models known to the author cannot simulate this type of scenario. The memory and the searching algorithm implemented in the new model allow the agents to differentiate between visited and unvisited spaces, so that they can explore a complete unfamiliar space and search for an exit or signage, without being trapped or making unnecessary repeated movement.

Overall, through these simulations, it is confirmed that the new model performed exactly as originally designed. Firstly, the new model is fully compatible with buildingEXODUS in simulating the scenarios without signage. This further validates the new modelling approach in simulating an evacuation with partial or full exit knowledge among the occupants. Secondly, it is proved that the new model is capable of more accurately representing the interaction between agents and signage. Due to this capability, the new model can be a useful tool to examine the configuration of a signage system and evaluate its effectiveness. Finally, the new model provides the potential to simulate a wide range of scenarios, such as occupants need to perform search for a way out due to the lack of the understanding of building layout or the loss of any part of familiar escape routes, the transaction from normal circulation to an emergency evacuation etc.

Chapter 7 Conclusion and Future Work

The work presented in this thesis is an attempt to improve the representation of the interaction between agents and signage system (especially chain signage) in evacuation modelling (and potentially circulation modelling) through developing a new signage-based navigation model which integrates signage (with direction), navigational graph, individual memory and search algorithm into the simulation of agent wayfinding during an evacuation. In this chapter, the major outcomes of the research are summarised, followed by a summary of this research addressing the original research questions, as set out in Chapter 1 (Section 1.2). Lastly, the areas where this research can be further developed are highlighted.

7.1. Conclusion

In the United Kingdom and European Union, the provision of means of escape in public buildings and work places is extensively addressed by relevant legislation and standards [the Regulatory Reform (Fire Safety) Order, 2005; the 89/654/EEC Directive]. According to British Standards BS 5499-4:2013 and BS 9999:2017, means of escape is a safe egress route or routes that are provided for building occupants to travel from any place within the premises to a place of safety. In large and complex buildings, multiple escape routes are provided so that the maximum possible number of occupants can be evacuated safely within the available safe-escape time (ASET) [ISO/TR 13387-8:1999, ISO/TR 16738:2009].

Escape routes guide the occupants to a place of safety at the shortest travel distance from each place within the premises. However, identifying a safe and shortest escape route can be difficult to the occupants. This is due to, firstly, an exit may not be directly and clearly visible from most the places within the premises. Secondly, in a large structure, escape routes can create a complicated network including changes in level and/or direction. And, thirdly, it cannot be assumed all the occupants are well familiar with the building layout and are able to efficiently identify the shortest escape route to an available exit. In some cases, even the occupants who are familiar with the building layout might not be familiar with some of the escape routes that are designed for an emergency evacuation.

The solution to this wayfinding difficulty is addressed using the escape route signage system which provides simple and clear identification of the means of escape [BS 5499-4:2013, BS EN ISO 7010]. The provisions of designing and setting up an escape route signage system in a building have been explicitly addressed in relevant national and international standards, such as BS 5499-4, BS 5499-10, BS ISO 3864-1, BS EN ISO 7010. The signs should indicate the primary escape routes within the building and each escape route normally requires a series of signs that form a signage chain along the route [Filippidis *et al.*, 2008]. An occupant who may be unfamiliar with the building can escape to a place of safety by correctly identifying the signage symbol, reading the text and following the direction of the escape route sign.

Despite the importance of signage systems as a solution to wayfinding difficulty and their wide usage in buildings to provide wayfinding assistance during both circulation and evacuation conditions, the effectiveness of signage remains unclear [Xie, 2012]. The building designers, engineers and officials generally assume that if the signage systems are installed according to the provided guidelines, the occupants will understand and comprehend the signs, and follow the message provided by the signs [Benthorn & Frantzich, 1999]. In past, the under-usage of emergency exits has been highlighted in high profile disasters, such as the Beverly Hills Supper Club fire in 1977 [Best, 1977], the Scandinavian Star Disaster in 1990 [The Scandinavian Star Disaster of 7 April 1990], the Cook County Administration Building fire in 2003 [James Lee Witt Associates, 2004], the Station Nightclub Fire in 2003 [Grosshandler *et al.*, 2005a, 2005b]. One of the reasons that contributed to these disasters is the inefficiency in the signage system in guiding the evacuees to emergency exits.

Due to the drastic development of pedestrian modelling, researchers are now able to study occupant's movement and behaviour in normal circulation and emergency scenarios [Gwynne *et al.*, 1999; Kuligowski *et al.*, 2010]. Evacuation modelling provide results close to real-world such as determining the sufficient time for the occupants to evacuate safely from the structure. This has led to the increased demand in the usage of pedestrian/evacuation models.

These evacuation models provide an ideal platform to simulate a wide range of occupant evacuation behaviour during an evacuation. However, most of the simulation models lack the capability to represent the interaction between agents and signs, especially a series of signs [Filippidis *et al.,* 2003] in normal circulation and emergency evacuation. This is because most simulation models focus on determining the evacuation efficiency of a structure in a relatively ideal situation, where it is commonly assumed in modelling process that the agents are aware of the location of some or all exits. Hence, these models ignore the active wayfinding process performed by agents [MassMotion (2015), PathFinder (2013), FDS-Evac (Korhonen and Hostikka 2008), STEPS (2010)].

A few evacuation models such as buildingEXODUS [Filippidis *et al.,* 2001, 2003, 2006, 2008; Xie *et al.,* 2007, Galea *et al.,* 2011], PEDROUTE [PEDROUTE V5 Manual], MASSEgress [Pan 2006] and work of [Chu *et al.,* 2015] can represent the interaction between the agents and signage. However, agents in these models lack the understanding of structure layout, space connectivity and therefore they have limit capability of following the signage direction. For instance, in buildingEXODUS, if an agent detects a sign, the agent will be directed to a designated location rather than following the signage direction [Filippidis *et al.,* 2006, 2008]. If the agent following a sign fails to detect the next sign in the signage chain or find an exit, the agent will execute arbitrary backtracking, searching behaviour [Filippidis *et al.,* 2006, 2008] or even random walk in MASSEgress [Pan, 2009]. This can potentially result in the agent being trapped in a loop and/or making unrealistic movement.

The work presented in this thesis attempted to address these known issues in presenting the interaction between agents and escape route signage system in evacuation modelling. This is through addressing the research questions raised in Chapter 1 which were as follows:

Question 1: How do people perform wayfinding in a built environment?

> ***(Q1.1): How does signage system influence people's wayfinding in a built environment?***
>
> ***(Q1.2): What are the factors influencing the effectiveness of signage?***

Question Q1.1 and Q1.2 are addressed together. In Chapter 2 (Section 2.3.2), various environmental factor influencing the wayfinding process were discussed. These factors include spatial differentiation, visual access, layout complexity, signage and smoke. It was found that in an emergency/circulation scenario, signage can influence the wayfinding performance of the building occupants [Wiesman (1981); Gärling *et al.,* [1986]; Hajibabai *et al.,* (2007)]. It was also noted that occupants prefer to leave the structure using familiar exits which are generally the entry points of the structure [Sime (1985); Shields and Boyce (2000); Nilsson *et al.,* (2008) and Olander (2015)]. Hence, in an emergency scenario, ignoring the escape route signage leading to emergency exits may result in reduced usage of emergency exits which may further create congestion around the main entrance and increases the evacuation time.

In Chapter 2 (Section 2.5), the interaction between the occupants and signage systems is described. In the real world, the interaction between the occupants and signage system is a complex process and influenced by various physical and psychological factors [Filippidis *et al.,* (2003, 2006, and 2008)]. Following the order in the interaction with signage, these factors include the visibility of the sign, the perception of the sign and the interpretation of the signage information and taking an action to follow the sign.

Primarily, the sign must be physically visible to the occupants (Chapter 2, Section 2.5.1). The visibility of a sign is influenced by the location of the sign, the size and design of the sign, the signage information quality, the internal layout of the building, the levels of lighting of the sign and the environment, and the presence or absence of smoke [Filippidis *et al.,* 2006].

To perceive a sign (Chapter 2, Section 2.5.2), first, an occupant must be located within a particular range of distance from the sign. And, second, the sign must be situated inside the occupant's field of view [Xie, 2011]. The probability of perceiving a sign also depends on the environmental conditions. An airport, for instance, is often populated with emergency evacuation signage and circulation signage and products advertisements. These create a visual clutter which may lead an occupant to lose the sight of an important sign [Filippidis *et al*., 2003, 2006]. The visual clutter also exerts a physiological pressure on an occupant creating an information abundance preventing them from discerning the sign.

The interpretation of sign depends on occupant's own interpretation of sign and their will to trust the information displayed by the sign (Chapter 2, Section 2.5.3). Other factors which influence the occupant's interpretation of sign include education background and the language in which sign information is displayed. Lastly, if the occupant correctly recognises and interprets the sign, the action taken by an occupant depends on their desire to believe and follow the signage information and the influence of other occupants and conditions [Xie, 2011].

Question 2: How does the impact of signage on evacuation performance is represented in existing models?

(Q2.1): What are the limitations in the existing models?

(Q2.2): What are the aspects of modelling that can be improved?

Q2.1 and Q2.2 are addressed together. The literature review conducted in Chapter 2 and Chapter 3 helped to identify the limitations in the existing modelling approaches and the aspects of modelling that can be improved. Based on these findings, a new signage-based navigation model is designed and developed (Chapter 4). The limitations in the existing modelling approaches are explained in Chapter 4, Section 4.2.

Despite the importance of signage in wayfinding, the interaction between the agents and signage especially series of signs has been generally either ignored or simplified in most evacuation/pedestrian models [Filippidis *et al.,* 2003]. In evacuation models such as MassMotion [2015], PathFinder [2013], FDS-Evac [Korhonen and Hostikka, 2008] and STEPS [2010], it is implicitly assumed that agents are aware of internal connectivity of the structure. These models simulate the relatively ideal scenario where the agents can use pre-computed map systems such as the potential map and the distance map (or equivalent map system) to navigate towards their desired target. The underlying assumption of using this approach is the agent has the full or partial familiarity of the building layout. Hence, the representation of the agent wayfinding process is ignored.

Evacuation models such as buildingEXODUS [Filippidis *et al.,* 2001, 2003, 2006, 2008; Xie *et al.,* 2007, Galea *et al.,* 2011)], PEDROUTE [PEDROUTE V5 Manual], MASSEgress [Pan, 2006], ALLSAFE [Kuligowski *et al.,* 2005; Kuligowski *et al.,*, 2010; Xie, 2011], E-SCAPE [Kuligowski *et al.,* 2005; Kuligowski *et al.,*, 2010; Xie, 2011], BGRAF [Kuligowski *et al.,* 2005; Kuligowski *et al.,*, 2010; Xie, 2011], Legion [Kuligowski *et al.,* 2005; Kuligowski *et al.,*, 2010; Xie, 2011], EvacSim [Kuligowski *et al.,* 2005; Kuligowski *et al.,*, 2010; Xie, 2011], MOBEDIC(EGRESS) [Kuligowski *et al.,* 2005; Kuligowski *et al.,*, 2010; Xie, 2011] and SGEM [Kuligowski *et al.,* 2005; Kuligowski *et al.,*, 2010; Xie, 2011] can represent the interaction between the agents and signage. However, a major limitation in all of these models is that due the limited capability of perceiving the environment, the agents lack a sense of direction and the internal connectivity of space. In addition, the agents in these models also do not keep a record of their past wayfinding experience. The details of the signage model implementations have been found mainly for PEDROUTE, buildingEXODUS and MASSEgress. Hence, the current techniques used by these three models were discussed in detail in Chapter 3 (Section 3.2.6).

In PEDROUTE (Chapter 3, Section 3.2.6.1), to model a circulation scenario, the model assigns the agent a target prior to the simulation. And, while simulating the evacuation scenario, PEDROUTE assigns the shortest route to the agents towards the available exit. The signage model allows the model user to manually navigate a few agents or the entire population towards a destination. A global compliance probability called SPRO is set to 100% by the model developers. Hence, it is assumed that if the agent “sees” a sign, they will start following the route indicated by the sign.

In buildingEXODUS (Chapter 3, Section 3.2.6.2), to create an escape route consisting of a series of signs, a model user has to manually connect the signs to form a chain along the intended route. To simulate the agent’s wayfinding behaviour of following the series of signs, the concept of redirection node was used [Filippidis *et al.*, 2008]. A redirection node provides the location of another redirection node associated with next sign in the signage chain. Hence, when an agent detects a sign, the redirection node conveys the agent the location of the redirection node of the next sign in the signage chain. The agent’s target is then set to visit the redirection node of the next sign by buildingEXODUS. Furthermore, due to lack of memory to store their past visited places, the agents are unable to remember their previously visited places. For example, if the agent following a sign fails to detect the next sign along the signage chain, the agent would execute arbitrary searching and backtracking behaviour [Filippidis *et al.*, 2006, 2008]. These behaviours may lead to unrealistic milling movement of the agents in some extreme cases.

Lastly, in MASSEgress (Chapter 3, Section 3.2.6.3) the agents navigate using their perception system. This means the agents in MASSEgress are able to perceive the environment through their own vision. However, the important detail like the theoretical background of creating the agent's vision is unclear from the discussion [Xie, 2011]. In addition, an object such as a sign, door, etc., is visible to the agent if it falls within the agent's field of view. Hence, it is implicitly assumed that the signage detection and compliance probabilities are 100%. The agent also lacks the memory to remember their past wayfinding experience. Thus, if the agent loses sight of their target or chosen exit, the agent walks randomly until a new goal is detected.

Lastly, the aspects of the modelling approach that can be improved include (Chapter 4, Section 4.2):

- **Optimal navigation path based on exit knowledge:** It is normally required that the agents have some form of knowledge of the location of exits and their targets. Based on this knowledge, the model can work out for the agents a shortest route available to evacuate the structure or to their target. The wayfinding process using external source of information, such as signage systems is largely ignored. As a result, the simulation results produced reflect a determined evacuation scenario rather than that based on human wayfinding in a real evacuation or circulation.

- **No sense of direction and internal connectivity of space:** The agents lack a sense of direction and space connectivity. Therefore, the agents are not able to follow a direction but heading for an assigned target.

- **Memory:** The agents do not store their navigation experience. Hence, the agents could make an unnecessary and unrealistic movement (such as being trapped in a loop or travelling repeatedly along the same route) if they have to retrace or search.

Question 3: How to expand the representation of human visibility without significantly increasing the demand for computational power?

> ***(Q3.1): What are the existing approaches in evacuation and circulation models for modelling agent's visibility?***
>
> ***(Q3.2): How to improve and utilise the representation of human visibility to better represent agent spatial awareness?***

Question Q3.1 and Q3.2 are addressed together. Chapter 3 looked at how the various evacuation/circulation models represent agents' vision (Chapter 3, Section 3.2.5). It was found that most of the evacuation/circulation models simulate the interaction between the agents and signage using the pre-computed map systems (potential map and distance map). For instance, in buildingEXODUS, the navigation and movement of the agents are controlled using either the potential map or the distance map. The potential map provides distance information between any nodes within a geometry to the nearest exit. The assumption of using the potential map system is that the agents have full knowledge of all available exits. Therefore, the agents can select the nearest exit and always take the shortest route to evacuate. The distance map is like the potential map in terms of the algorithm used to construct the map. However, the difference is, one distance map is created for each exit. The use of the distance map depicts the scenario where the agents may have partial knowledge of the building layout, i.e. they are aware of one or several exits but not necessarily the nearest exit.

An exception is MASSEgress (Chapter 3, Section 3.2.6.3) where the agents have visual perception and the movement independent of any pre-computed information. An agent can 'see' the exit signs, exits, obstacles and the other agents within their field of vision. However, this modelling approach is computationally expensive as it requires frequently updates of the agent's field of view.

Other techniques like visibility graph, sub-goal method, navigational graph and isovist were studied (Chapter 3, Section 3.2.5). The purpose of these techniques was to provide a means of visibility of space to the occupants. Chooramun *et al.*, [2010] utilise a concept of Navigational Graph which consists of waypoints and path segments. The waypoints act as points of reference to guide the agents towards a goal point and path segments connect visible waypoints to each other, signifying the traversable path. A navigational graph provides the agents with a sense of the internal layout of the structure and space connectively without a demand for additional computational power during a simulation. However, the work of Chooramun *et al.,* [2010] did not include the agent's wayfinding using the signage systems.

This thesis has led to the development of a new signage-based navigation model (Chapter 4). The new model is partly based on the previous research performed by Chooramun *et al.,* [2011], Filippidis *et al.,* [2001, 2003, 2006, and 2008] and Xie *et al.*, [2005, 2012]. In this thesis, the signage visibility [Filippidis *et al.*, 2001, 2003, 2006, 2008; Xie *et al.,* 2007] and the navigational graph are combined which allow the agents to follow the direction indicated by the signs, i.e. the direction of the escape routes. The signage visibility in the new model is based on the buildingEXODUS approach to represent the visibility of a sign called Visibility Catchment Area (VCA). The VCA of a sign represents the physical extent to which the sign is visible to the agents in the structure. When the agent is in the VCA of a sign and facing the general direction of the sign, the agent can detect the sign. In addition, in the new model, the signage detection is based on existing empirical data suggesting in the real world 38% of occupants could detect a sign if it is physically visible and subsequently, 97% of them would use the information provided by the sign for wayfinding [Xie *et al.*, 2012].

Question 4: How to efficiently represent and store the information agent perceived to form an understanding of building layout?

> ***(Q4.1): How to store agent's wayfinding experience?***
>
> ***(Q4.2): How the stored wayfinding experience can be used to build up individual navigation experience?***

Question Q4.1 and Q4.2 are addressed together. In most evacuation models it is commonly assumed that agents are aware of the internal connectivity, the location of exits and their targets [SIMULEX (Thompson, 1994), PEDROUTE (PEDROUTE V5 Manual), buildingEXODUS (Galea *et al.,* 2011)]. Hence, to provide an agent with a means of navigating to their target, these models use map systems such as the potential map and the distance map to guide the agents in navigation. Using the map systems, the agents use an optimal path to reach their desired target. Thus, the agents ignore the wayfinding process using an external source of information, such as signage systems. The agents also lack the capability to remember their past visited places, therefore they cannot use their past navigation experience to guide their wayfinding

In the new signage-based navigation model, the agent memory is introduced which allows the agent to create an individual navigational experience (Chapter 4, Section 4.4). The agent's memory stores the wayfinding information including visited places and perceived signs. The stored information enables the agent to differentiate visited and unvisited spaces and routes. The memory allows the agents to avoid visiting the space where they could not find viable exits. Furthermore, the memory allows the agents to navigate in an environment without relying on an assigned target. This is particularly useful in modelling the agent wayfinding behaviour in an unfamiliar environment (Chapter 4, Section 4.5.3). Lastly, the memory allows the agent to perform backtracking if the agent reaches a place where there are no viable exits or they did not find any useful wayfinding clues (Chapter 4, Section 4.5.3.2).

Question 5: How the introduction of spatial awareness and individual navigation experience can improve the modelling of wayfinding behaviour in an evacuation and circulation?

> ***(Q5.1): How to represent occupant's decision-making process based on their perception of the environment and individual navigation experience?***

In this thesis, a new signage-based navigation model is proposed and implemented to address the limitations in the existing modelling approaches and improve the representation of the interaction between the agents and signage in wayfinding (Chapter 4, Section 4.3). The improvement is achieved through the introduction of agent's spatial awareness (Chapter 4, Section 4.2.1.1), individual memory (Chapter 4, Section 4.4) and exit route decision making (Chapter 4, Section 4.5) using the perceived space and signage information.

In the new signage-based navigation module, the agent's decision-making capability to decide what action to perform under different scenarios is controlled through the Navigation Module (Chapter 4, Section 4.4). This module provides the agent with a cognition in following three distinct navigation scenarios:

Navigation Strategy 1 (NS1): Agent navigation with full or partial familiarity with the exits (Chapter 4, Section 4.5.1)

NS1 controls how an agent navigates in a structure with full or partial familiarity with the structure layout. To model the agent's wayfinding behaviour with full familiarity with the exits, the agent checks all visible waypoints from their current location and selects the one with minimum potential value to their intended exit or target. Similarly, when an agent has partial familiarity with a single exit, the agent checks all visible waypoints from their current location and selects the one with minimum distance value to their intended exit or target. It should be pointed out that the implementation of NS1 is intended to ensure that the new modelling approach is compatible with any existing modelling approaches that can simulate the same evacuation scenarios with full or partial agent familiarity.

Navigation Strategy 2 (NS2): Following Signs along the route (Chapter 4, Section 4.5.2)

NS2 controls the simulation of a scenario where the agents with or without previous knowledge of the structure can find an exit using the signs configured as a signage chain along the intended escape route.

Navigation Strategy 3 (NS3): Agent without familiarity with building layout or with invalid exit knowledge (Chapter 4, Section 4.5.3)

NS3 simulates the agent's wayfinding behaviour with no previous familiarity with the exits. In this scenario, the agent checks all visible waypoints from their current location and use BFS to search for an exit or a sign.

It should be pointed out that, subject to the changing in situations, such as detecting a sign or following a sign and travelling long enough distance without finding an exit or another sign, the agents can change navigation strategy in navigation.

7.2. Major findings

This study presents a new signage-based navigation model that can be incorporated with the circulation/evacuation models. The model has been written using C++ and tested using the buildingEXODUS evacuation software as the test platform. The existing circulation/evacuation models have various capability of simulating agent navigation behaviour. But most of them focus on estimating the evacuation efficiency of a structure in a relatively ideal situation where it is commonly assumed in modelling and simulation that the agents are fully or partially familiar with the simulated environment hence ignoring their active wayfinding behaviour. The new navigation model developed is more sophisticated and attempts to expand the capability of existing circulation/evacuation models in representing agent navigation by incorporating signage and past navigation experiences into cognitive wayfinding behaviour.

In Chapter 2, an extensive literature review on human wayfinding in a familiar and an unfamiliar built environment was conducted to examine how occupants perform wayfinding. A variety of human and environmental factors which influence wayfinding were studied. The human factors include previous familiarity with the structure, social communication, spatial orientation, cognitive mapping, route strategies, culture, gender, age and special needs. The environmental factors include spatial differentiation, visual access, layout complexity, signage and smoke. This thesis focuses on examining the impact of signage on occupant wayfinding during evacuation scenarios. Furthermore, the provision of the signs described by relevant safety legislation and signage standards and the understanding of the interaction between signage and occupants were discussed.

In Chapter 3, how the wayfinding in a built environment and the impact of signage system on wayfinding are implemented in evacuation modelling was explained. This chapter also described the methods used by three distinct evacuation models, namely, PEDROUTE, buildingEXODUS and MASSEgress to explain the interaction between occupants and exit signs. Chapter 2 and Chapter 3 provided the basis for the study presented in this thesis.

In Chapter 4, the design and implementation of the new signage-based navigation model are presented. The new model is partly based on previous research performed by Chooramun [2011], Xie *et al*., [2005, 2007], Filippidis *et al*., [2001, 2003, 2006, and 2008] and utilises the concept of navigational graph to provide a sense of internal space connectivity and direction to the agents. The new model addresses the identified knowledge gaps in Chapter 2 and Chapter 3 by providing a better representation of the interaction between agents and exit signs.

The new signage-based navigation model provides three distinct navigation strategies which were introduced and explained in Chapter 4. These strategies are:

- **Navigation Strategy 1 (NS1): Agent navigation with full or partial familiarity (Chapter 4, Section 4.5.1).** In this scenario, it is assumed that agent has either full or partial familiarity with the structure.

- **Navigation Strategy 2 (NS2): Agent following the signs along the escape route (Chapter 4, Section 4.5.2).** In this scenario, an agent detects and follows the signs along the escape route during an evacuation to reach a place of safety.

- **Navigation Strategy 3 (NS3): Agent with no previous familiarity or invalid exit knowledge (Chapter 4, Section 4.5.3).** This is a special scenario where the agent has no previous familiarity with the structure or any available exit. Hence, to perform wayfinding the agent executes the searching behaviour (Chapter 4, Section 4.5.3.1) to find an exit/sign.

Furthermore, the following are two important features of the new model:

- **Agent following the signage direction (Chapter 4, Section 4.5.3.1)**

In the new model, the navigational graph [Chooramun, 2011] provides a sense of direction and space connectivity to the agents. Combined with the signage visibility [Filippidis *et al.,* 2001, 2003, 2006, 2008; Xie *et al.,* 2007], the model can represent the process of agents detecting a sign and follow the direction indicated by the sign.

- **Adaptive navigation behaviour using memory (Chapter 4, Section 4.4).**

Each agent in the new model is equipped with a memory to create an individual navigation experience. The agent's memory stores the past visited places and perceived signs which allow the agent to differentiate visited and unvisited spaces and used and unused signs.

In Chapter 5, the verification and validation of the new signage-based navigation model are presented. The three navigation strategies, agent's ability to follow signage direction and agent's memory were verified through a series of component tests (Chapter 5, Section 5.3). Due to a lack of quantitative validation data for evacuation models, the new signage-based navigation model is validated qualitatively against one of BS 5499-4:2013 demonstration case with a series of signs.

Finally, a large-scale evacuation case based on a complex hypothetical geometry was conducted. The results were analysed and described in Chapter 6. Through these simulations and the comparision with the buildingEXODUS model, it is confirmed that the new model performed exactly as originally designed. Firstly, the new model is fully compatible with buildingEXODUS in simulating the scenarios without signage. This further validates the new modelling approach in simulating an evacuation with partial or full exit knowledge among the occupants. Secondly, it is proved that the new model is capable of more accurately representing the interaction between agents and signage. With this capability, the new model can be a useful tool to examine the configuration of a signage system and evaluate its effectiveness. Finally, the new model provides the potential to simulate a wide range of scenarios, such as occupants need to perform search for a way out due to the lack of the understanding of building layout or the loss of any part of familiar escape routes, the transaction from normal circulation to an emergency evacuation.

In summary, there are two major achievements of this work.

1. Improved the representation of the interaction between agents and a series of signs (i.e. chain signage) within evacuation modelling through the introduction of signage direction, navigational graph, individual memory and navigation decision-making algorithm.

In public buildings, especially those large buildings and those with a complex layout, it is not possible to have direct sight of the exits at most of the places within the premises. In order to facilitate an evacuation in an emergency, it is required by building safety regulation and standards that primary escape route from each place to a place of safety should be properly planned. Escape route signs, as part of the management of means of escape, are required to be placed along these routes to give the occupants the necessary direction information, so that they can be guided to a place of safety. Perceiving the signs and following the signage direction are important part of evacuation behaviour of building occupants.

Most evacuation models focus on estimating the evacuation performance of a building in a simplified or idealistic situation, where it is commonly assumed that the agents are aware of the location of some or all exits, their targets, as well as the internal space connectivity, ignoring the agents' adaptive wayfinding behaviour using external source of information (such as signage system) and their active navigation experience. There are a few models which have the capability of modelling the interaction with signage, such as buildingEXODUS, MASSEgress, PEDROUTE etc. However, due to the limitations in their modelling methods, the simulated behaviour of interacting with signage are still not satisfying [Chapter 2 and Chapter 3]. The main issue is that the agents in these models lack the capability of perception and a sense of space connectivity. The former is crucial for perceiving both the signs and the environment, while the latter is crucial for simulating oriented movement. In buildingEXODUS, the agents with limited perception capability can perceive a sign within a certain range, but they will rely on the location of next target indicated by that sign to move. In MASSEgress, a model that does simulate human vision to a greater level, the agents do not possess a sense of space connectivity. The agents may 'see' a sign and move into that signage direction, but the movement is not guided by the space connectivity. Therefore, none of these models can simulate the process of perceiving a series of sign and following the intended route indicated by these signs to a satisfying level that approximates how people use signage in reality.

The new signage-based navigation model is built upon the original signage model which has been developed and tested in buildingEXODUS. The new model inherited the following features of the original model:

- Using the concept of visual catchment area (VCA) to represent signage visibility under normal lightening conditions.
- Using the detection, perception and compliance probabilities to represent the physical and psychological aspects involved in the perception of the signs.

The new model introduces the following new features to address the known issue in order to improve the representation of the interaction between agents and a series of signs:

- Introducing signage direction based on relevant signage standard [BS 5499-4:2013].
- Introducing navigational graph to give the agent a sense of space connection.

In the new model, when successfully perceiving a sign, the agents get the exact direction indicated by the sign, in relation to both the position of the sign and the arrow direction in the sign. Then the agents check the space connectivity around them represented by the navigational graph to find the closest direction to the signage direction. The agents move into this direction while continually checking the space connectivity further down the route to adapt their direction of movement. This process continues until the agents detect another sign (start to follow the newly detected sign), find a final exit (successfully escape the premises) or under certain conditions, give up following the signs (revert to previous navigation strategy).

In this way, the new model can simulate the movement of agent following a signage direction along the intended escape route more accurately.

2. The model can be potentially expanded to simuate more complex navigation behaviour.

With the introduction of active navigation experience through individual memory, the agents are able to differentiate visited and unvisited spaces, used and unused signage. This allows the agents to make more informed navigation decisions based on their past navigation experience they obtained from previous visits or built up while moving within the premesis. Besides, the information may be used to build a cognitive understanding of the building layout so that the agent can make more advanced navigation decisions. Based on the new features introduced, the new model opens the potential to simulate a wide range of scenarios, such as occupants need to perform search for a way out due to the lack of the understanding of building layout or the loss of any part of familiar escape routes, the transaction from normal circulation to an emergency evacuation etc.

7.3. Future work

The new signage-based navigation model is intended to produce an improved representation of the interaction between agents and signage in simulating agent wayfinding behaviour for evacuation modelling (and potentially circulation modelling). The new model combines signage visibility and navigational graph to provide the agents with a sense of space connectivity and direction and allow them to follow the direction. The new model also introduces memory to agents and uses individual navigation experiences in wayfinding decision-making. The new model can simulate the agent's wayfinding behaviour with full, partial and none familiarity with the structure. In essence, the new model expends the capability of existing evacuation modelling in simulating agent navigation in an evacuation. However, the new model can still be further expanded and improved. The potential improvement and fields of interest are now suggested for future work.

7.3.1 Introducing variable decision distance to the reference point

In the new signage-based navigation model, the navigational graph is used to guide the agents in the simulation environment. Each waypoint in the navigational graph acts as a reference point for guiding the agent's movement. In the new model, when an agent moves towards a target waypoint, the agent will not start looking for next target until the agent is within a decision distance to the current target. This decision distance was arbitrarily set to a fixed value of 1m [Chooramun, 2011]. In a scenario with a large number of agents within a small region, several agents may use a single waypoint at the same time causing congestion around the particular waypoint.

This issue can be solved by introducing a variable decision distance. This means each agent has a different decision distance than the others. This would relief the competition for the small area around the target waypoint.

7.3.2 Implementing the actual human field of vision capabilities of the agents

In the new signage-based navigation model, using the navigational graph the agents have a sense of space connectivity of the structure. Since the agents lack a field of vision, they are not able to perceive the impact of other agents and follow other agents. Similarly, in absence of the agent's vision, an agent is not able to perceive the risks in the environment.

An important area for future research may be the implementation of actual human field of vision of the agents. There has been some work on representing humans' field of vision in an evacuation model [Pan, 2007]. To implement an actual human vision, a potential issue can be the computational cost of calculation. However, this can be addressed using the GPU technology. More research needs to be performed to implement real-time human vision in evacuation/circulation models.

7.3.3 Simulating agents' response to smoke and fire hazards

The presence of smoke and the other fire hazards is an important factor that influences people's wayfinding in an evacuation [Gwynne *et al.,* 2001b]. The new signage-based navigation model described in Chapter 4 lacks the representation of agent behavioural response when they encounter smoke and fire hazards. Further development under the frame of the new model is required to simulate agent's response to smoke and fire hazards during an evacuation.

7.3.4 Simulating multi-floor structures

At present, the new signage-based navigation model has been designed for only single floor structures which should be expanded to multiple floors. While this feature will add more sophistication to the new model, the introduction of multiple floors will also add the complexity through the stairs and elevators. In the new model, there is no waypoint defined for representing stairs and elevators. Each floor has a navigational graph and the linking of navigational graphs on multiple floors has not been implemented due to time constraints.

7.3.5 Introduce new dynamic signage

In the new signage-based navigation model, the interaction between the agents and signage was modelled using the conventional static escape route signs and circulation signs (Chapter 5, Section 5.4 and Chapter 6, Section 6.3). According to the empirical data, 38% of occupants who were unfamiliar with the structure detected the static sign and subsequently, 97% of them used the information provided by the static sign [Xie *et al.* 2012]. Whereas, using a new dynamic signage system 77% of occupants were able to see the sign and 100% use the information provided by the sign [Xie *et al.* 2014]. The presentation of the new dynamic signage may be required to reflect the new development in building wayfinding system.

7.3.6 Implementing all the possible signage direction

BS 5499-4:2013 and ISO 3864 prescribe eight recommended combinations of signs containing arrow direction and supplementary text (Chapter 4, Section 4.5.3.1). In this thesis, five combinations of them are implemented and tested. These are, sign with an up arrow, sign with a right arrow, sign with a left arrow, sign with an up right arrow and sign with an up left arrow. The remaining three signage directions (sign with a down right arrow, sign with a down left arrow and sign with a down arrow) can be implemented in the new model to allow the simulation of all possible signage directions.

7.3.7 Modelling leader behaviour

At present, the new model does not simulate the social behaviour such as leader influence on the wayfinding. In an evacuation scenario, members of arranged structured groups (such as families) likely to remain together and follow the leader [Pan, 2006]. A leader can be an agent among the group of agents with knowledge of the building. In the future implementation of the new model, in Navigation Strategy 3 (Chapter 4, Section 4.5.3), where agents with no previous familiarity with the exits and no signage available, the agents may follow a leader to evacuate the structure. This modification would require further research in introducing agent's social identity, risk perception and improved decision making.

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