Modeling the Wayfinding Queuing Bottleneck in Autonomous Evacuation Navigation System Using Simulation Approaches

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***Abstract*—In the event of an emergency evacuation, wayfinding that is finding the safest and shortest path to the main exit is considered to be a critical problem, especially for unfamiliar occupants. Besides, the time taken to reach the nearby exit will be increased by a variety of bottleneck such as queuing stages. Therefore, a simulation of the occupant evacuation is presented to identify and minimize the queuing bottleneck using an autonomous evacuation navigation system (AENS). AENS is proposed to solve an indoor wayfinding problem because it is independent, reliable and capable of eliminating human as an agent during the emergency evacuation. Thus, this study compares the queuing bottleneck at the door by conducting simulation without and with the AENS using 100, 150 and 200 occupants as the design parameter. The implementation of AENS has enabled the identification, acceleration and minimization of the queuing bottleneck. Moreover, it has proven that the evacuation time for the design parameters has been reduced by 19.9%, 23%, and 32.6% respectively.**

***Index Terms*—bottleneck, dynamic signage, evacuation navigation system, wayfinding.**

I. Introduction

Current development in high-rise buildings with its complexity has caused wayfinding to the nearest exit during emergencies such as fire, to be more challenging. This is especially so for those who are unfamiliar with the building. In the event of a fire scenario, most of the losses of human life are caused by lung damage due to smoke inhalation, collapse of building structures, and collision during the evacuation. The time taken to evacuate is the main factor in avoiding such a catastrophe [1, 2, 3] due to the crucial time within the first three to four minutes. Hence, the occupants must react actively and quickly. However, at the same time, they need to make a decision on the right path to follow, either follow others or follow their own instinct. Their decision is crucial as it is influenced by several factors such as environmental complexity, dynamically changing situations, time pressure, and the background of the ad hoc situation.

Moreover, it has been proven that unfamiliar occupants either use the familiar path (the path used during the first time entrance) as their exit selection, follow other people, follow based on personal instinct, follow spacious environment, follow light or follow building emergency evacuation signage in the event of a fire or smoke, when they intend to withdraw from a current location to a previous location [3][4][5]. Yet, we do not know the accurate data to answer the question “how long is the evacuation time for the occupants in a high-rise building?” The time prediction differs during a fire drill in comparison to actual case of fire [6]. Some researchers have developed evacuation techniques using cellular automata [7], social force [8], and animal behavior [9] in predicting human behaviors during an emergency evacuation, and in improving the evacuation safety management. Nevertheless, the time taken to reach the nearby exit will increase due to bottleneck problems such as the critical path, barriers, as well as human behavior such as herding, and queuing stages. This is due to the existence of the gap between the fire detection and the evacuation process, whereby the occupants do not know the hazardous location, and the minimal information on the signage available does not help the occupants to reach the safest route.

Therefore, this study proposes an autonomous evacuation navigation system (AENS) to generate an effective evacuation preparedness solution and efficient tools to reduce evacuation time towards the safest and shortest path. Hence, this study focuses on the identification, acceleration and minimization of the bottleneck queuing at the door with the implementation of AENS. In addition, it is predicted that the time taken to reach the nearby staircase will be reduced by the proposed system.

This section explains briefly the problems related the perspective of time taken in wayfinding during an emergency evacuation. The rest of the paper is structured as follows. Section II presents an overview of the conceptual framework for AENS, followed by bottleneck identification. Section III describes the methodology used for the simulation model, such as the floor plan layout, pathfinder software used, microscopic models using cellular automata, and three simulation design parameters involved in this research using two types of methods. The results and analysis in Section IV compares the simulation bottleneck, and the simulation time taken based on the design parameters using two methods that are, with and without the AENS. Finally, section V concludes the research.

II. AENS Conceptual Framework and Bottleneck

A. Overview of the Conceptual Framework for AENS

The AENS was developed based on the integration of the involved systems, beginning from the detection until the emergency evacuation that forms one coherent system as to avoid the complexity and high cost incurred, as illustrated in the conceptual framework in Figure 1. The capability of the existing components system was linked together with the resources in order to achieve its purpose and mission that is to design the wayfinding navigation system that might help occupants to find the safest and shortest route to the exit. AENS is more independent, reliable and able to eliminate human as an agent. It generates navigation through a specific dynamic signage system during an emergency evacuation.

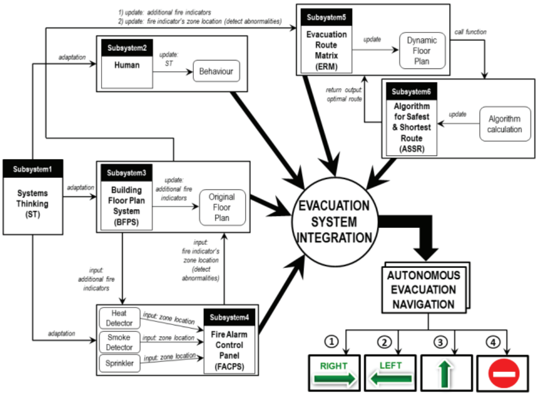

Figure 1: Conceptual Framework: System Integration for AENS

The conceptual framework of system integration (SI) for AENS, starts from the adaptation of systems thinking (ST) to the existing subsystem [10]. ST changes the system behavior into a system point of view and studies the connection between the sub-systems. ST adapted human and integrated to be part of the system and they need to follow the instruction of the emergency evacuation. ST concepts have also been adapted into the fire alarm control panel system, and building floor plan system called FACPS and BFPS. Both, FACPS and BFPS must be integrated so that BFPS knows the location of hazards. With the proactive fire indicator in FACPS, it will trigger siren for emergency evacuation and send the involved fire indicator's location information to BFPS. Once BFPS receives it, the floor plan is updated automatically and it sends the latest updated information to the evacuation route matrix (ERM). ERM stores information of the floor plan layout together with the specific fire indicator's location. ERM calls another subsystem, an algorithm for the safest and shortest route (ASSR) to perform a calculation for the safest and shortest route using a specific algorithm. Each of the subsystems play an important role to ensure that accurate information is given to AENS to provide the safest and shortest route. In the end, once the AENS receives the "optimal route" information, it provides 4 types of DSS guidance; 1) right, 2) left, 3) straight and 4) no entry. In the previous submitted research paper, the no entry sign "X" was used but currently it has been we changed to a standard "no entry" sign.

B. Bottleneck Identification

Bottleneck refers to a phenomenon in a process, stages, or segments where the performance of the capacity of the entire system causes it to slow down, get congested, delay or stop. Any single thread or multiple threads of bottleneck need to reach a synchronization point before the other threads can proceed in order to avoid one or many waiters [11]. In the event of an emergency evacuation, attention need to be given to [12] resolving whether the capacity of a bottleneck increases linearly or step wise through the bottleneck width experiments. Moreover, doors [13] and stairs [14] are the highest areas which contribute to the bottleneck problem and increases the evacuation time taken. Thus, proper action needs to be taken to speed up the evacuation process in order to ensure the occupant's safety.

III. Simulation Model Methodology

A. Floor Plan Layout

The simulation of this study involves several steps beginning from the two-dimensional conversion using AutoCAD of the original 13th floor office building floor plan layout as illustrated in Figure 2, with legends main entrance, left and right staircase exit, and three sub-exits. The occupants are randomly allocated in the building, and the computation time is taken from the currently allocated location to the nearby staircase.

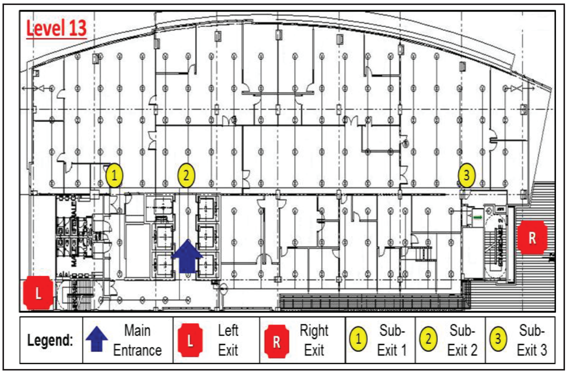

Figure 2: Level 13 of the Office Building Floor Plan Layout

B. Pathfinder Software

Using the 2D AutoCAD floor plan, the file was imported into the Pathfinder simulation software. The pathfinder is an agent-based egress and human movement simulator, which provides a graphical user interface for simulation design and execution for results analysis. With the high-quality 3D visualization, human models represent a range of cultures, ages, attire, and emergency responders with easy tools to create movies that document the results [15]. Since the simulation is focused on the bottleneck identification, Pathfinder has the advantages related to the occupant movement based on exit selection and specific instruction on the door that will be involved.

C. Microscopic Models Using Cellular Automata

The regional evacuation has been focused by using a microscopic model that considers each individual and model interaction between the individuals. Another reason for the typical use of this model is to find good lower bound estimates for evacuation scenarios. Hence, this enabled the examination of the local phenomena like lane formations or bottlenecks and their influence on evacuations. The cellular space concept as modeled by [16] has been used. The floor plan area is 66m x 27m with three sub-main exit doors to reach either the right or left staircase and is divided into 132 x 54 square cells. The compositions of all cells are named as cellular space. Each of the cellular space of this floor plan can hold only one person with the size of 0.5m x 0.5m and the specific zones for the evacuation were named for easy references. This study is void of hazardous areas, obstacles, and specific characteristics of occupants, such as age, gender or disabilities. As mentioned before, the standard movement time is used and the focus is on the time taken to reach the nearby staircase exit.

D. Simulation Design Parameter

This section analyzes the deviations of the bottleneck problem due to the different design parameters method used. For this purpose, two types of method were tested; firstly, without the AENS implementation (NA) and secondly, with the AENS implementation (YA). Both methods were tested using a number of occupants as the design parameters; 100, 150 and 200 occupants as the dependent variable and time taken to reach the nearby staircase as the independent variable with a specific simulation name; 100NA, 100YA, 150NA, 150YA, 200NA, and 200YA.

IV. Result and Analysis

A. Simulation Bottleneck Comparison

Figure 3, Figure **4** andFigure **5** depict the comparison of the simulation bottleneck for 100, 150 and 200 occupants based on two types of methods, that is without (NA) and with the AENS (YA). The blue line represents the method without the AENS and the red line represents the method with the AENS implementation. Door number 36 and 37 are on the left and right staircase and door number 4, 7 and 30 are the sub-exit doors available in the floor. A slight difference was evident between both methods, but it has been proven that the peak bottleneck scenario can be minimized using AENS. Although the sub-exit door number 7 shows that a higher number of occupants has used the door as in Figure 3 and Figure 4, AENS is still been able to minimize the bottleneck at door number 36 and 37 as plotted.

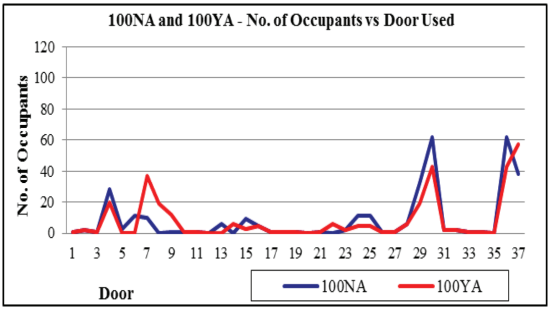

Figure 3:Bottleneck Comparison for 100NA and 100YA

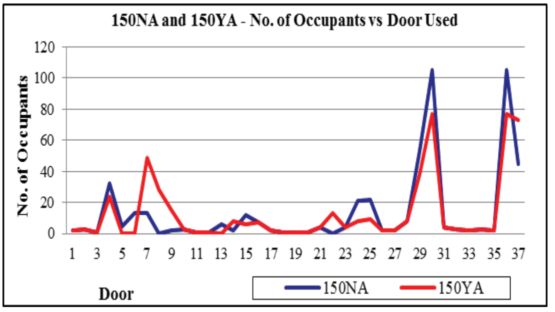

Figure 4:Bottleneck Comparison for 150NA and 150YA

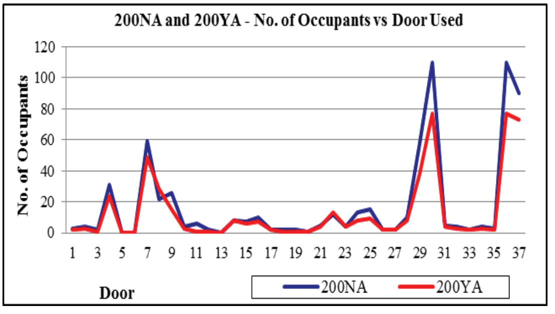

Figure 5:Bottleneck Comparison for 200NA and 200YA

B. Comparison of Simulation Time Taken

Next, the time taken was analyzed in seconds(s) by collecting the minimum, maximum, average and standard deviation, as illustrated in Table 1 (the shaded rows refer to the use of the same design parameter using different method). The result highlight that the minimum time taken was 6.1s, which is the same for all the simulations. The minimum and maximum time taken for the specific design parameter with different methods were also compared; without AENS (NA) and with AENS (YA).

Table 1
Comparison of Arrival Time between NA and YA

Simulation	*Min(s)*	*Max (s)*	*Average(s)*	*Std. Dev (s)*
100NA	6.1	73.4	33.7	17.9
100YA	6.1	58.8	28.9	12.2
150NA	6.1	120.7	51.9	32.9
150YA	6.1	92.9	40.4	21.5
200NA	6.1	127.7	52.7	32.5
200YA	6.1	86.1	44	19.3

The bar graph as in Figure 6 was plotted in order to show the significant time reduction between the design parameters. The maximum time taken in the simulation of 200 occupants indicates a high significance with a 32.6% of reduction from 127.7s to 86.1s, followed by 150 occupants with 23% of reduction from 120.7s to 92.9s, and 19.9% reduction from 73.4s to 58.8s contribute by 100 occupants. Based on the result, it can be assumed that there will be a better and a significant reduction of time taken through the AENS implementation of a bigger crowd and higher occupant capacity.

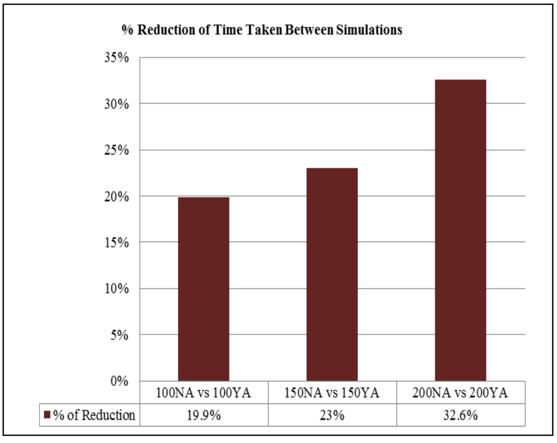

Figure 6: Reduction of Time Taken Between Simulations

V. CONCLUSION

Most of the evacuation research implies that the door is the bottleneck problem and proposed for a modification. Nevertheless, modification for the wider door width cannot be easily done because it acquires a high cost in the renovation and involves the changes of the building structure. Therefore, this research projected a proper simulation methodology to simulate evacuation using existing floor plan layout as to prove the significance of the AENS implementation in minimizing the bottleneck problem during emergency evacuation wayfinding. Through this simulation, we are able to reduce the time taken with a significance improvement for 100, 150 and 200 occupants. In the view of the significance of the results, we aim to verify them using different spatial layouts that are inclusive of internal obstacles for future research.

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