Impact of evacuation design parameter on users' evacuation time using a multi-agent simulation

Abstract

Emergency management is a fundamental issue in building management. Therefore, this study was established to simulate the required times and movement conditions for user evacuation from Campus Infrastructure Building in a 3D environment. Eight simulations are carried out by a multi-agent evacuation simulator, Pathfinder, considering 100% and 70% users capacity with a combination of random, divide, zone 1 and zone 2 access selection. The users evacuated were handled by the A* algorithm in the steering mode of 3D evacuation simulation. The evacuation flow was investigated with the user density heat map and Fruin's Level of Service (LOS). This study found the best path planning obtained from the divide access factor and the impact of the user's capacity is relying on total evacuation time. The critical space is caused by the access width fewer than 1.5 meters for every floor, and by widening some spaces helped to improve the evacuation flow.

Keywords: Emergency management, evacuation planning, multi-agent simulation, 3D simulation, evacuation flow

1.0 Introduction

In tandem with the increase of elevated building development, the user evacuation activities have become a significant study, specifically for emergency management planners and policymakers [1][2][3]. It is not easy to evacuate a mass volume of users in an efficient and effective manner in an indoor environment due to complex individual behavior [4][5]. The evacuation activities in an indoor environment are difficult to forecast due to the different types and locations of accidents that are too common [6][7][8]. In most cases, users need to be transferred as quickly as possible in difficult situations such as increasing user density at a time and unclear knowledge of access selection [9][10]. The probability for the user to be stuck in dangerous situations such as falling or being trapped in the building is high. In addition, the distance to a safe place also cannot be estimated by the user because of planning limitations to transfer the user [11][12]. When the priority of transferring users during emergencies is essential, the knowledge of the best method to manage the movement of the user evacuation is necessary so that the activities can be carried out systematically and efficiently [13][14]. In some instances, evacuation planning structure has to be identified to secure the safe environment of the building. This is because the nearest distance does not guarantee user security due to the uncertainty of accident location within the building [15][16]. Therefore, it is important to provide a user-friendly and highly efficient user transfer plan for user safety in the indoor building environment such as the ability to accommodate large amounts of users at one time [17][18].

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Currently, the evacuation path for an indoor environment is entirely dependent on the corridor and stairs of a building [19]. Corridors and stairs width are developed without taking into account the ability to accommodate large amounts of users at one time. For instance, there are several solutions for evacuation purposes such as Platform Rescue Systems (PRS), Controlled

Descent Devices (CDD) and Escape Chutes [20][21]. The viewpoint of the alternative evacuation method is based on the concept of an evacuation system that applies to oil and gas industries. The system structure utilized for the PRS can be practical as the use of a safety lifeboat for the ship during an evacuation crisis. As it is on the ship, the lifeboat is held tight on the side of the boat and utilized just during the evacuation crisis. The details of the PRS were discussed by Mansor et al. [22] and the first PRS model was introduced to a 21-story building in Ramat Gan (Israel) in July 2004 [20][21]. The brake chute is barrel-shaped and made of heatproof texture or mesh. Each chute arrangement has its function to control the drop speed of the evacuee [22]. In South Korea, the CDD is equipped in the hotel rooms. It contains a set of tools with an abseil belt and plunge line associated with the window frame, and a hammer to break glass in case of emergency. The application of CDD is wide around the globe, mostly in Japan, Korea, Taiwan, Thailand, China, France, Spain, Germany, Italy, Sweden, Finland, Mexico, Australia and Canada [20][22]. Furthermore, it was additionally announced that the brake chute and CDD are mandated to be introduced in structures, for example in control towers, hotels, and etc. in Japan and France [22]. Unfortunately, the PRS, CDD and escape chutes are only suitable for high-rise buildings with a minimum of five floors.

There are some studies conducted to improve the user movement flow from the indoor environment perspective. For example, Minegishi and Takeichi [23] focused on the evacuation from the spectator stands, merging and on-ground situations where the exit access width and the on-ground situation being simulated for design method and crowd management policy. As can be seen in the aforementioned literature, ~~T~~the evacuation flow needs to be planned by phases according to stands in order to avoid the accumulation of evacuees and the accumulation of sequencing due to the limited exit access width and on-ground space due to large-scale evacuees. Gwynne and Rosenbaum [24] have given recommendations for the interpretation and methods to calculate the effective width reduction under numerous circumstances based

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on the observation of user distribution. They discovered that the actual effective width of the user evacuation path is generally more comprehensive than applied in design practices. Lundstrom et al. [25] discussed the relationship between access width and user behavior during the process of evacuation using the tunnel route model [7]. They found that the path with 1-meter width led to higher motion speeds, and there was a linear relationship between dynamic flows of users with access width.

Furthermore, the user's access width is recognized as a mandatory aspect of the evacuation regulation in many countries. Ji et al. [26] recommended that the exit access width should be the same as the access path width so that the user's evacuation flow can run smoothly [27][28]. They found out that at the point when the exit width is nearly the equivalent or more extensive than the width access path, the biggest limit of evacuation can be reached.

Generally, the path selection relies on the distance to the exit access and user capacity as both plays essential roles in reflecting the time taken to evacuate users [29][30]. Therefore, the objective of this study is to identify the combined effect of the access selection and the user capacity on evacuation time and examine the movement conditions aimed at recommending for evacuation planning improvements. The Campus Infrastructure Building (CIB) model ~~that~~ located at Selangor, Malaysia was chosen to validate the proposed method, and the details of the CIB are shown in Table 1. CIB was chosen for validation purposes because it is directly involved with office management work as well as a storage place for electronic properties that are vulnerable to fire. Review of legislation under Section 181, Street, Drainage and Building Act 1974 (Act 133) (Amendment) 2012, Sel. P.U. (A) 142/2012 found that the access width within CIB was compliant for safety purposes with the minimum width of 552mm or 0.552m width [31]. During the simulation process, the variables' values were adjusted to find out the consequence on the evacuation process. The evacuation flow was investigated with the user

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heat map and Fruin's Level of Service (LOS) [26] both were used as an indicator to identify the critical space to improve the evacuation flow.

Table 1. Campus infrastructure building information

Item	**Content**
Building type	Elevated building
Number of levels	Three-level
Dimension of each floor	2,112.115 meter square (m^2)
Location of evacuation path	Adjoining with office compartment
Access to evacuation path	Open access
	Divided by door
Number and location of exit access	Two accesses in 1st floor
	One access in 2nd floor
Number of staircases on each floor	One stair connects 1st, 2nd and 3rd floor
	One stair connects 2nd and 3rd floor

2.0 Methodology

The methodology of this study contains two parts, evacuation planning survey and evacuation simulation process. The existing evacuation planning was surveyed based on the evacuation guide used in CIB, while the user evacuation process was replicated by Pathfinder as a multi-agent evacuating simulator. The framework for this study shown in Figure 1.

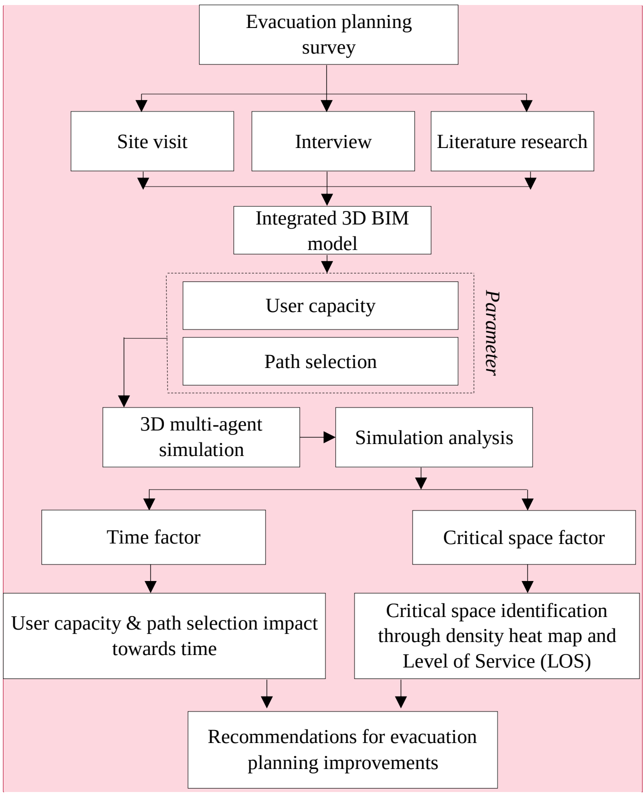

Figure 1. Framework of the impact of evacuation planning on user evacuation time using a multi-agent simulation.

2.1 Evacuation planning survey

An evacuation planning survey was conducted to gain some basic information in order to support the building evacuation simulation model such as existing evacuation planning, user capacity conditions and the path structure design. These parts were separated into two main activities. First, interviews were conducted with the officer and operators of CIB. The information on path distribution within CIB, the usage of each compartment and the capacity of users that are~~is~~ based on each worker's roles were deliberated and collected. Secondly, the

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existing evacuation path is surveyed on site to find the path connections from each compartment to the exit access to gain an overview of the path space optimization and user evacuation process. An example of the compartment arrangement within CIB is shown in Figure 2.

Figure 2. Compartment and corridor arrangement in 3rd floor of CIB

The distribution of user position within CIB is well distributed around each floor while the exit access is located at the edge of each floor. Therefore, the evacuation starts from all around the floor and the evacuation flow is a unidirectional scenario. It is presumed that no specific staff is take in charge to coordinate the evacuation process.

2.2 Evacuation simulation process

2.2.1 Fundamental of model

Pathfinder is used for evacuation simulation to simulate user evacuation activities in an indoor environment. It was used because of its capabilities in simulating the evacuation process more efficiently without the need to set up a field experiment -with high-costs and risky conditions. The steering mode which is a model based on Reynold's [32] steering behavior model and later sophisticated by Heni et al. [33] was used in Pathfinder to handle the simulation of user evacuation [34]. The user behavior was set up as an independent agent with dissimilar characteristics such as age and pre-movement time [35]. The user speed calculation is set based on Xiong et al. [36] equation as follows:

$$\mu i = \begin{cases} 1.4 & \rho \leq 0.75 \\ 0.0412\rho^2 - 0.59\rho + 1.867 & 0.75 < \rho \leq 4.2 \\ 0.1 & \rho > 4.2 \end{cases} \quad (1)$$

μi is user speed in m / s, and ρ is user density based on user / m^2 (Di). ρ can be calculated based on the size and area of the site. The size taken is 0.6m x 0.30m based on the average individual size and the site area is 0.38m x 0.38m as described by Xiong et al. [36] in Figure 3. As a result, the most appropriate user speed is 1.19 m / s.

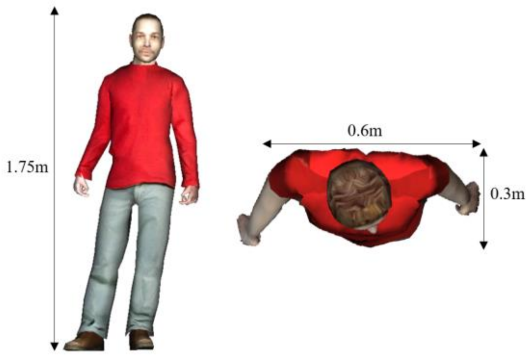

Figure 3. Average individual size

Besides that, a combination of collision handling and steering mechanisms was applied in the steering mode in order to manage the users' flow towards their target exit access in an emergency situation. These mechanisms help to replicate the user movement to the safety exit by moving along the evacuation path and stray from any obstacle [37][38]. The principle of steering mode has been summarized in Figure 4.

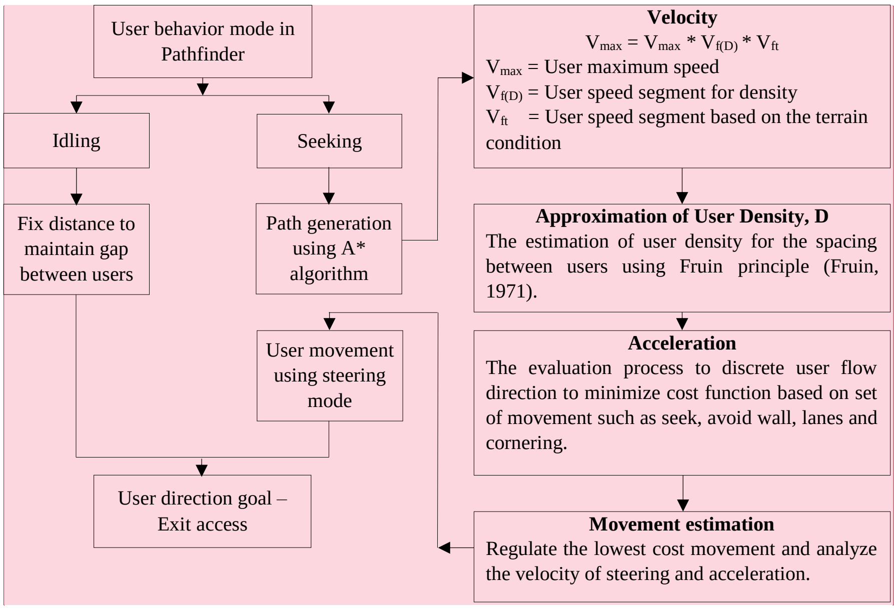

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Figure 4. User evacuation process through steering mode in Pathfinder.

The CIB environment is represented in a 3D geometry model where the 3D model was integrated from Building Information Modelling (BIM) model through the method suggested by Abdul Rahman and Abdul Maulud [39] to maintain the geometry structure and accuracy. In Pathfinder, the CIB demonstration in a 3D geometry mode where the navigation mesh is represented as a 2D triangulated surface within the 3D geometry model and shown in Figure 5.

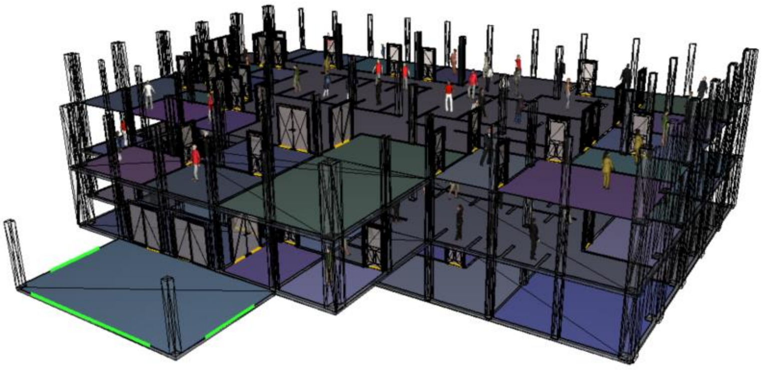

Figure 5. 3D geometry model of CIB.

On top of that, the validation and verification of Pathfinder ~~have been~~were conducted through several tests such as fundamental unidirectional flow, diagram tests and pedestrian behaviour tests at corridors and stairways by Thunderhead Engineering [40]. The result shows that Pathfinder can replicate an excellent representation of using actual movement with the real situation and it has been used widely in the research field for people evacuation simulation in recent years [41][42].

2.2.2 Evacuation time measurement

Time taken to evacuate users is crucial in this study. It has become an indicator to identify if emergency management is good enough for implementation or not. There are two indicators measured based on the recorded time for user evacuation, which includes the impact of path selection over time and the effect of different user capacities over time. Therefore, the time taken is measured and evaluated through several measurements as follows:

- t_1 = time taken for user to exit from the floor (risk zone).
- t_2 = time taken for user to fully exit from building (16.5m from exit access as mentioned by Fire Prevention Standard for Building Design of China [7].

The evacuation dimension and definitions are shown in Figure 6.

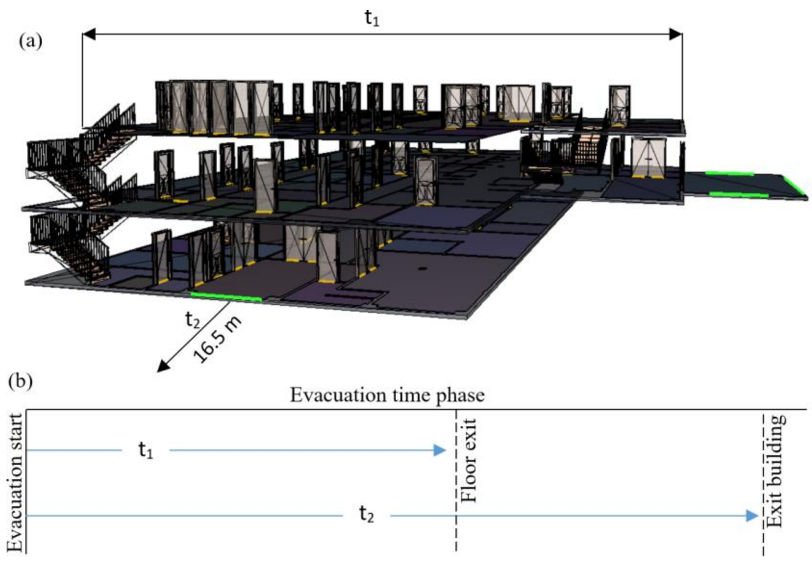

Figure 6. (a) Evacuation time management measured, and (b) Evacuation time phase.

2.2.3 Evacuation simulation parameter

During the evacuation process, users have to transfer from the office compartment to the evacuation walkway quickly towards the exit access. In order to identify which aspect can affect the evacuation time the most, two parameters tested in this study are the user capacity, d_1 and path selection by the users, d_2.

- User capacity parameter (d_1)

In terms of user capacity, the total number of users for the CIB is 155 users, with each level having different capacities. Details of user capacity are as described in Table 2. Siikonen et al. [43] in their~~his~~ study used a percentage ratio of 50% of the total user capacity [44] ~~for case study~~ in San Francisco but in this study, the testing for CIB was done in two stages. The first stage (d_{1a}) involves 100% of total users while the second stage (d_{1b}) goes for 70% of the total users as high capacity is required as a precautionary measure and has a high impact on emergency management as used by Pan et al. [7]. The breakdown of this percentage is to determine the effect of the user's capacity on the simulation results.

Table 2. User capacity consideration for d_1 parameter

No.	Floor	User capacity, d_1 (100%)	User capacity, d_2 (70%)
1	1st floor	64	45
2	2nd floor	54	38
3	3rd floor	37	26
Total		155	109

- Path selection (d_2)

This aspect of path selection is used in assessing user behavior as described by Wang and Sun [45] as the optimal segmentation path where testing is conducted in four stages. For the first stage (d_{2a}), the exit access selection decision is set randomly while the second stage (d_{2b}) of exit access selection is divided by the user's proximity zone (zone 1 and zone 2) to exit access. Each zone is evaluated by its proximity to the exit access based on the distance measured on the field from one node to another. The distribution of nodes, zones and accesses are shown in Figure 7. The third (d_{2c}) and fourth (d_{2d}) stage is performed using only one access per level for each stage. The third stage will use D1F1, D1F2 and D1F3 while the fourth stage will use D2F1, D2F2 and D2F3 as the exit accesses. This zone division is intended to test the result if there is any restriction on either one of the accesses during emergencies.

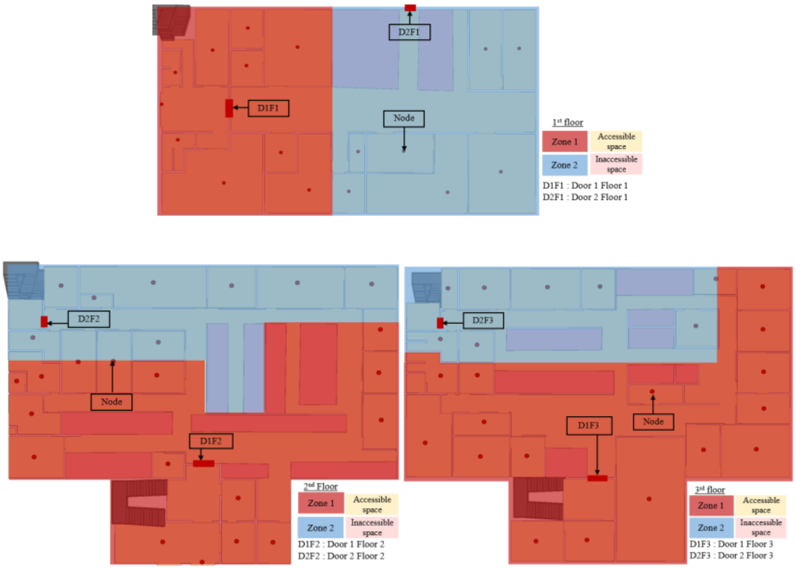

Figure 7. The exit access and zones fraction within each floor

By considering the parameters used in this study, d_1 with two designed input (d_{1a} and d_{1b}) and d_2 with four designed input (d_{2a}, d_{2b}, d_{2c}, and d_{2d}), a total of eight combinations of d_1 and d_2 were simulated. The parameters involved in the emergency evacuation model are listed in Table 3.

Table 3. Parameter in the simulation model

Item	**Content**			
User capacity (d_1)	100% (d_{1a})	1st floor: 64	2nd floor: 54	3rd floor: 37
	70% (d_{1b})	1st floor: 45	2nd floor: 38	3rd floor: 26
Access selection (d_2)	Random access (d_{2a})			
	Divide access (d_{2b})			
	Zone 1 access (d_{2c})			
	Zone 2 access (d_{2d})			
Parameter simulation (d_1+ d_2)	$d_{1a}\ d_{2a} = S_1$	$d_{1a}\ d_{2b} = S_2$	$d_{1a}\ d_{2c} = S_3$	$d_{1a}\ d_{2d} = S_4$
	$d_{1b}\ d_{2a} = S_5$	$d_{1b}\ d_{2b} = S_6$	$d_{1b}\ d_{2c} = S_7$	$d_{1b}\ d_{2d} = S_8$

2.2.4 Evacuation algorithm

In performing 3D simulations, the A* algorithm was used. The simulation aspect used is based on the user's position to move from their starting location to the exit by choosing the path that follows the arrangement route to their exit. This path selection process affects the overall simulation results, as the time spent walking and waiting in the queue is taken into account in order to anticipate the path chosen to achieve the user's objectives. The A* algorithm is used to calculate the economical path so that users can select to get out of the model. An important aspect of the A* algorithm is F = G + H. F, G, and H are variables for each node point calculated to obtain a new node. F is the total number of nodes, G is the distance between the current node and the beginning node, while H is the approximate distance from the current node to the last node. Since F is the total number of nodes, the sum of F can be calculated based on Equation 2 as follows:

$$currentNode.f = currentNode.g + currentNode.h \tag{2}$$

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An example of the path generation process and pseudocodes of the A* algorithm can be seen in Figure 8 and Figure 9. By using the A* algorithm, the computation time to find the best path is shortened due to the fact that the best path is identified based on the nodes that provide the best chance of generating the most suitable path.

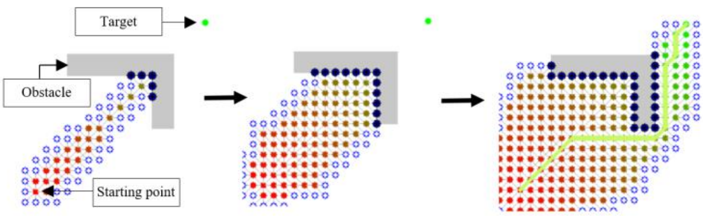

Figure 8. A* algorithm path generation process

```
// A* (star) Pathfinding

// Initialize both open and closed list
let the openList equal empty list of nodes
let the closedList equal empty list of nodes

// Add the start node
put the startNode on the openList (leave it's f at zero)

// Loop until find the end
while the openList is not empty

// Get the current node
    let the currentNode equal the node with the least f value
    remove the currentNode from the openList
    add the currentNode to the closedList

// Found the goal
    if currentNode is the goal

// Generate children
    let the children of the currentNode equal the adjacent nodes

    for each child in the children

        // Child is on the closedList
            if child is in the closedList
                continue to beginning of for loop

        // Create the f, g, and h values
            child.g = currentNode.g + distance between child and current
            child.h = distance from child to end
            child.f = child.g + child.h

        // Child is already in openList
            if child.position is in the openList's nodes positions
                if the child.g is higher than the openList node's g
                    continue to beginning of for loop

        // Add the child to the openList
            add the child to the openList
```

Figure 9. A* algorithm pseudocodes

3.0 Results

Based on the results of the eight 3D simulations performed, the observation was carried out based on two main factors, namely the time factor and critical space factor for user evacuation activity.

3.1 Time factor

Overall time comparisons become an indicator to ensure that the user's evacuation activity is smoothly conducted or otherwise. For this study, the period for the entire eight simulations was recorded and compared to identify the possible causes of time difference for the transfer process.

3.1.1 The impact of user capacity towards time

From the results, by considering the user capacity factor, it is found that the time difference between S_1 and S_5 is a minimum of 7.80 seconds as shown in Table 4. This is in contrast to the differences between the other simulations, S_2 and S_6, S_3 and S_7 and S_4 and S_8, where the average time difference is greater than 9.00 seconds. The results show that the higher the time spent on evacuating the user, the higher the impact on the user's capacity during an emergency. In addition, the aspect of access selection by the user is also influential because the random access option is free from the dependency on specific access selection. It allows users to decide to evacuate through which access at a time, unlike other simulations, where the specific access is decided for the user. This is supported by findings from the time period of the last user through specific access as shown in Figure 10(a). The duration of the last user through the D1F1 and D1F2 exits for the S_2 and S_6 differs, even though both have the same specific exit access. The reason is the uneven distribution of user positions that makes the movement of the user generally unmanageable. The distribution of users can be controlled through a restructuring of office space to provide a specific path to exit access.

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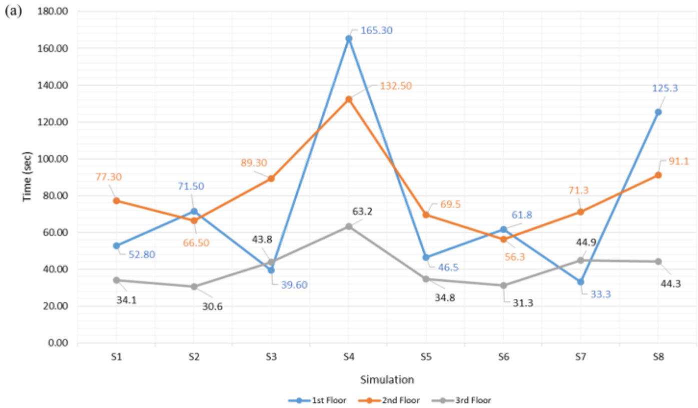
Table 4. Time difference due to differencet of user capacity

Path selection (d_2)	User capacity (d_1)		Time exited, t_2 (sec)		Different (sec)
	100%	70%			
Random access	S_1	S_5	77.30	69.50	7.80
Divide access	S_2	S_6	71.50	61.80	9.70
Zone 1 access	S_3	S_7	89.30	71.30	18.00
Zone 2 access	S_4	S_8	165.30	125.30	40.00



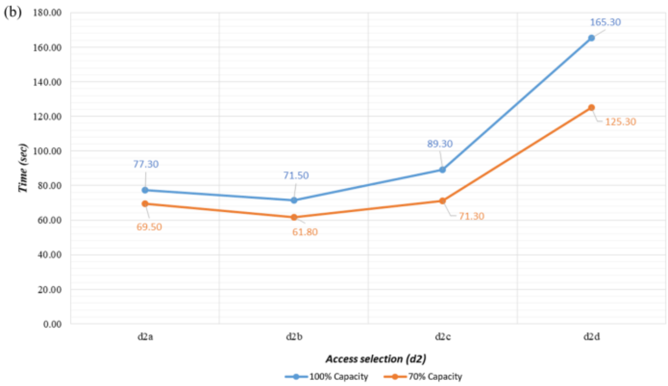


Figure 10. Time taken for (a) user exited from their floor (t_1); and (b) user fully exited from the building (t_2)

3.1.2 The impact of path selection towards time

The overall time comparisons recorded for the eight simulations performed are shown in Figure 10(b). The results showed that S_2 and S_6 recorded the shortest amount of time to evacuate users as both simulations have similarities from the perspective of access selection, namely divide access. S_2 recorded a time of 71.5 seconds and S_6 61.8 seconds, which are shorter times than other simulations. The path selection of divide access not only provides the shortest time, but the density distribution of the path usage is also more appropriate, which causes the shortest amount of time recorded.

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3.2 Critical space factor

Identifying critical spaces is important to ensure that the planning process for the user evacuation process is implemented effectively. The identification of critical space based on the correlation between path density heat map and space usage LOS information [46] was examined. Both user density and LOS flow information are important because the correlation between these two identities can be used to improve the evacuation activities based on Equation 3 as stated by Wen and Chang [47] where Q is the space flow, P is the user density and C is the user speed. Grid space allocation is performed to facilitate the identification of critical space positions, as shown in Figure 11.

$$Q = \frac{P_{n+1} - P_n}{C_{n+1} - C_n} \tag{3}$$

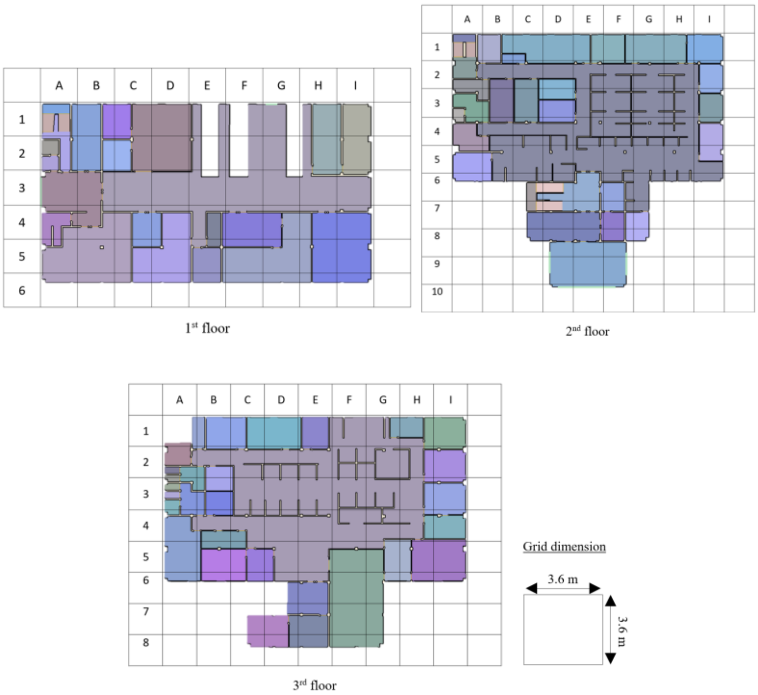
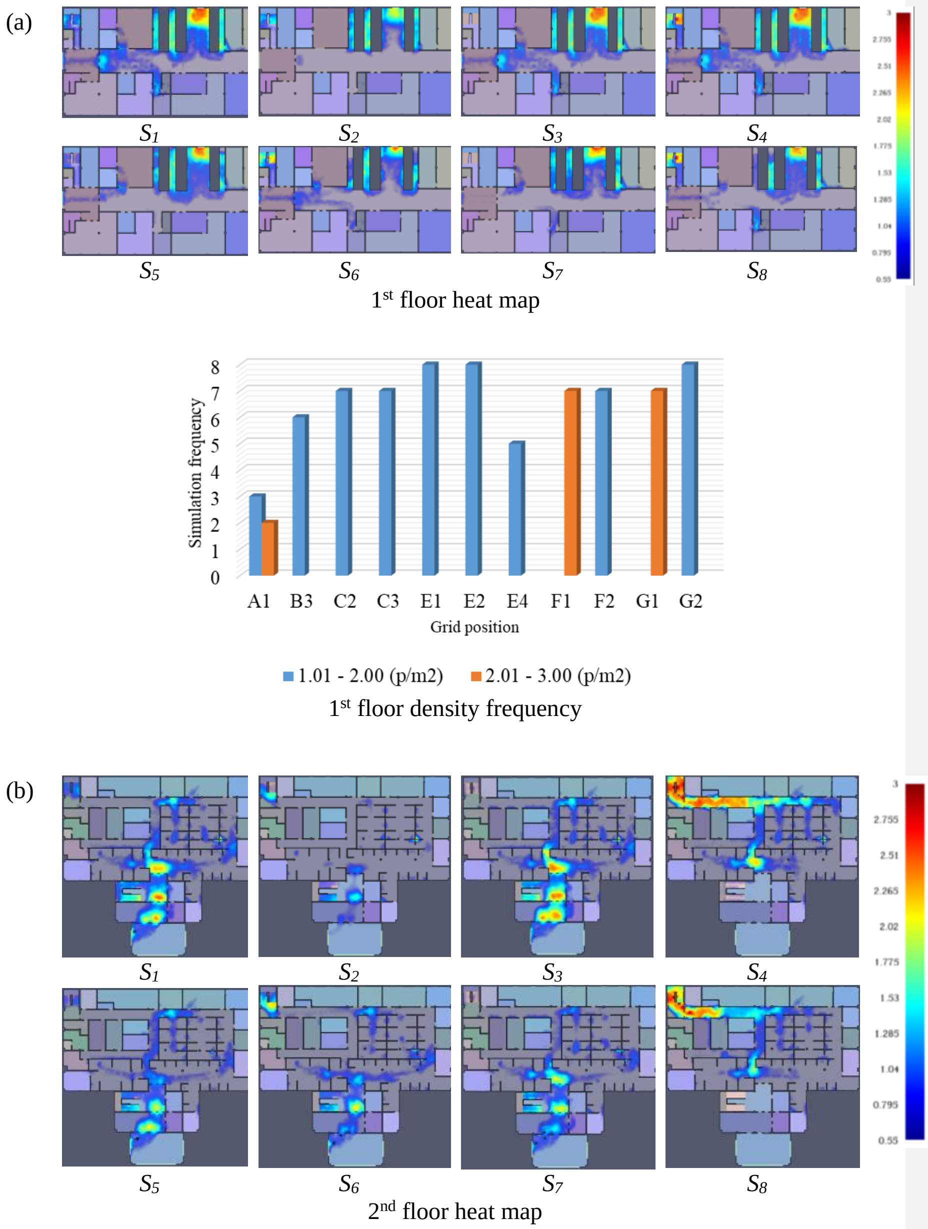
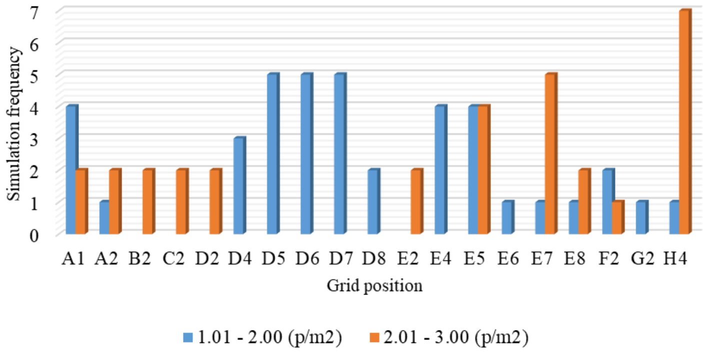


Figure 11. Grid space allocation for each floor

3.3 Path density heat map

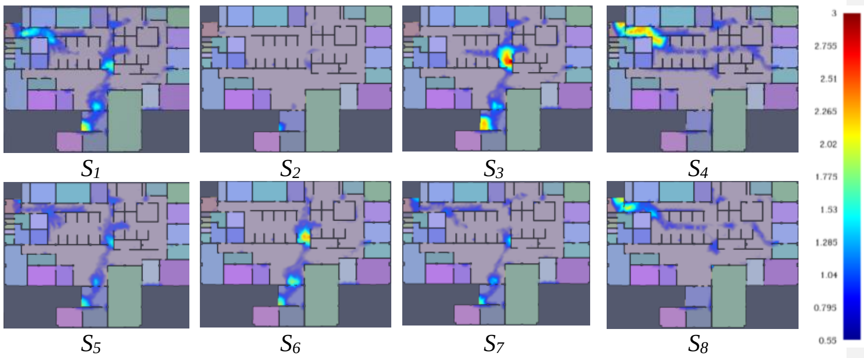
Detailing on heat maps are divided by floors and areas within in between 0.01 to 3.00 users per square meter (p/m^2). Ranges between 0.01 p/m^2 to 1.00 p/m^2 is classified as low density, 1.01 p/m^2 to 2.00 p/m^2 is classified as average density, and 2.01 p/m^2 to 3.00 p/m^2 is classified as dense. For the 1st floor, the average user density is detected on grids, A1, F1 and G1. The focus on grid A1 is because the area involves a staircase that links between the 1st floor, 2nd floor and 3rd floor. As such, the A1 grid is indeed fundamental in the user's path. The next grids, F1 and G1, cover the exit area for D2F1 access. This area is the centre of user density due to its proximity to user-occupied office space. From this evaluation, it was found that the D1F1 access in the B3 grid only affects a user density of less than 2.00 p/m^2 and gives the impression that the flow of a user through the access is smooth. The overall findings of the heat map information by the grid for the 1st floor is shown in Figure 12(a).



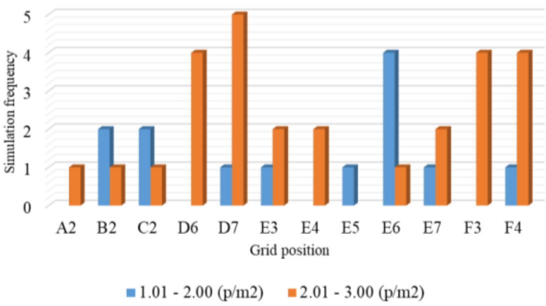


2nd floor density frequency

(c)



3rd floor heat map



3rd floor density frequency

Figure 12. Overall result and heat map summary for (a) 1st floor, (a) 2nd floor and (c) 3rd floor

For the 2nd floor, the average user density is detected in two zones. For zone 1 it involves grids E5, E7, E8 and H4 while zone 2 involves grids A1, A2, B2, C2, D2, E2 and F2. Density in zone 1 is due to three main factors. First, the access in the H4 grid next to the office space is too limited to accommodate the capacity of the users where visible frequencies occur for seven simulations. The second factor is due to the closeness of the accesses to each other, such as the access to the E5 and E7 grids where the frequency occurs in four simulations for the E5 grid and in five simulations for the E7 grid. The third factor involves the staircase area used by users on the 3rd floor as in the E7 grid. Concurrently, the zone 2 density occurs due to the exit access in relation to the staircase area used by the user from the 3rd floor in grid A1 and grid A2 where the frequency occurs in two simulations. The graphs of density heat map for the 2nd floor are as shown in Figure 12(b).

For the 3rd floor, the user density is detected in three groups of regions. First in grids A2, B2, C2. This area involves access to zone 2 where it provides access to stairs. However, the frequency of this area involves only one simulation. Second in grids D6, D7, E6 and E7 where this area is also the access to the stairs through zone 1 but has a high frequency of four simulations for grid D6, five simulations for grid D7, one simulation for grid E6 and two simulations for grid E7. The third involves intermediate access in the middle of the 3rd floor, which is the main access involving the E3, E4, F3 and F4 grids. Frequency density is two simulations for grid E3, two simulations for grid E4, four simulations for grid E7, and four simulations for grid E8. The graphs of grid heat density maps for the 3rd floor are as shown in Figure 12(c).

3.4 LOS on space usage

The LOS space utilization evaluation details are divided into six categories according to the Fruin-based LOS model [46] as shown in Table 5.

Table 5. LOS categories according to the Fruin-based LOS model.

LOS	Space (m^2/p)	Access width (m)	Flow condition
A	≥3.25	1.93-1.80	Free flow
B	2.30-3.25	1.80-1.67	Small conflict
C	1.39-2.30	1.67-1.52	Slow flow
D	0.93-1.39	1.52-1.36	Partially limited
E	0.46-0.93	1.36-1.18	Fully limited
F	≤0.46	0.95-0.68	Compact

Attention is given to access that disrupts the user evacuation flow based on space usage information involving the categories of flow conditions E and F LOS. This category was chosen as an indicator to indicate that the flow condition was not smooth for emergency situations as described by Campisi et al. [46].

For the 1st floor, on average, the flow condition E was detected due to D1F1 access for grid B3 and the flow condition F was derived from D2F1 for grid G1 as shown in Figure 13(a). The use of space above 2.17 p/m^2 is because D2F1 access cannot accommodate large numbers of users at a time. A 1.2m wide access can only accommodate one user at a time. This is stated by Zegeer [48] where the Federal Highway Administration's (FHWA) Pedestrian Facilities Users Guide states that a 1.5m wide access will allow two people to pass by in a smooth flow [49][50]. This is also supported by a study conducted by Pan et al. [7] where the minimum recommended access width for launching user transfer flows is 1.4m to 1.5m wide. That is also proved in this study when D2F1 access is extended to 1.5m, user density in D2F1 access decreases from flow condition F to flow condition E. Expansion of D2F1 access also affects user density in D1F1 access where user density flow in D2F1 access decreases from flow condition E to flow condition D. The difference in the use of space can be seen in Figure 14.

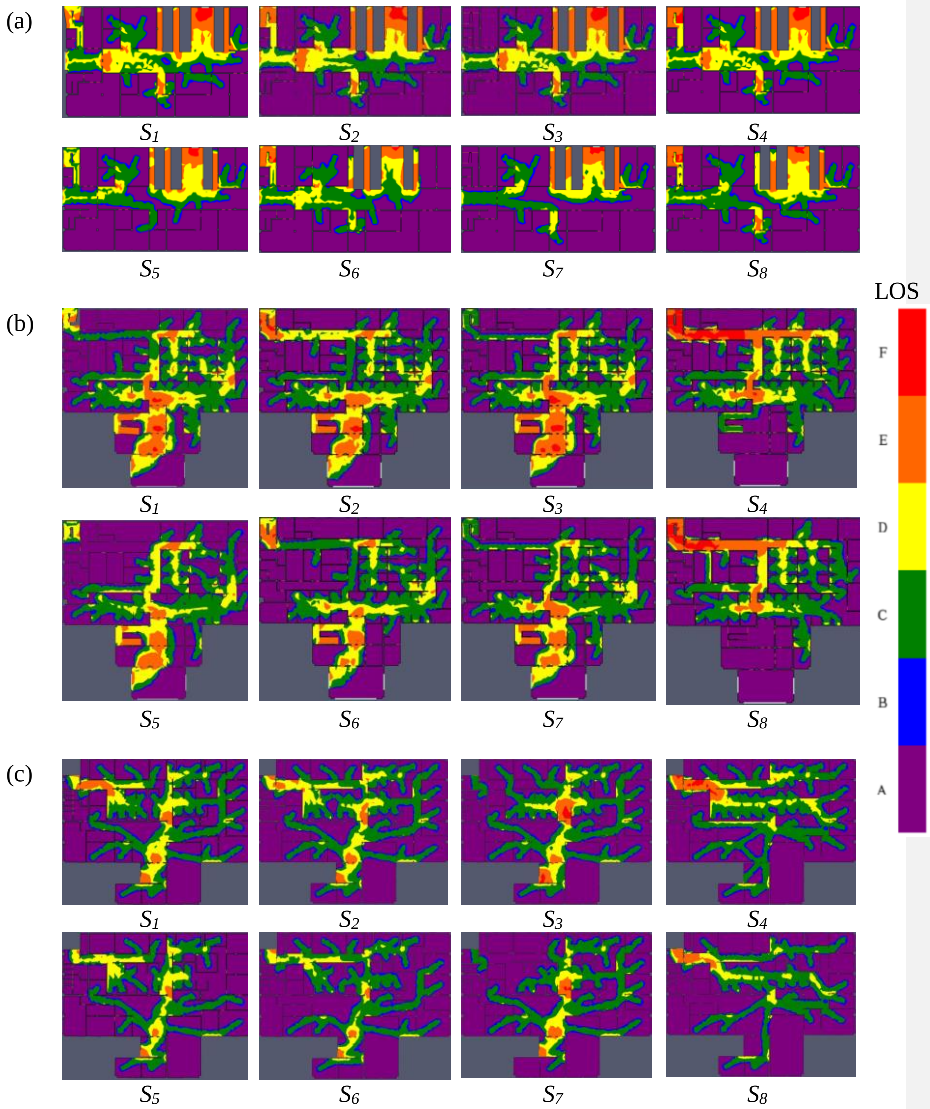


Figure 13. Overall result LOS for (a) 1st floor, (a) 2nd floor, and (c) 3rd floor

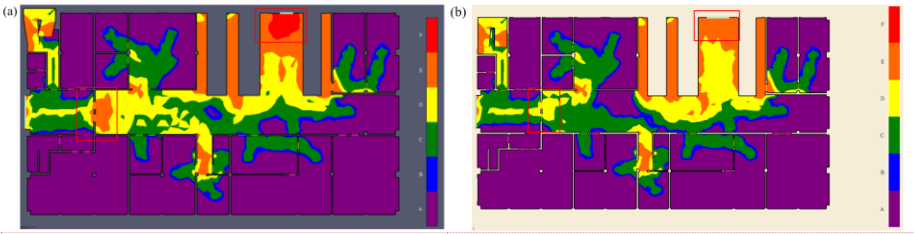


Figure 14. Changes in LOS flow conditions in D1F1 and D2F1 before (a) and after (b) access widening.

Commented [BP9]: Please increase the font size of (a) and (b) and make it bold.

On average, for the 2nd floor, E and F flow conditions were detected as a result of access to grids E5, E6, E7 and E8 as seen in Figure 13(b). The used space in the E5 grid above 2.17 p/m^2 is due to access of the E5 grid as the main access to the 2nd floor that connects the building's interior space to the exits of the building. It has two 0.8m wide access that can accommodate one user per access at a time. In order to optimize the space at a time, the user space allocation can be implemented as done in S_2. Through the S_2 evacuation method, it was found that the use of space was in the flow condition E compared to other simulations that reached the flow condition F.

As for access in the E6 grid, the user density is a continuation of the density that occurs in the E7 grid. This is due to the density occurring in the E7 grid due to the combination of the 2nd floor and 3rd floor user capacities that go down the stairs in the D7 grid. The number of users doubled and the two 0.8m spreads on the E7 grid could not accommodate the overwhelming number of users. The solution can be achieved as described before by combining two 0.8m widths to one 1.6m width access to allow two people to pass adjacent to the free flow as described by Quezon and Kumala [50] and Pan et al. [7]. This is also proven in this study when access to the E7 grid is consolidated, the flow of user density decreases to the flow condition E. The difference in user density can be seen in Figure 15.

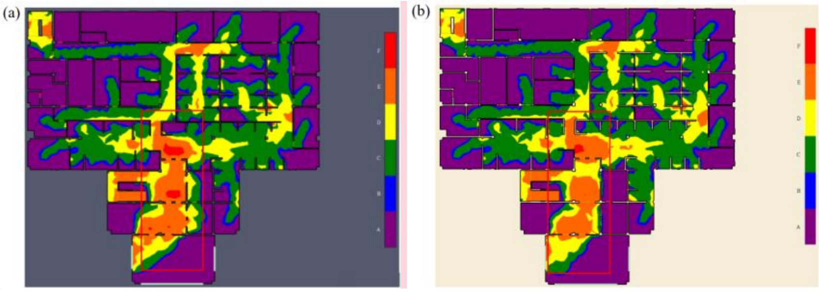


Figure 15. Changes in LOS flow conditions in E7 grid before (a) and after (b) access widening.

Commented [BP10]: Please increase the font size of (a) and (b) and make it bold.

The average flow conditions for the 3rd floor, E and F, were detected as a result of access to grids D7, E3, F3 and E6 as in Figure 13(c). The D7 grid density above 2.17 p/m^2 is due to the fact that the D7 grid access is the main access for 3rd floor users to get to the 2nd floor through the stairs. The E3 and F3 grids are the main access points for D1F3 with a width of 0.8m and can only load one user at a time. Obstacles caused by workers' cubic fractures can be rearranged to allow them to accommodate more specialized users in emergency situations. For access points on grid E6, the flow condition E is due to this space having two 0.8m wide access that can accommodate one user per access at a time. Combining two 0.8m width access to create one 1.6m width access will allow two people to access adjacent to the free flow as described in the Pedestrian Facilities Users Guide and supported by a study conducted by Pan et al. [7] where the recommended minimum access width is 1.4m to 1.5m wide to reduce user density at a time. This is also evident in this study; when access to the E6 grid is consolidated, the user density of flow condition E decreases. The difference in user density can be seen in Figure 16.

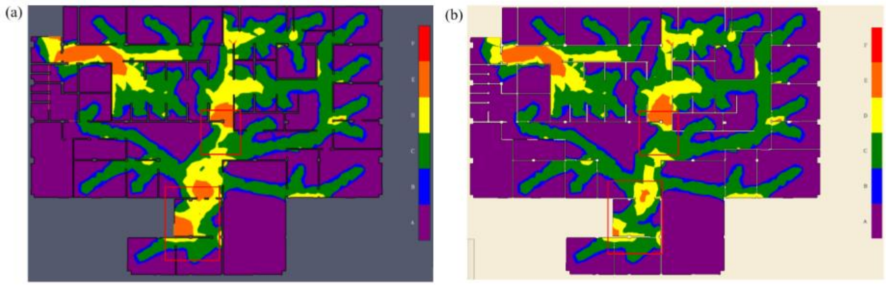


Figure 16. Changes in LOS flow conditions E in E6 grid before (a) and after (b) access widening.

4.0 Discussion

Based on the results obtained from input parameters and simulation validation, it is divided into two factors; the time factor and the critical space factor. The effects of the time factor based on eight simulations that were performed showed that the divided access recorded the fastest time in evacuating users. S_2 recorded a time of 71.5 seconds which is 56.75% faster than the longest time recorded for 100% capacity and S_6 recorded a time of 66.0 seconds which is 50.68% faster than the longest time recorded for 70% capacity. The information is shown in Table 6.

Table 6. Time different percentages

User capacity (d_1)	Simulation	Time exited, t_2 (sec)	Time different percentages (%)
100%	S_1	77.30	53.24
	S_2	71.50	56.75
	S_3	89.30	45.98
	S_4	165.30	100.00
70%	S_5	69.50	44.53
	S_6	61.80	50.68
	S_7	71.30	43.10
	S_8	125.30	100.00

As for the user capacity aspect, thise study found that the higher the time spent on user transfers, the higher the impact on user capacity in evacuation users. The distribution of users within the compartment is also influencing and can be controlled through a restructuring of office space by providing a specific path to exit access to minimize the impact. The final result of the critical space factor found to be 1st floor access on-grid G1, 2nd floor access on grids E5 and E7, 3rd floor access on grids D7, E3, E6 and F3 should be given attention. This is because these accesses affect the flow of the user evacuation process and user density is frequently detected in these areas. Some suggestions such as access widening and divide access have been made. The following suggestions have also been tested and the results are shown in Figure 17, prove towhich would help improve the flow of the user evacuation process. The high rate of flow per time is crucial in an emergency situation. These results are also in line with a study conducted by Pan et al. [7] where the minimum recommended access width for smooth user transfer flows is 1.4m to 1.5m wide.

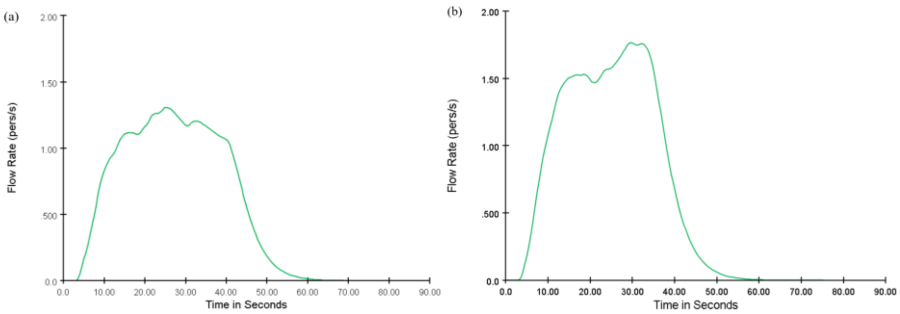


Figure 17. Changes in D2F1 flow rate before (a) and after (b) access widening.

Conclusion

The basis of this study has been applied to evaluate the impact of evacuation planning structure on user evacuation time. An assessment has been conducted on the CIB and an understanding was concluded of how different scenarios influence evacuation time. Significant findings in this paper include the identification of critical space based on specific capacity and path selection behaviour to improve the evacuation flow. In order to enhance the user evacuation process, improvement measures should be implemented to minimize the impact of emergency situations on users. A comprehensive solution can be implemented as a simulation testing framework for the user evacuation process that can be used to replicate a real-world scenario with the user. In addition, the seamless design of evacuation planning in the form of multiple preferences of designs, the proper used equations while designing the evacuation path, the path distance toward exits, and the location of the stairs needed to take into account. For example, the division of access based on distance and time can be implemented to help facilitate the process of evacuating users. The action of improved access points such as the widening of exit access space can be taken into account as the simulation results show that there is a positive impact on the widening of accesses that were identified as critical spaces.

Disclosure statement

No potential conflict of interest was reported by the author.

Data and Code Availability Statement

The data and codes that support the findings of this study are available figshare.com with the identifier https://doi.org/10.6084/m9.figshare.12000540.v1

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