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Critical Egress Parameters Governing Assisted Evacuation in Hospital Buildings

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Abstract: This paper presents the critical egress parameters that influence emergency evacuation in a typical hospital building. A parametric study of a 20-story hospital building is conducted using a computer model "Pathfinder" to simulate the evacuation efficiency and assess the influencing parameters. The main egress parameters that influence the evacuation efficiency, including the location of stairways, number of stairways, location of the fire, exit width, and number of low-speed occupants are varied. Two scenarios are simulated: one being the regular (practice) evacuation drill and the other is the actual fire drill. The result shows that the location of stairways significantly affects the total evacuation time with the optimal stairway arrangement consisting of one stairway outside the core of the building. Similarly, the story level at which the fire occurs is another key parameter with fires at lower levels being critical to dictating the evacuation time in a hospital building. The total evacuation time when the fire occurs between the third and sixth floor is found to be 170 min which is 36% and 15% higher than fires at the top story levels (15–18th floor) and the intermediate story levels (9–12th floor), respectively.

Keywords: fire; emergency; hospital; assisted evacuation; egress parameters

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1. Introduction

Within the lifecycle of any structure, hazards of both natural and manmade origins are inevitable. Ensuring life safety during these circumstances becomes a paramount concern. There are two primary approaches in ensuring life safety during such hazards: constructing robust structures capable of withstanding extreme loading conditions for extended periods and designing for efficient evacuation in case of emergency in buildings. These approaches must work in synergy to effectively minimize casualties in any given situation.

Fire hazards, which can arise from both accidental and intentional causes, have historically resulted in significant loss of life and property damage [1]. With rapid urbanization and increasing number of high-rise buildings, fire risk in buildings have increased significantly due to higher severity and intensity of fires [2]. As per the NFPA report of 2021, the United States witnessed approximately 1.35 million fire incidents [3]. These fires resulted in the loss of 3800 civilian lives, 14,700 reported civilian injuries, and property damage amounting to an estimated $15.9 billion [3]. A considerable portion of these fires, about 36 percent, occurred within structures. However, progress in minimizing fatalities and injuries associated with fires has been slow, with the rate of deaths per 1000 reported residential fire increasing from 7.1 in 1980 to 7.9 in 2021 [3]. A key factor contributing to this issue is the rise of tall multipurpose structures and intricate egress routes in contemporary constructions. This complexity is particularly pronounced in hospital buildings, where a wide array of personnel and functional spaces complicates the evacuation process. Thus, a more comprehensive evacuation framework is needed to address the intricate nature of hospital building evacuations during emergencies.

Building codes, categorized as prescriptive-based [4,5], performance-based, and objective-based [6–10], ensure the safety of occupants in buildings by providing sets of rules or analytical models for design [11]. The International Building Code (IBC) [4] and the National Fire Protection Association (NFPA) [5] standards are commonly used for prescriptive designs in the US, while the Society of Fire Protection Engineers (SFPE) Handbook [12] offers guidance for performance-based designs, necessary for complex structures that do not conform to conventional codes. Performance-based designs mainly rely on analytical and numerical models to quantify the level of safety provided by the building [11].

Evacuation models specified by the SPFE, and in other design manuals, require inputs like pre-evacuation time and occupants' movement speed to simulate building evacuations during emergencies [11]. Obtaining real fire evacuation data in hazardous situations is challenging, leading to the use of fire drill data as an alternative to approximate evacuee responses in real emergencies. Several studies have compiled evacuation drill data to understand occupant evacuation behavior, serving as a basis for constructing evacuation models [11,13–17]. Some researchers have conducted unannounced fire drills to enhance the realism of the data and explore evacuees' behavior [11,14]. However, these studies exclude hospital occupancy since even conducting a fire drill in critical buildings like hospitals can disrupt operations and might lead to dangerous outcomes. Thus, the shortage of specific research data for evacuation processes in hospital buildings underscores the necessity for the development of tailored evacuation models for such structures.

Ensuring the thorough assessment of evacuation efficiency requires addressing multiple critical aspects of the evacuation process, including configuration, environment, occupant behavior, and procedures [18]. The geometric characteristics of the egress system, such as the width, number, and arrangement of exit paths (stairs), are crucial factors influencing the efficiency of the evacuation process [6]. Further, in some occupancies such as hospital buildings, assessing these parameters by performing multiple physical fire drills is not feasible. Thus, the use of several analytical and computer models is the most desirable medium to study these parameters in such a critical building.

2. Fire Problem in Hospitals

During the period from 2011 to 2015, fire departments in the United States reportedly responded to an average of 1130 fires in hospital buildings. These incidents resulted in an average of 32 civilian injuries per year and caused direct property damage estimated at $8.8 million annually [19]. However, the fire problem in hospital buildings in other countries and especially developing nations is more alarming than the statistics for the United States. Although there is no comprehensive global record of fatal hospital fires, academic research and media reports indicate that such incidents are relatively common, particularly when compared to the United States, where hospital fires are infrequent and seldom result in fatalities [20].

Furthermore, since 2020 the cases of fires in hospitals have increased by two folds after the onset of the COVID pandemic era [21]. The presence of an oxygen-rich environment in post-COVID hospitals has increased the risk of the quick spread of fire and fatal injuries during such fire events. One of such case was reported on 24 April 2021, when a fire at Ibn al-Khatib hospital in Baghdad, Iraq, claimed the lives of 82 people. The fire spread after an oxygen tank caught fire and exploded [22]. The explosions triggered a swift ICU blaze that spread to multiple floors overnight due to the absence of proper fire safety (protection) measures. Most of the fatalities occurred because of inhaling smoke while attempting to escape [22]. A similar event occurred in a hospital in Romania on 1 October 2021 which killed seven people [23]. While the COVID-19 pandemic has elevated the utilization of oxygen within numerous hospitals, consequently raising the potential fire hazard, experts contend that the fundamental problem remains rooted in the inadequate application or adherence to safety codes, which has been a persistent factor contributing to the global problem of hospital fires long before the pandemic [19].

Recently, a hospital fire in Beijing, China, resulted in at least 29 deaths [24]. Chinese authorities attribute the fire at Changfeng Hospital to possible negligence, stating that sparks from construction work ignited flammable paint within the hospital building. The fire resulted in 29 deaths, just below the threshold for the most serious fire, which required investigation by the State Council. Most of the victims were patients at Changfeng Hospital. The average age of the patients who died in the fire accident was 71 [24]. Following the fire, public safety officials across China conducted impromptu inspections of hospitals and elder-care facilities to ensure that evacuation routes were clear [24].

The Beijing hospital fire incident brings to the forefront the critical importance of recognizing the heterogeneous speed of patients within healthcare facilities, particularly when formulating evacuation regulations. Hospitals cater to a diverse range of patients, each with their unique physical abilities and medical conditions. To ensure their safety, evacuation protocols must be flexible and accommodating, allowing for variations in mobility and pace. By prioritizing the varying needs of patients in hospitals, including the elderly and those with disabilities, emergency planning can better address the heterogeneity of patient populations, ultimately enhancing the chances of a swift and successful evacuation during emergencies. Some of the notable hospital fire in recent times are listed in Table 1.

Table 1. Major fires in hospitals in the last decade.

Fire Incident	Country	Date	Casualty	Cause of Fire
Changfeng Hospital	Beijing, China	18 April 2023	29 dead, and 39 injured	Sparks from internal construction's flammable paint [24]
Ibn al-Khatib hospital	Baghdad, Iraq	24 April 2021	82 dead	Explosion of leaking oxygen cylinder [22]
Romanian Hospital	Constanta, Romania	1 October 2021	7 dead	Oxygen tank caught fire [23]
Ahmednagar Civil Hospital	Ahmednagar, India	6 November 2021	11 dead	Electric short circuit [25]
Sanko University Hospital	Gaziantep, Turkey	19 December 2020	9 dead	Explosion by malfunction of oxygen therapy machine [26]
Sejong Hospital	Miryang, South Korea	26 January 2018	37 dead, and 130 injured	Electric short circuit on the first floor of the emergency room [27]
ESIC Kamgar Hospital	Mumbai, India	20 December 2018	8 dead, and 145 injured	Electric short circuit caused inflammable material kept during construction to catch fire [28]
Sultanah Aminah Hospital	Johor, Malaysia	25 October 2016	6 dead, and 1 critically injured	Electrical arcing, coupled with the presence of leaking medical gases rich in oxygen [29]

3. Complexities in Evacuation in Hospital Buildings

Hospital evacuation poses unique challenges due to the presence of patients with complex medical conditions, reliance on critical life-support equipment, and the necessity of specialized personnel for safe transfers. These complexities set hospital evacuations apart from those of other buildings, demanding meticulous planning, clear communication, and stringent adherence to specialized protocols. Some of the major evacuation parameters which differentiate hospital buildings from residential and office buildings are presented in Table 2.

Table 2. Comparison of evacuation parameters for hospital buildings, office buildings, and residential buildings.

Evacuation Parameters	Hospital Building	Office Building	Residential Building
Occupant Diversity	Wide range of staff, patients, and visitors	Limited to office employees and negligible visitors	Limited to household members
Mobility/Speed	High density of slow-speed occupants mainly consisting of dependent and elderly personnel	Mostly normal-speed occupants	Consist of low-speed occupants but not significantly high
Fire Probability	Very high due to presence of highly flammable equipment and chemicals.	Low due to lack of highly flammable objects.	High due to the presence of flammable household objects.
Evacuation Complexity	Complex due to multiple floors, specialized equipment, and patient mobility issues	Relatively straightforward due to standard floor layouts	Simple due to standard floor layouts.
Training Requirements	Need for specialized equipment and trained personnel for patient transport	Basic fire safety training for employees	General awareness of evacuation routes and fire extinguisher locations
Safety Protocol	Stringent safety measures due to vulnerable patients	Standard safety protocol for office occupants	General safety awareness for residents

While evacuation models are available, most of them focus on self-evacuation rather than assisted evacuation, with limited studies exploring the latter scenario [30]. This does not represent the full picture when planning for buildings such as hospitals. When it comes to hospitals, fire evacuation is a complex process that necessitates a well-defined strategy and effective execution which typically involves assisting patients who are unable to evacuate independently [7]. However, planning for the evacuation of people with reduced mobility (PRM) poses significant challenges in hospitals [31]. These difficulties stem from the high number of patients who may need assistance during evacuation, saving patients with connected life devices, the limited availability of staff, the requirement for multiple staff members to aid a single patient, the exhaustion experienced by staff due to repeated trips, and the potential obstruction of stairs by teams assisting patients, which could result in delays in evacuating others [31]. Thus, the generalized evacuation model for any common building occupancy cannot be used as a reference for designing the framework for emergency evacuation in hospital buildings.

Another parameter in the evacuation model of hospitals which differs from normal occupancy is the "pre-evacuation time". Pre-evacuation time, although crucial, remains poorly documented in fire safety engineering but plays a significant role in evacuation analyses especially in hospital environments. The SPFE [12] handbook presents a chapter discussing the pre-evacuation time and travel phase for different building occupancies. The chapter is a summary of various papers documenting the pre-evacuation and travel phase of people in the building. Similarly, refs. [32–35] present the pre-evacuation and travel speed for different profiles of people and staff in a hospital environment. Although there is a lack of actual data regarding hospital evacuations, it remains crucial to evaluate whether existing models can effectively depict this process or if the development of new or revised models is necessary.

Previous research on hospital building evacuations focused mainly on self-evacuation rather than assisted evacuation to study various input characteristics like pre-evacuation time, travel speed, or egress parameters like egress width at various junctions (door, corridor, and stairways). Jiang et al. [8] conducted a study at SJ Hospital, a large facility in Shenyang, China. It revealed that hospital occupants exhibited slower evacuation speeds (70~90%) compared to regular occupants in a general building. The study highlighted the importance of wider egress paths and efficient evacuation instructions for effective hospital evacuations. D'Orazio et al. [9] compared the efficacy of the evacuation model to simulate a hospital environment by comparing the simulation result of a hospital ward with the real fire drill. The profiles of occupants were suitably changed in the evacuation to represent realistic travel speeds; however, no provisions for actual wheelchairs or beds were included in the model. It was observed that the real fire drill took less time to evacuate as people were aware of the activity. The study concluded that such evacuation model could be used to build a safe egress framework with the contribution of detailed field drill results. Ronchi et al. [7] presented a modelling strategy to develop assisted hospital evacuation by calibrating pre-existing egress models. They validated that assisted evacuation in hospitals can be simulated with current evacuation modelling tools. However, these studies did not account for the spaces occupied by wheelchair and bedridden patients during movement in a hospital, which would significantly influence the movement of other occupants. Zou et al. [10] used a modified cellular automata approach to simulate hospital evacuation, accounting for movement spaces for wheelchairs. The study concluded that prioritizing wheelchair occupants during evacuation would increase the efficiency of the evacuation. The study, however, did not discuss the role of egress parameters like width and the location of the fire on the overall evacuation of hospitals with assisted occupants.

To overcome some of the above-mentioned drawbacks, this paper evaluates the influence of egress parameters as prescribed in codes like the International Building Code (IBC) [4] and the National Fire Protection Association (NFPA) [5] during emergency evacuation in a hospital environment. Furthermore, assisted evacuation is modelled to simulate a more realistic hospital environment. A parametric study of different evacuation scenarios is modelled using Pathfinder 2023.1.0524 software [36] to assess the role of egress width, the location of the fire, and number and location of the exit stairways on the total evacuation time of a hospital building. Wheelchairs and beds are innately modeled in the software to account for the assisted evacuation with varying occupant speeds.

4. Methodology

4.1. Description of Building

Following the modelling strategy presented by Ronchi et al. [7] to calibrate pre-existing egress models, the office building plan used in Kodur et al. [7] has been suitably modified to represent a hospital building to ensure it aligns with the guidelines put forth by prescribed codes such as NFPA 101 [5] and IBC [4].

The selected building is 20 stories tall, with each floor being approximately 3.05 m (10 feet) high. Its floor layout is rectangular, covering an area of approximately 2675 square meters (36.58 $\times$ 73.15 m) or 28,800 square feet (120 $\times$ 240 feet) (refer to Figure 1). Inside the building, there are two staircases located at the core (identified as A and B in Figure 1), along with six occupant elevators, and two service elevators. Furthermore, there are 16 rooms where wheelchair-using patients are treated and 16 rooms for bedridden patients (refer to Figure 1). It has been assumed in the simulation that at the start of any given evacuation, the wheelchair and bed ridden patients are in their respective rooms and are not travelling before the evacuation commences. This has been put in place to simplify the model and focus on other egress parameters rather than the random position of those patients. In addition, all floors are assumed to be identical throughout the building's height, and each floor accommodates 120 occupants (see Figure 2) which conforms to the occupant load for hospital building as per NFPA 101 [5] which is 240 ft^2/person or 22.3 m^2/person. All dimensions and arrangements of the egress components in the building adhere to the guidelines of IBC 2018 [4] and NFPA 101 [5].

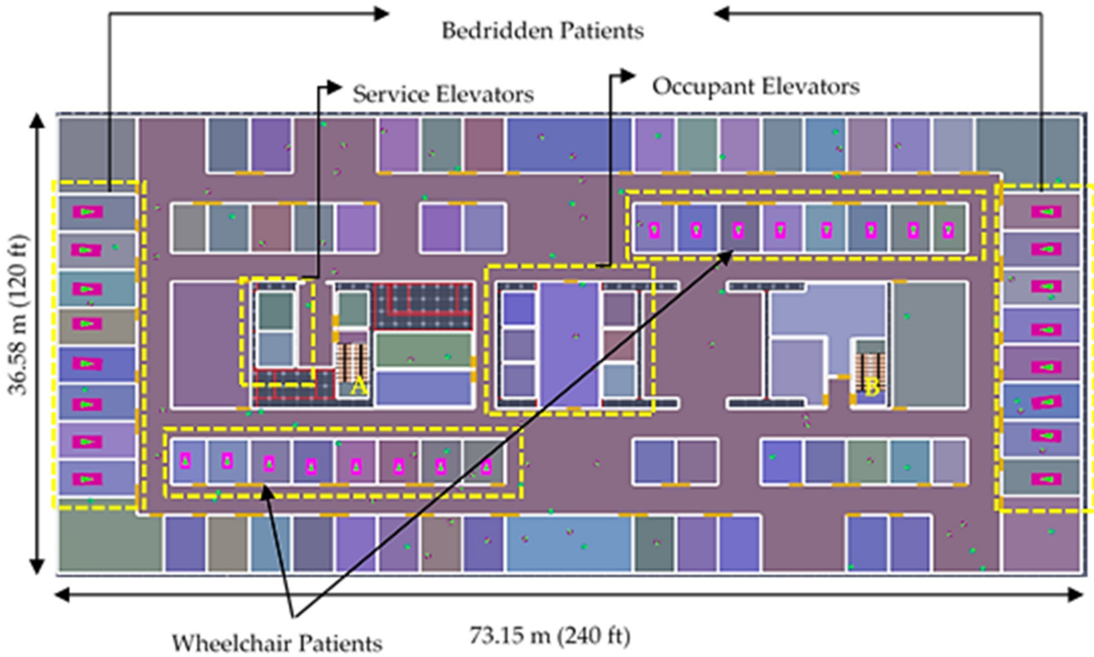

Figure 1. Floor plan for the hospital model with two typical stairways required as per IBC 2018 [4] and NFPA 101 [5].

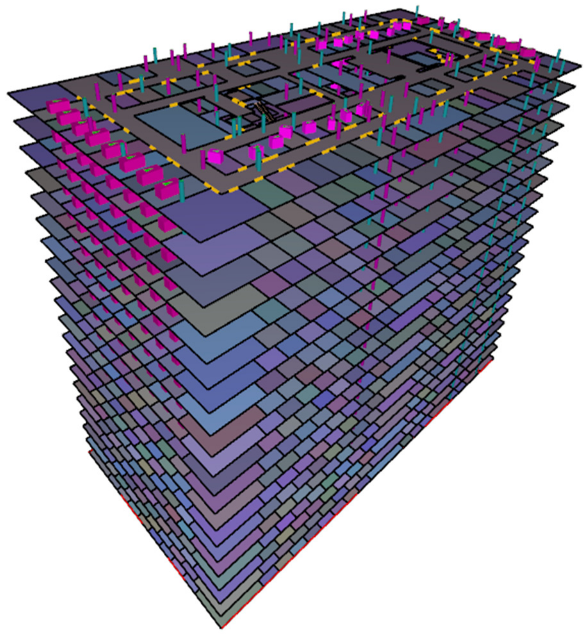

Figure 2. Corner view of the hospital building.

4.2. Selection of Evacuation Model

The computer software Pathfinder 2023.1.0524 [36] was utilized to carry out evacuation simulations. Pathfinder can model how occupants move within a structure, considering real-time issues such as congestion points, queuing, and bottlenecks. This software provides two modes for simulating occupant motion: the SFPE model and steering model.

The SFPE mode is simpler and is based on the hydraulic model outlined in the SFPE handbook [12]. In this mode, the occupants' speed depends on the density while the flow through the building is influenced by the size of the egress components (e.g., doors, corridors, stairways). This mode can be used for a symmetric building with a simple egress route and simple components. For the current study, a hospital building with asymmetric configuration and a complex egress route is chosen, thus the second mode, steering, has been used to model the evacuation scenarios.

To ensure the reliability of the predictions of Pathfinder, a comprehensive verification and validation process was conducted. Verification tests were specifically designed to examine the implementation of evacuation modes and occupant behavior. These tests included floor rate tests for each egress component, behavior tests to verify grouping behavior, merging, collisions, and speed tests [37]. On the other hand, validation tests relied on published experimental data from various sources. These experiments covered aspects such as unidirectional and bidirectional flow in corridors, turning and merging behavior in T-junctions, and more. For detailed information about these tests and their outcomes, refer to the Pathfinder verification and validation document [37].

4.3. Input Data for Pathfinder

The floor plan of the selected hospital building (see Figure 1) is created in AutoCAD 2023 and imported into the Pathfinder software with its respective dimensions. Pathfinder identifies two distinct categories of variables concerning human actions and choices: occupant profile and occupant behavior [7]. The calibration of these variables is essential for accurately simulating assisted evacuation in a hospital building.

4.3.1. Occupant Profile

This factor regulates occupant speed, size, and visual distributions during the evacuation process. In the context of hospital evacuations, the occupant profile establishes the unimpeded walking speed for each person or emergency group using a pseudo-random variable derived from a distribution [7]. During horizontal evacuations, factors like occupant density, geometry, and obstacles impact the unimpeded walking speed (ex: at the floor level).

In the current study, four separate profiles are created to simulate assisted evacuation in hospitals, namely, "Assist_Bed", "Assist_WC", "Assistant", and "Non-Assisted". The "Assist_Bed" profile refer to patients who are bed ridden. "Assist_WC" refer to patients in wheelchairs. "Assistant" refers to nurses as well as other medical staff who assist bedridden and wheelchair-using patients. "Non-Assisted" occupants include visitors, doctors, and other medical staff not in charge of assisting and who can self-evacuate during the evacuation. The travel speed of different profiles is selected based on the data available in the published literature [12,32]. Out of 120 occupants on each floor of the hospital building, 16 belong to "Assist_Bed", 16 belong to "Assist_WC", 48 belong to "Assistant", and 40 belong to "Non-Assisted". The summaries of occupant profiles are presented in Table 3. Table 4 presents the details of the hospital bed and wheelchair used.

Table 3. Details of occupant profile in each floor.

Profile Name	No. of Occupants per Floor	Profile Detail	Travel Speed (m/s)	Source for Travel Speed
Assisted_Bed	16	Bedridden patients	0.52 (1.7 ft/s)	Rahouti et.al [32]
Assisted_WC	16	Wheelchair-using patients	0.52 (1.7 ft/s)	Rahouti et.al [32]
Assistant	48	Nurses and other medical staff with supporting roles	1.19 (3.92 ft/s)	SPFE [12] handbook for density less than 0.05 person/ft^2
Non-Assisted	40	Healthy patient, visitors, and doctors with no supporting roles	1.19 (3.92 ft/s)	SPFE [12] handbook for density less than 0.05 person/ft^2

Table 4. Details of patient assistance devices in the hospital.

Assistance Device	Size (m)	Assistant Required per Device
Hospital bed	0.76 × 1.32 × 1 (2.5 × 4.33 × 3.28) ft	2
Wheelchair	1 × 2.15 × 1 (3.28 × 7.05 × 3.28) ft	1

4.3.2. Occupant Behavior

Occupant behavior demarcates the role of each profile. It specifies for the occupant whether to seek assistance or aid or to go to any exit. As pre-evacuation time is an important parameter for assisted evacuation in a hospital environment, the wait time for each profile is specified within the occupant behavior.

In the current study, three occupant behaviors are created, namely, "Assisting", "Assisted", and "go to any exit". "Assisting" is assigned the behavior "Assist Occupants"; "Assisted" is assigned the behavior of "Wait for Assistance"; and "go to any exit" is the default occupant behavior which gives occupants liberty to choose any exit possible. To account for the preparation time for bedridden patients and wheelchair-using patients by the hospital staff, a wait time of 90 s for "Assisting" and 60 s for "Assisted" behavior is input based on recommendations in the previous literature [12,32–35].

4.4. Simulation Parameters

It is presumed that all other occupants who do not need assistance or are not aiding the patients will begin to self-evacuate simultaneously, and the evacuation process will solely utilize stairways, not elevators. Figure 3 illustrates the measurements of various components involved in calculating the evacuation time.

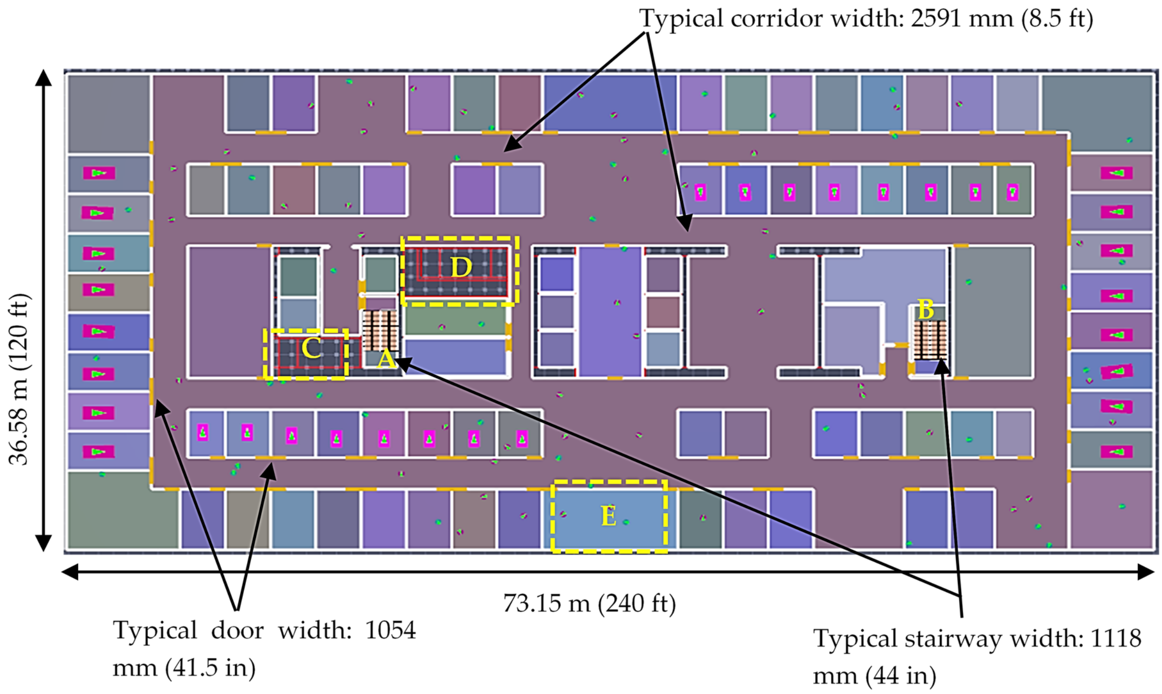

Figure 3. Dimensions of egress components as per IBC 2018 [4] and NFPA 101 [5].

The simulation incorporates specific steering mode parameters, specifically the steering update interval and minimum flow rate factor, set at 0.1 s and 0.1, respectively. The steering update interval determines how frequently the steering calculation is refreshed during the simulation time, impacting the simulation's speed [6]. A higher value results in a faster simulation but may compromise its accuracy by affecting the occupants' decision-making abilities.

On the other hand, the minimum flow rate factor comes into play when occupants are deciding which door to use in case of door queues. If this factor has a non-zero value, it ensures that the queue near the door appears to be flowing constantly, discouraging occupants from switching doors when the flow rate is low [6].

4.5. Necessity of Assisted Evacuation Model in Hospital Environment

As previously discussed, evacuation efficiency depends on configurational, environmental, behavioral, and procedural aspects of the evacuation. The configurational aspect covers geometric restrictions imposed by the building's layout and floorplans such as the egress width, number of exit paths, etc. The environmental aspect covers the impact of any heat, toxic gases, and their flow patterns on the occupant's speed. The procedural aspect covers the action of trained personnel, their level of training, and the level of occupant training. The behavioral aspect covers the response or change in the behavior of occupants and their physical and mental ability during evacuation [18]. These governing aspects differ from conventional egress models which mainly focus on self-evacuation rather than assisted evacuation. As assisted evacuation is an integral part of hospital evacuation, it is vital to evaluate how these governing aspects affect the evacuation time from one model to the other.

For this purpose, a comparative study is conducted with the office building plan presented by Kodur et al. [6] with the same plan calibrated to be used for hospital evacuation. Two scenarios are compared for both the occupancy plans: one is a normal evacuation drill, and the other is a real fire drill where fire is assumed to be occurring on the third floor blocking stairway A from the third to the sixth floor in both the occupancy cases. The simulation data are also compared with the data from Kodur et al. [6]. The occupant load for both buildings (office and hospital occupancy) is as per NFPA 101 [5] and IBC 2018 [4].

The result from the comparative study shows that the time required to completely evacuate a hospital building with assisted evacuation during an evacuation drill is considerably higher than the self-evacuation of the hospital building. The total time to evacuate a 20-story hospital building with 120 occupants per floor, including the assisted patients and staff, is 98 min which is more than three times higher than the self-evacuation time for the same hospital configuration and occupant load. Furthermore, as per Kodur et al. [6], the total evacuation time for a 32-story office building with an occupant load of 250 per floor considering self-evacuation is 87 min which is still lower than the evacuation time for assisted evacuation.

Thus, it is clearly evident that the egress parameters influencing the emergency evacuation of an office building cannot be made the basis for developing a framework for emergency evacuation in a hospital building. Thus, a thorough study of the critical egress parameters influencing emergency evacuation in a hospital building is carried out.

5. Critical Parameters Governing Evacuation

To quantify the influence of main parameters on evacuation efficiency, a comprehensive parametric study is carried out using Pathfinder. In the parametric study, the influence of various configurational, environmental, procedural, and behavioral aspects of egress on the total evacuation time in hospital occupancy is studied using two scenarios, namely, varying evacuation drill configurations and varying fire scenarios. In the first scenario, the effect of change in the location of stairways, number of stairways, and width of stairways on the total evacuation time is analyzed. Also, the impact of assisted evacuation on the total evacuation time is assessed by varying the level of assistance required. In the second case, the impact of the location of the fire on the total evacuation time in hospital occupancy is evaluated.

5.1. Evacuation Drill

5.1.1. Number of Stories

Hospital buildings, however, are not built as tall as residential or office buildings, but there is significant effect of the number of stories on the total evacuation time of a hospital building. The presence of a high proportion of temporary or long-term disabled patients in a hospital building necessitates assisted evacuation. Vertical evacuation in particular becomes difficult in a hospital building with assisted evacuation due to the use of assistant devices to carry the patients. The increase in the number of stories results in increased fatigue and slow movement of occupants leading to increased bottlenecks and an increase in the total evacuation time. In the current study, three different heights of hospital buildings are evaluated, namely, 10-, 20-, and 30-story buildings. A three-staircase arrangement (A, B, C stairway as shown in Figure 3) is assumed to be present in the building.

The results of evacuation plotted in Figure 4 show that there is a significant increase in the evacuation time with an increase in the number of stories of the building from 10 to 30 stories. The total evacuation time for the hospital building with 30 stories is 128 min which is almost three times the total evacuation time for the hospital building with 10 stories (49 min), while the evacuation time is 103 min for a 20-story hospital building. Thus, necessary provisions, such as a wider egress path, as necessitated by IBC 2018 [4] and NFPA 101 [5] need to be provided to ascertain the safe and efficient evacuation of a hospital building with a higher (more than 10) number of stories.

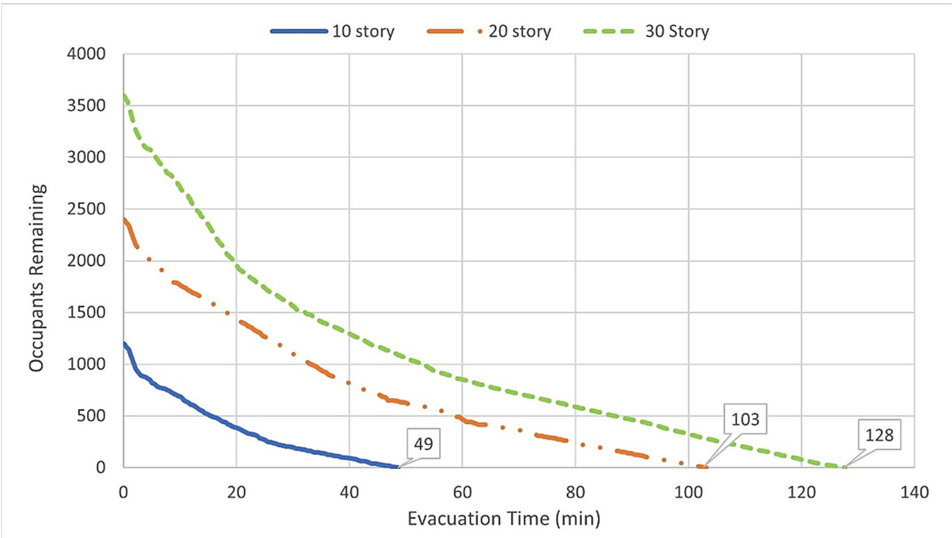

Figure 4. Evacuation time with different numbers of stories.

5.1.2. Location of Stairways

The location of stairways is a crucial parameter that influences the egress efficiency in a hospital building, especially during assisted evacuations. Hospital buildings accommodate a diverse set of occupants with different modes (ex: wheelchair users, walkers) of travel, capability of patients, and travel speeds. Therefore, it is vital to balance the travel distance for each occupant to increase the overall evacuation efficiency. Considering this, prescribed codes provide a series of guidelines on the location of exit paths in a building to maximize efficiency during evacuation. According to IBC 2018 [4], the total horizontal travel distance to an exit should not exceed 125 ft. or 38.1 m, whereas in NFPA 101 [5], it is limited to 150 ft. or 45.72 m. Additionally, IBC 2018 [4] and NFPA 101 [5] stipulates that the minimum distance between two staircases should be one-half of the length of the maximum diagonal dimension for general buildings and one-third the diagonal dimension for buildings equipped with an automatic sprinkler system. All these guidelines aim to maximize the availability of egress paths in case of blockages during fire incidents.

In the current study, three different locations of stairways are simulated using the Pathfinder program. The location of each respective staircase is marked alphabetically (from A to E) and presented in Figure 3. Staircases A to D are within the core, while staircase E is outside the core. The first two cases consider all three staircases to be inside the core (A, B, C in Case 1 and A, B, D in Case 2), while in the third case, the arrangement consists of two stairways in the core and one outside the core (A, B, E).

The results show that the total evacuation time is the least for the Case 3 stairway arrangement A, B, and E (with two stairways in the core and one outside the core), with an evacuation time of 70 min. The evacuation time increases by 49% for the Case 1 arrangement A, B, and C, with an evacuation time of 103 min (see Figure 5). The plot illustrated in Figure 5 shows the trend of evacuation, with the total occupants remaining to exit the building plotted on the y-axis vs. the total time elapsed during the evacuation. The second case of stairway arrangements A, B, and D have a total evacuation time of 77 min, which is closer to the arrangement A, B, and E (Case 3). It is also seen that the total time to evacuate for the arrangement A, B, and C is more than the time required to evacuate with two stairways. The main reason for the drastic increase in the evacuation time is the increased congestion and bottlenecks present for the arrangement A, B, and C due to the closer proximity of staircase A and staircase C, which are separated only by a wall (see Figure 3). In the absence of situational awareness (information about progression of fire and congestion on several stairways), people tend to evacuate from the closest exit possible. This results in more people being inclined towards exiting from staircase A and C causing bottlenecks and congestion at the corridor as well as the entrance for these stairs due to limited flow capacity. The same stairway arrangement was used by Kodur et al. [6] for evaluating the evacuation time for a high-rise office building. In their study, also, it was noted that the total evacuation time for the A–B–D arrangement within the core was slightly less (67 min) than the A–B–E arrangement (74 min). Since Kodur et al. [6] used self-evacuation for the simulation, the absence of space-consuming wheelchairs and beds made it easier for occupants to go to the stairs which were centrally located in the core and easily accessible. However, this was not the case for assisted evacuation in a hospital building wherein the location of stairways outside the core helps in modulating the space-consuming traffic of assisted patients. Thus, providing a staircase outside the core of the building seems to be a better strategy to reduce the stagnant traffic of beds and wheelchairs present in a hospital environment.

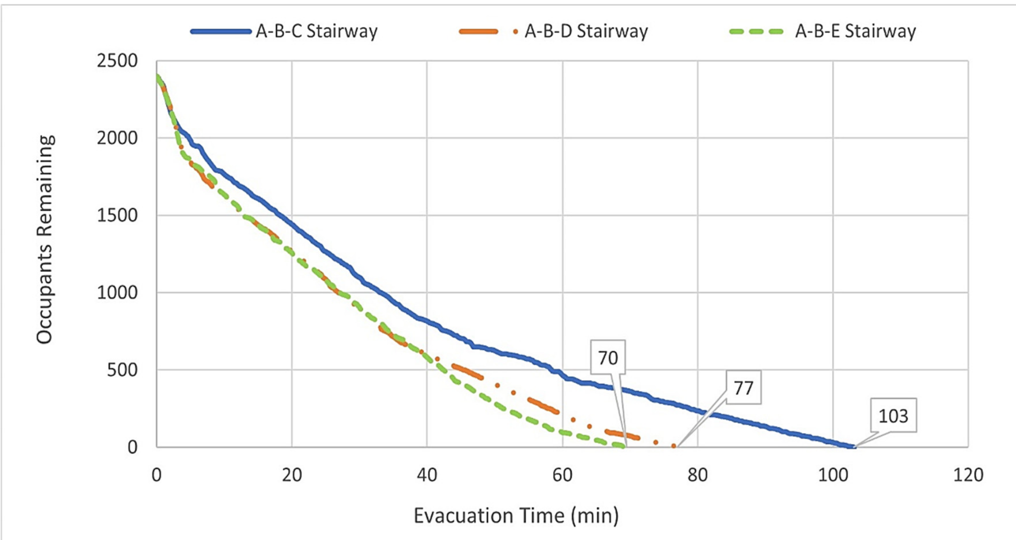

Figure 5. Evacuation time with different locations of stairways.

5.1.3. Number of Stairways

As per IBC 2018 [4] and NFPA 101 [5], the minimum number of egress stairways required for a hospital building is two when the occupant load is less than 500, three when occupant load is between 500 and 1000, and four if the occupant load is more than 1000 per floor. However, these occupant loads are not cumulative and depend only on the number of occupants on that floor. Increasing the number of stairways in a building would decrease the occupant load per stairway which reduces the chances of bottlenecks and delays, ultimately optimizing the evacuation time. However, stairways take considerable floor area, thus the location and the number of stairways should be properly regulated so that it is practical and feasible in the long run.

In the current study, three different cases of stairways are evaluated. The first case comprises two stairways (A and B). The second case comprises three stairways (A, B, and E), while the third case comprises two stairways (A and B) at the top 10 stories, and three stairways (A, B and E) below the 10th story. It is assumed that the occupants would be aware and trained of an additional stairway for the bottom 10 stories and suitably utilize the additional stair to evacuate the building during an emergency.

The simulation results (See Figure 6) show that Case 2 with three stairways has the lowest evacuation time of 70 min, while in Case 1 with two stairways the evacuation time increases to 98 min (29% increase). Although, the codes do not account for the cumulative occupant load while prescribing the number of egress stairways, it plays a significant role in the evacuation time. It is observed that the merging of occupants from the upper floors tends to create more congestion at the bottom floors, increasing the total evacuation time. Thus, the addition of egress stairways at lower stories can be a reasonable solution to achieve economical and time-efficient evacuation. The result of the third case further bolsters this statement as the total evacuation time for the Case 3 with two stairways for the top 10 stories and three stairways for the bottom 10 stories is 77 min (21% lesser evacuation time than case one) which is closer to the evacuation time of the second case. These results agree with the trends shown by Kodur et al. [6] for the 32-story office building with the same configuration where there is a 17% reduction in the evacuation time with two stairways for the top 16 stories and three stairways for the bottom 16 stories.

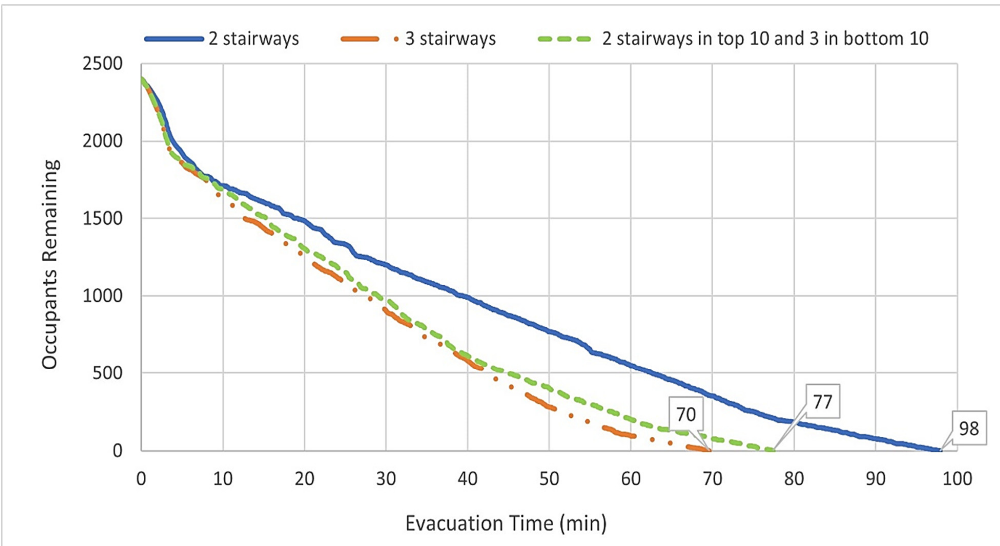

Figure 6. Evacuation time with different numbers of stairways.

5.1.4. Stairway Width

The width of the stairway controls the flow of occupant traffic in a building. In a hospital environment with assisted evacuation, where wheelchairs and beds are present in good numbers, it is important to fix the width of the stairway for optimal evacuation results. NFPA 101 [5] prescribes the minimum width of a staircase for hospital occupancy in a high rise building to be 1.117 m (44 in.). The width prescribed by this code is based on the cumulative occupant load. If the cumulative occupant load is more than 2000, the width of the stairway should be a minimum of 1.422 m (56 in.). It is evident that an increase in the egress width will increase the traffic flow, thus reducing the evacuation time. However, there should be a limitation to the increase in egress width as it occupies considerable floor area, making the building economically infeasible.

In the present study, three different stairway widths are simulated for assisted evacuation in the hospital building: 1.117 m (44 in.), 1.422 m (56 in.) (Egress width from NFPA 101 [5]), and 1.676 m (66 in.) (50% increase in the minimum staircase width). A three-staircase arrangement (A, B, C stairway as shown in Figure 3) is assumed to be present in the building. The dimensions of the assistance devices, as modeled in Pathfinder, are presented in Table 2. Furthermore, the dimensions of normal occupants modeled as cylinders in Pathfinder are 0.46 m (1.5 ft) wide and 1.8 m (5.9 ft) high.

The analysis results from the study (see Figure 7) show that there is a reduction in the total evacuation time by 9% and 21% with an increase in the stairway width from 1.117 m (44 in.) to 1.422 m (56 in.) and 1.676 m (66 in.), respectively. However, it is clear from the results that the reduction in the evacuation time is not considerable compared to the effect of increasing the staircase width. This is mainly due to the space consumed by the assisting devices. The space consumed is such that no parallel flow of occupant traffic can move together to supplement the traffic flow. If we are to allow for two separate flows of occupant traffic, the required egress width becomes considerably large. Thus, increasing the egress width to reduce the evacuation time does not seem like a viable option. This result is in agreement with the findings by Kodur et al. [6] for an office building where similar results were obtained for office occupancy. Furthermore, solely depending upon the stairway width to decrease the total evacuation time could be a bad option as the blockage of that stairway due to fire would lead to dire consequences.

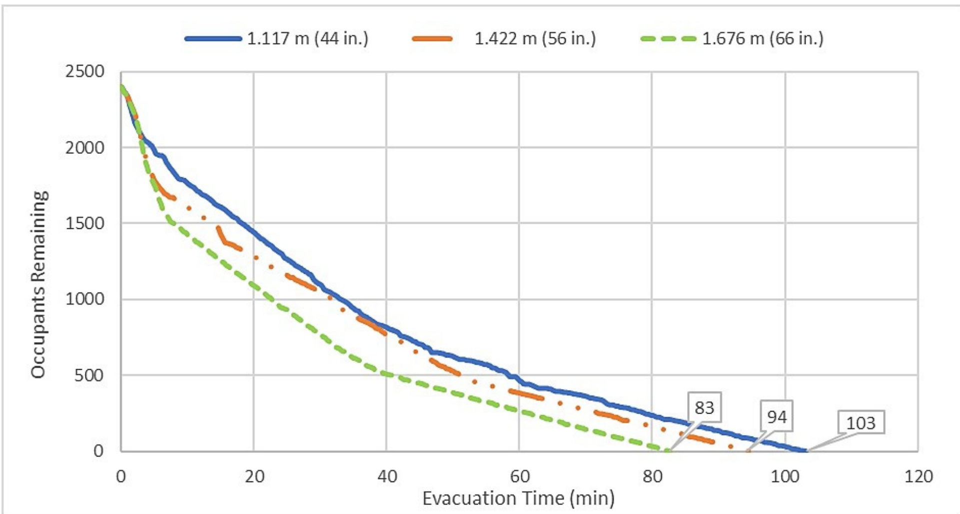

Figure 7. Evacuation time with different staircase widths.

5.1.5. Mobility and Speed of Occupants

The variation in speeds affects the flow of occupant traffic during evacuation. Minegishi [38] conducted an experimental study (non-disabled pedestrian and a slow-speed pedestrian of age 20–28 years) and observed the change in pedestrian flowrate with varying percentage of slow speed pedestrians on the 1.2 m (3.937 ft.) wide path. The researchers noted a reduction in the overall flow rate to 71% in the 10% slow-speed-pedestrian mixed case and to 61% in the 20% case. Thus, the percentage of low-speed occupants can be an important parameter in hospital occupancy which is generally composed of a diverse range of occupants with the possibility of a larger percentage of slower mobility occupants. It becomes, furthermore, evident when we consider assisted evacuation in a hospital environment.

Current prescriptive codes [4,5] do not account for the variation in occupant speed while specifying egress dimensions for the emergency evacuation.

In the current study, three different cases are studied to evaluate the influence of low-speed occupants on evacuation time. In the first case, the hospital occupancy is considered as an outpatient ward with no assisting devices and no low-speed occupants (self-evacuation scenario). The second case comprises one-third of the total occupants who vacate at a low speed per floor, i.e., low-mobility occupants. These low-mobility occupants also include medical staff who assist the occupants on wheelchair and beds. The third case comprises two-thirds of the total occupants per floor who vacate at a low speed.

The results presented in Figure 8 show that the total evacuation time increases by almost 3 times to 79 min when one-third of the occupants move at a low speed, while it increases by 3.5 times to 98 min when the number of low-speed occupants increases to two-thirds of the total occupant population. It is observed that the slow-speed occupants obstruct the path of the normal-speed occupants who are not able to move past them due to a limited egress width and higher occupant density thus lowering the flowrate. The egress width becomes further limited due to the space occupied by the assistance device (wheelchair and bed). It is apparent that the presence of low-speed occupants adversely affects the occupant flow rate. Thus, optimum strategies such as phase-wise evacuation and a dedicated exit for low-speed occupants needs be incorporated to better modulate this low flow rate.

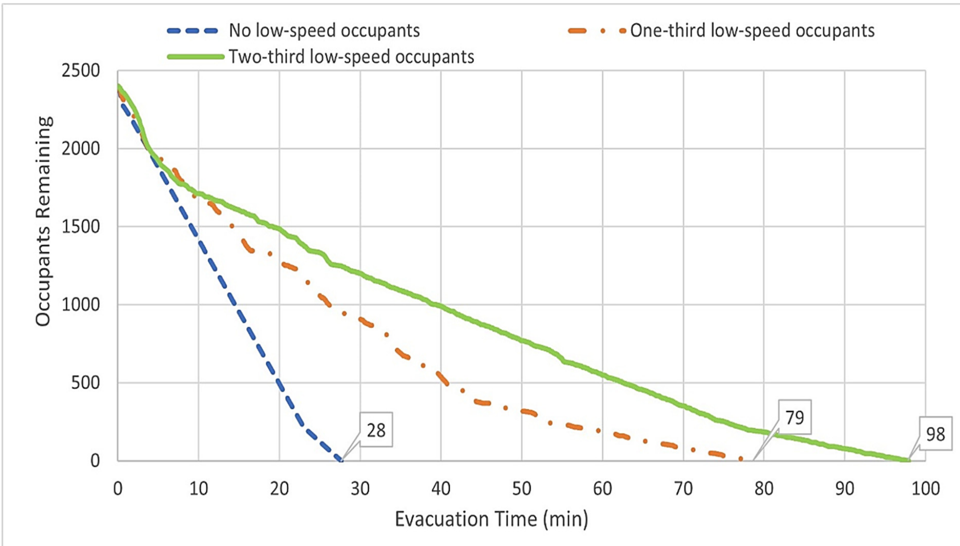

Figure 8. Evacuation time with different numbers of slow-moving occupants.

5.2. Fire Scenario and Location

The actual fire scenario in a building is much different from that simulated during an evacuation drill. The changes due to anxiety in occupant's behavior as well as dynamic change in the propagation of fire and gas leads to the prolongation of the evacuation time. Thus, evacuation simulation of the most critical parameters considering a fire scenario is a must when proposing any new evacuation framework. Considering that, the location of the fire influences the evacuation time immensely. The start of a fire blocks the evacuation passages not only at the core of the fire origin, but also in the surroundings due to the spread of harmful smoke and gases.

In the current study, the effects resulting from a fire starting at three different locations have been evaluated. In the first case, the fire origin is on the third floor, with the gas and smoke from the fire blocking stairway A from the third to the sixth floor (See Figure 3 for the location of stairway A). It represents a scenario of a fire at a lower level in the building. Similarly, in the second case, the fire starts at the 9th floor blocking stairway A from the 9th to 12th floor. It is the scenario that occurs on an intermediate level. Finally, the third case comprises fire on the 15th floor with blockage of stairway A from the 15th to 18th floor. It reflects the scenario of a fire towards the top levels of the building. The simulation considers only two stairways (A and B) for evacuation.

The evacuation times plotted in Figure 9 show that the evacuation time becomes critical when the fire is located at the lower end of the hospital building. The total evacuation time when the fire is on from the third to sixth floor is 170 min, which is 36% and 15% higher than a fire at the top level and the intermediate level. This result agrees with the conclusion drawn by Kodur et al. [6] for the office building with the same occupancy which considers the location of a fire at a bottom level to be the central case for designing any fire evacuation framework.

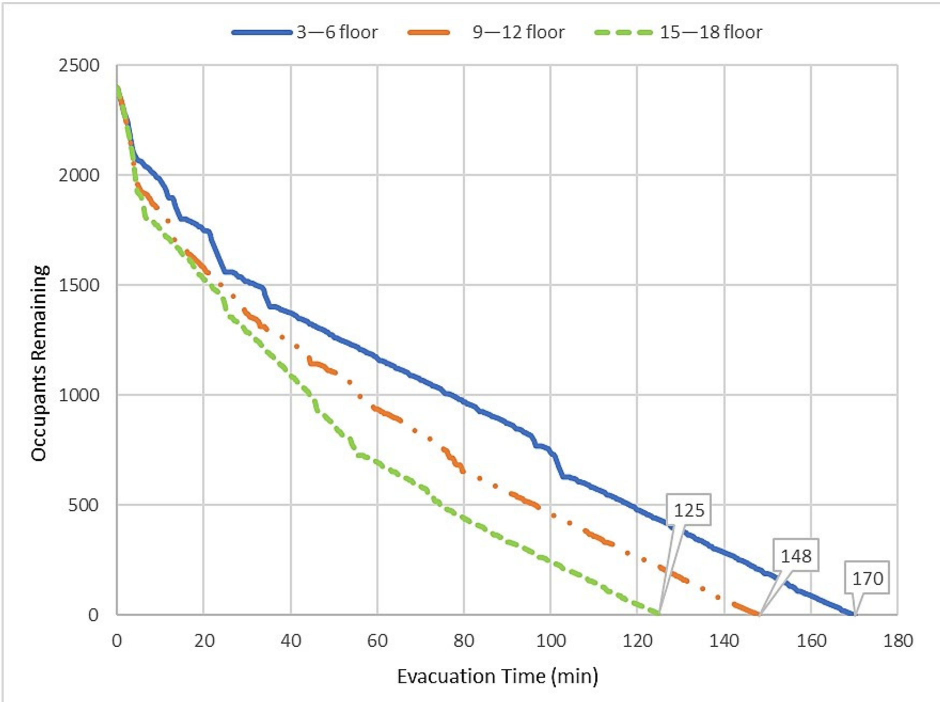

Figure 9. Evacuation time with different locations of fire.

5.3. Comparison of Evacuation Times in Hospital and Office Buildings

To quantify the differences in the evacuation efficiency, the simulation results of the assisted evacuation in the hospital building are compared with the results of the office building presented in Kodur et al. [6]. It is essential to consider that the unique characteristics of office and hospital buildings, along with their distinct emergency procedures and structural attributes, can have a notable influence on the time required for evacuation. Furthermore, the addition of heterogeneous mobility and functioning of occupants in both buildings can lead to different egress parameters influencing the total evacuation time. The summary of all the cases simulated while evaluating the egress parameter influencing the total evacuation time in a hospital building is presented in Table 5.

It can be observed from the results that vertical evacuation is more difficult in a hospital building compared to an office building due to the presence of assisting devices and a higher density of dependent occupants. However, the addition of an extra stairway outside the core of the hospital building helps to divert space-consuming assisting devices and dependent occupants, thus reducing the overall evacuation time in a hospital building. On the other hand, the most efficient stairway configuration for an office building is to have all the stairways inside the core of the building with a sufficient gap between them as specified in IBC 2018 [4] and NFPA 101 [5]. Thus, for a hospital building, stairways spaced with larger gaps (at larger distances) than the minimum stipulated distance in the prescribed codes should be chosen.

Table 5. Summary of comparative evacuation times in a hospital and office building.

Varied Parameter	Cases	Staircase Used	Evacuation Time (min) (20-Story Hospital Building)	Evacuation Time (min) Kodur et al. [6] (32-Story Office Building)
		Evacuation Drill		
Number of stories	10 stories	A–B–C	49	-
	20 stories	A–B–C	103	63
	30 stories	A–B–C	128	-
Location of stairway	3 stairways within core	A–B–C	103	113
	3 stairways within core	A–B–D	77	67
	2 stairways in core and 1 outside core	A–B–E	70	74
Number of stairways	2 stairways	A–B	98	87
	3 stairways	A–B–E	70	67
	2 in top 10 and 3 in bottom 10	A–B in top 10 and A–B–E in bottom 10	77	72
Staircase width	1.117 m (44 in.)	A–B–C	103	113
	1.422 m (56 in.)	A–B–C	94	102
	1.676 m (66 in.)	A–B–C	83	80
Number of low-speed occupant	None	A–B	28	87
	One-third of the total occupants per floor	A–B	79	-
	Two-thirds of the total occupants per floor	A–B	98	-
		Fire Drill		
Fire location at different story levels	3rd–6th story (lower level)	A–B	170	182
	9th–12th story (intermediate level)	A–B	148	152
	15th–18th story (top level)	A–B	125	117

The number of stairways and the staircase width influences the evacuation time for both occupancies in a similar manner. It is recommended to use an additional stairway at lower stories where the merging density is greater. The staircase width, however, does not significantly influence the evacuation time for both the occupancies, as a greater egress width than that considered in the simulation would result in an uneconomical design. While the influence of the number of low-speed occupants on the evacuation time is not evaluated for an office building, it can be seen from the simulation of the hospital building that the increase in the density of low-speed occupants significantly hinders the flowrate and thus increases the overall evacuation time, thus lowering the efficiency in evacuation.

Finally, the location of the fire along the vertical height of the building also affects the total evacuation time for both the occupancies considerably. However, the influence is more prevalent in case of hospital buildings than office buildings due to higher complexities in evacuating slow-moving dependent occupants with assisting devices. It can be observed from the results that a fire in the lower stories is a critical parameter while designing an evacuation framework for both a hospital and office building.

6. Limitations and Future Studies

This study evaluated the influence of the egress width, fire location, and the number and placement of exit stairways on the total evacuation time of a hospital building. The assisted-evacuation simulations were carried out under a realistic hospital environment. However, the assisting devices considered are limited to specific dimensions of a wheelchair and a bed assumed in the analysis. Other assisting devices with varying preparation times that are commonly used in hospitals have not been modeled. Additionally, the study assumed that vertical egress occurs solely through stairways and does not evaluate other means of vertical egress, such as elevators. The hospital building is also assumed to function similarly throughout its levels to simplify the analysis, without considering separate departments with different functions and occupants. Furthermore, the hospital building simulated is limited to a maximum of 30 stories in height.

The role of situational awareness in optimizing the evacuation efficiency considering assisted evacuation of hospital occupancy can be studied in future research. The egress model with situational awareness can be modelled in simulation software, and the results can be compared with the present study. Furthermore, research towards practically implementing this approach can be conducted. As this study is limited to only hospital buildings, the research can further be extended to nursing homes and homes for the elderly, where there is a presence of low-speed occupants needing assistance.

7. Conclusions

Based on the results in this paper, the following conclusions can be drawn:

1. The time to evacuate a hospital building, with assisted evacuation (two-thirds low-speed occupants considering assistance), is significantly longer as compared to self-evacuation scenarios in the same hospital building (about 3.5 times higher) or self-evacuation scenario in an office building (about 1.5 times higher) of a similar height, floor layout, and egress paths. Thus, specific evacuation strategies are to be developed for hospital building considering all the critical parameters.
2. The positioning of stairways significantly impacts evacuation durations in hospitals. Among the configurations studied, the arrangement with two stairs inside and one outside the core offers the shortest evacuation time by dispersing slow-moving occupants with assisting devices, thereby reducing the overall congestion.
3. Increasing the number of strategically placed stairs in a hospital building enhances the egress capacity and reduces the total evacuation time, mitigating critical bottlenecks and congestion. Demonstrated by the A, B, and C stairway arrangement (103 min) taking longer to evacuate compared to the A, B stairway arrangement (98 min). Economically, prioritizing more stairs in the bottom half, where the merging density is higher, significantly decreases the total evacuation time.
4. The presence of low-speed occupants adversely affects the occupant flow rate. The total evacuation time increases by almost three when one-third of the occupants move at a low-speed, while it increases by three and a half times when the number of low-speed occupants increases to two-thirds of the total occupant population in a hospital building. Higher proportions of slow-moving occupants elevate the likelihood of hindering those moving at a regular pace, consequently reducing the flow rate.
5. The location of the fire is an important parameter which influences the egress time in a hospital building. The evacuation time is the highest when a fire occurs at the lower levels (stories) of a hospital building. The total evacuation time for a fire on the third to sixth floor of a 20-story hospital building is 170 min, which is 36% and 15% higher than a fire at the top level (15th–18th story) and the intermediate level (9th–12th story).

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