Emergency evacuation of people with disabilities: A survey of drills, simulations, and accessibility

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Abstract: A natural or man-made disaster may destabilize the structure of a building and endanger the lives of its occupants. Evacuating occupants in the shortest possible time is the first reaction in such situations, often referred to as indoor emergency evacuation. Indoor emergency evacuations pay little attention to people with disabilities (PWD) who face additional challenges in emergency situations than people without disabilities. This work highlights the major findings in literature with regard to emergency evacuation of PWD and underscores the related shortcomings and gaps for future research. Current studies can be categorized in: evacuation drills, computer evacuation models, and indoor accessibility measures for PWD. Evacuation drills are focused on assessing the ability of PWD to negotiate different surface types and bottlenecks, but none on understanding their behavior and decisions during an emergency evacuation. Computer simulations are focused on developing evacuation plans by minimizing the overall evacuation time, but fail to capture the dynamics, uncertainties, and complexities in a real-world evacuation scenario. Only few studies are devoted to measuring the accessibility of indoor environments to PWD, most of which are not suitable for wayfinding purposes. Finally, we discuss research gaps in developing indoor spatial models, accessible, personalized, and collaborative wayfinding, and real-time dynamic evacuation systems with accessible user-interfaces.

Subjects: Simulation & Modeling; Navigation; Disability

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PUBLIC INTEREST STATEMENT
Emergency evacuation of people with disabilities (PWD) carries more subtleties than those without disabilities. For this reason, researchers have studied different aspects of this topic, from performing evacuation drills and modeling accessibility, to developing computer simulations for assessing different evacuation plans. We not only summarize their findings and underscore their merits but also highlight their shortcomings and shed light on future research venues to facilitate the emergency evacuation of PWD.
Keywords: emergency evacuation; indoor wayfinding; people with disabilities; evacuation drill; computer simulation; accessibility

1. Introduction

Today, more people with disabilities (PWD) are living on earth than ever before (Spence, Lachlan, Burke, & Seeger, 2007). According to the United Nations Office for Disaster Risk Reduction (UNISDR, 2013), 15% of the world’s population lives with some sort of disability. Around 12.6% of the working population (Rehabilitation Research and Training Center on Disabilities Demographics and Statistics, 2005) and 12% of the US population representing over 37 million people (U.S. Census Bureau, 2011) have some sort of communicative, physical, or mental disability, of which over 50% are between 18 and 64 years of age (U.S. Census Bureau, 2011). Between 10% and 20% of Europeans (Lena, Kristin, Staffan, Sara, & Elena, 2012), between 14% and 17% of residents of England (Boyce, Shields, & Silcock, 1999c), almost 20% of Australians (ABS Disability, 2009), and 6.34% (82.96 million people) of China’s population suffer from various types of disability (Jiang et al., 2012). The percentage of adults with disabilities who live alone is twice the percentage of adults without disabilities who live alone (Spence et al., 2007), thus less likely to have an assistance.

An emergency evacuation is required after a fire, earthquake, or landslide because the building may lose its stability during a short period of time. Sometimes, fatalities due to crowding and evacuation of a building outnumber those due to emergency events (Liu, Liu, & Wu, 2013; Sagun, Bouchlaghem, & Anumba, 2011). To mitigate congestions and casualties during evacuation of high-rise buildings or other large and complex structures and to minimize evacuation time and save more people, evacuation plans and precautions must be taken into account. During emergency evacuation, PWD are less likely to receive a help from others than in non-emergency situations. Considering their specific requirements and slow movement in comparison with people without disabilities during rapid changes in emergency situations, PWD are less likely to take the required actions during evacuation in time.

Emergency evacuation of PWD is usually approached in the literature from three perspectives: Evacuation drills, computer evacuation models, and accessibility. Sections 2, 3, and 4 summarize major findings in each of these categories and debate research shortcomings. Section 5 discusses what is yet to be done to boost PWD’s survival chances during emergency evacuations, followed by conclusions in Section 6.

2. Evacuation drills

2.1. Pre-evacuation time

Proulx (1995) performed an evacuation drill in four residential buildings in four different cities. All buildings were six or seven stories high with an average population of 150 people, 30 of whom (20%) were PWD. People who use a cane or walk slow, people with visual impairments or multiple sclerosis, those carrying children, and people over 65 years old were included in the drill while people who use a wheelchair (PWW) and occupants with other types of mobility impairments were excluded. The pre-evacuation time, which is the elapsed time between the alarm and the moment the person leaves his/her apartment, ranged from 0 to 25 min with an average of 6 min. Very large delays in this drill were because some people did not hear the alarm and the bells were very far from their apartments. They started to evacuate only after they saw firefighters or firefighters knocked on their door. However, most residents started to evacuate 2.82 min after they heard the alarm. The reasons for this delay were, according to evacuees, finding their children or pets, collecting personal belongings, getting dressed, and taking a look at the corridor or balcony (a more detailed report about pre-evacuation times is provided by Shi et al. (2009) for different building and alarm system types). The required time to evacuate the building through stairs was 1.62 min for PWD and 1.20 min for others on average. It shows that the main issue in low-rise
buildings is the delay time not the time spent to go down the stairs. The average stair descent speed of occupants was 0.56 m/s where children aged 2–5 and people over 65 years old were the slowest groups with an average speed of 0.45 and 0.43 m/s, respectively. This speed includes the time taken to rest, to peek into the corridors, or to chat with neighbors. No congestion or crowding was observed on stairs during evacuation. Statistical analyses showed that gender had little influence on speed. Peacock, Reneke, Kuligowski, and Hagwood (2017) reported a pre-evacuation time of 6.6–28.5 min with a mean of 14.2 min and a movement speed of 0.07–0.94 m/s with a mean of 0.28 m/s on descending the stairways for people with mobility impairments. They collected this data from 170 people with mobility impairments during two indoor fire drill evacuations. However, their definition of pre-evacuation time is different in that it not only includes the time before initiating the evacuation but also the travel time from an occupant’s original location in the building to the stairway. They also concluded that the pre-evacuation time consistently occupies much of the total evacuation time.

2.2. Movement speed
All reported speeds on stairs in this article are based on the distance over the pitch line of stairs, indicated in Figure 1. Jiang et al. (2012) designed an evacuation drill at a subway station in Beijing to investigate the effect of disability, passage width, and gender on speed during horizontal and stair descending/ascending movements. The width, tread, and rise of the stairs were 3.0, 0.32, and 0.14 m, respectively. The stairwell consisted of two flights with 11 and 12 steps, respectively. The landing linking the two flights was 1.8 m deep. Participants comprised 40 unassisted PWD, 20 single-crutch PWD, 40 double-crutches PWD, and 17 people without disabilities. Participants were all older than 20, mostly between 40 and 60 years old. The numbers of male and female participants were almost equal. All participants were asked to move at their highest speed. Their results are summarized in Table 1. Willingness of most single-crutch and double-crutches participants to use the stair handrail as additional support reduced the impact of passage width on speed during stair descending/ascending movement in comparison to horizontal movement. The following can be inferred from Table 1: Males move 13% to 50% faster than females, people without disabilities move fastest followed by no-aid PWD (63%–80% of the able-bodied movement speed), people who use a single-crutch (31%–59% of the able-bodied movement speed), and people who use double-crutches (20%–53% of the able-bodied movement speed), people move fastest on horizontal surfaces followed by when descending stairs (39%–77% of the horizontal surface movement speed) and when ascending stairs (30%–61% of the horizontal surface movement speed), and passage width has a negligible effect on the movement speed unless the passage is too narrow (< 60 cm).

Boyce, Shields, and Silcock (1999a) investigated the movement speed of people who are blind and people with mobility impairments on indoor horizontal surfaces (50 m long), ramps (with a slope of 3° to 4° and a continuous handrail on either side), stairs, and 90° turns. The movement speed for each group on each type of surface is given in Table 2 and the time it takes each group to make a 90° turn is reported in Table 3. These speeds do not include rest periods. The expression assisted walking in Tables 2 and 3 means that this person needs other people’s help to walk and unassisted walking means that this person can walk without others’ help. Assisted and unassisted walking groups include people who are blind. The expression assisted wheelchair user means that this person needs someone to push the wheelchair and unassisted wheelchair user means that

Figure 1. Rise, tread and pitch line in a stairwell.
Table 1. Speed (m/s) of different mobility-impaired groups varied with passage width, gender, and surface type where H, D, and A stand for horizontal surface, descending, and ascending stairs, respectively

| Passage width (m) | Unlimited  | 0.9    | 0.8    |
|------------------|------------|--------|--------|
|                  | Male | Female| Male | Female| Male | Female |
| Surface type     |      |       |      |       |      |       |
| No-aid PWD       | 1.34 | 0.89  | 0.78 | 1.17  | 0.71 | 0.66  |
| Single-crutch    | 1.00 | 0.51  | 0.47 | 0.79  | 0.35 | 0.33  |
| Double-crutches  | 0.89 | 0.40  | 0.36 | 0.61  | 0.24 | 0.18  |
| Able-bodied      | 1.69 | 1.19  | 0.98 | 1.47  | 1.13 | 0.90  |

| Passage width (m) | 0.7   | 0.6   | 0.5   |
|------------------|-------|-------|-------|
|                  | Male | Female| Male | Female| Male | Female |
| Surface type     |      |       |      |       |      |       |
| No-aid PWD       | 1.34 | 0.90  | 0.78 | 1.19  | 0.70 | 0.64  |
| Single-crutch    | 0.96 | 0.51  | 0.46 | 0.77  | 0.35 | 0.33  |
| Double-crutches  | 0.83 | 0.40  | 0.36 | 0.57  | 0.24 | 0.17  |
| Able-bodied      | 1.63 | 1.19  | 0.98 | 1.47  | 1.13 | 0.90  |
| Type of floor         | Type of mobility impairment                | Number of participants | Speed (m/s) | Std. of speed |
|----------------------|-------------------------------------------|------------------------|-------------|--------------|
| Horizontal surface   | People without disabilities                | 6                      | 1.25        | 0.32         |
|                      | Unassisted walking using no device         | 52                     | 0.95        | 0.32         |
|                      | Unassisted walking using crutches          | 6                      | 0.94        | 0.30         |
|                      | Unassisted walking using stick             | 33                     | 0.81        | 0.38         |
|                      | Unassisted walking using walking frame     | 10                     | 0.57        | 0.29         |
|                      | or rollator                                |                        |             |              |
|                      | Assisted walking by others                 | 18                     | 0.78        | 0.34         |
|                      | Motorized wheelchair                       | 2                      | 0.89        | -            |
|                      | Unassisted manual wheelchair               | 12                     | 0.69        | 0.35         |
|                      | Assisted manual wheelchair                | 16                     | 1.30        | 0.34         |
| Ramp (upward)        | People without disabilities                | 6                      | 1.01        | 0.41         |
|                      | Unassisted walking using no device         | 19                     | 0.68        | 0.24         |
|                      | Unassisted walking using crutches          | 4                      | 0.46        | 0.33         |
|                      | Unassisted walking using stick             | 20                     | 0.52        | 0.24         |
|                      | Unassisted walking using walking frame     | 5                      | 0.35        | 0.33         |
|                      | or rollator                                |                        |             |              |
|                      | Assisted walking by others                 | 8                      | 0.53        | 0.17         |
|                      | Motorized wheelchair                       | -                      | -           | -            |
|                      | Unassisted manual wheelchair               | 1                      | 0.7         | -            |
|                      | Assisted manual wheelchair                | 7                      | 0.89        | 0.20         |
| Ramp (downward)      | People without disabilities                | 6                      | 1.26        | -            |
|                      | Unassisted walking using no device         | 19                     | 0.68        | 0.24         |
|                      | Unassisted walking using crutches          | 4                      | 0.47        | 0.35         |
|                      | Unassisted walking using stick             | 20                     | 0.51        | 0.20         |
|                      | Unassisted walking using walking frame     | 5                      | 0.36        | 0.35         |
|                      | or rollator                                |                        |             |              |
|                      | Assisted walking by others                 | 8                      | 0.69        | 0.21         |
|                      | Motorized wheelchair                       | -                      | -           | -            |
|                      | Unassisted manual wheelchair               | 1                      | 1.05        | -            |
|                      | Assisted manual wheelchair                | 7                      | 0.96        | 0.15         |
| Stairs (upward)      | People without disabilities                | 8                      | 0.70        | 0.24         |
|                      | Unassisted walking using no device         | 19                     | 0.43        | 0.13         |
|                      | Unassisted walking using crutches          | 1                      | 0.22        | -            |
|                      | Unassisted walking using stick             | 9                      | 0.35        | 0.11         |
|                      | Unassisted walking using walking frame     | 1                      | 0.14        | -            |
|                      | or rollator                                |                        |             |              |
|                      | Assisted walking by others                 | 4                      | 0.29        | -            |
| Stairs (downward)    | People without disabilities                | 8                      | 0.70        | 0.26         |
|                      | Unassisted walking using no device         | 19                     | 0.36        | 0.14         |
|                      | Unassisted walking using crutches          | 1                      | 0.22        | -            |
|                      | Unassisted walking using stick             | 9                      | 0.32        | 0.12         |
|                      | Unassisted walking using walking frame     | 1                      | 0.16        | -            |
|                      | or rollator                                |                        |             |              |
|                      | Assisted walking by others                 | 4                      | 0.13        | -            |
this person can propel the wheelchair on his/her own. The following can be inferred from Table 2. People without disabilities move fastest on average and their speed is almost the same on different surfaces, except when descending or ascending stairs where their speed is reduced by half. PWW move faster than people who use crutches or walking frames on horizontal surfaces and ramps but have more difficulty negotiating the stairs. These observations are in accordance with those made from Table 1. Table 3 highlights how time-consuming it is to make a 90° turn, especially for PWD.

Shi et al. (2009) and Christensen, Collins, Holt, and Phillips (2006) also compiled a list of movement speeds of people with different types of disabilities on different types of indoor surfaces. Kuligowski, Peacock, Wiess, and Hoskins (2013) summarized the results of seven studies on evacuation speeds of elderly and people with mobility impairments on stairwells. They showed that this speed for elderly ranges from 0.11 m/s (while being assisted) to 1.37 m/s (without assistance) in different studies. They implemented an evacuation drill in a six-story assisted-living residential building, hosting 45 elderly and residents with mobility impairments, to measure their speeds on stairwells. If an old person needs cane, stair chairs, or assistance to go down the stairs, he/she is categorized in the impaired group and in the old group otherwise. The stair width, tread, and rise were 1.12, 0.30, and 0.17 m, respectively. To calculate the speed, they considered the travel distance as the summation of diagonal distances along the stair treads (Figure 1) and the horizontal distances on the landings. They reported an average speed of 0.29, 0.25, 0.21, 0.11, and 0.21 m/s for elderly, people with mobility impairments who use a cane, assisted by another resident, assisted by a firefighter, and using stair descent device, respectively. These speeds do not take into account congestions or clogging effects because no congestion was observed during evacuation. They also showed that there was not any decreasing pattern in residents’ speed during evacuation, suggesting no fatigue effect.

Fang et al. (2012) estimated an average speed of 0.81 ± 0.13 m/s for downward movement on stairs in an emergency evacuation drill of an eight-story building with 163 participants (no PWD) distributed unevenly on different floors, half of whom were placed on the fifth and sixth floors. They showed that this speed changes between 0.77 and 0.86 m/s based on evacuees’ density and physical strength. These speeds are calculated based on the summation of inclination distance on stairs (Figure 1) and the turning length on landings between flights. It is noteworthy that Lavender et al. (2014) showed that travel speeds using stair descent devices can be within the travel speed range of other building occupants.

### 2.3. Doorways

In an attempt to measure the capacity of building’s exit doors during an emergency evacuation, Daamen and Hoogendoorn (2010) performed 16 experiments in laboratory. The
emergency capacity of a doorway is measured as the maximum number of people who can pass through it in one minute under emergency conditions if the door is 1 m wide. The emergency door capacities in their experiments ranged from 132 to 186 with an average of 168 people per minute per meter, when the door is 180° open. Their experiment population included equal numbers of children, adults, and elderly, but no PWD. They showed that a door does not have to be 180° open for the maximum capacity and an opening angle of 150° is sufficient for a free outflow. If the door is only 90° open in the escape direction, the average capacity reduces to 132.6. Inclusion of 5% PWD in the population (three blindfolded participants and three PWW) reduced the average emergency doorway capacity to 121.2 when the door is 180° open. Other emergency doorway capacities reported in the literature include 90.0, 106.2, 106.8, 108.0, 132.0, 135.0, 137.4, and 193.8 people per minute per meter (Daamen & Hoogendoorn, 2010).

Boyce, Shields, and Silcock (1999b) performed experimental tests to determine the time required to open a closed door and pass through it for different groups of people with mobility impairments. The door’s width was 83 cm, fitted with a door closer. The time is measured since the door leaf starts to move until the participant has passed the doorway. Their results are summarized in Table 4. People who use walking frames or rollators take almost two times longer and PWW take almost three times longer than people who use no devices to pass doorways. It shows the difficulty of opening a door and keeping it open while passing the doorway for PWW and people who use walking frames and rollators. Doors with a pulling mechanism seem to be the most difficult for PWW to negotiate since up to 71% of manual wheelchair users and almost all motorized wheelchair users fail to successfully pass them. Although these percentages fall to 29% and 50% for doors with a pushing mechanism, they are still much higher than the failure rates for other PWD.

2.4. Lifts
Turhanlar, He, and Stone (2013) argued that on one hand, people with mobility impairments cannot negotiate stairs without assistance of others and on the other hand, elevators are mostly shutdown during an emergency. Turhanlar et al. (2013) and Luo and Wong (2006) showed that using lifts for evacuation in addition to stairs and elevators can significantly decrease the total evacuation time. By assessing a sample of 1,755 applications of 81 general passenger lifts over three years throughout Australia, Turhanlar et al. (2013) estimated that in 99.3% of times, shifts are available and operate soundly. However, their sample only includes application of shifts under normal conditions not in case of fire or any other emergency event. Using lifts in an emergency situation requires special approval because not only lifts are not as safe as fire isolated stairwells but also occupants may over crowd and halt a lift (Williamson & Demirbilek, 2010). Fire isolated stairwells are the safest egress route (Williamson & Demirbilek, 2010) but also the most challenging for PWD.

2.5. Building’s exit door choice
Current building codes, regulations, and standards falsely assume that all available exit doors would be equally used in case of an emergency evacuation. According to evacuation drills reported by Shi et al. (2009), most occupants (50.1%) prefer the nearest exit door and the rest choose an exit based on familiarity (19.5%), following the emergency staff (25.2%), or following the crowd (5.2%). Sagun et al. (2011) implemented evacuation drills in three buildings with one, two, and three floors, respectively, and multiple exit doors and a population of 80–120 people in each building (no PWD). Their evacuation drill results showed that the perceived distance from a user’s current location to exit doors and familiarity with exit doors play the most significant roles in choosing an exit door with a contribution of 44% and 17%, respectively. The other factors include the door that the user entered through, emergency signs, visibility, following other people, crowd flow force, bottlenecks, obstacles, and orientation by fire marshals.
| Door’s mode of operation | Type of mobility impairment | Number of participants | Closing force of door closer (N) | Percentage of failures to negotiate the closed door | Mean time required to negotiate the closed door in successful cases (second) | Std. of time |
|--------------------------|----------------------------|------------------------|-------------------------------|-----------------------------------------------|-------------------------------------------------|-------------|
| Pull                     | Walking using no device    | 63                     | 21 1.3                        | 3.3                                           | 1.5                                              |             |
|                          |                            | 30                     | 1.4                          | 3.2                                           | 1.0                                              |             |
|                          |                            | 42                     | 2.6                          | 3.7                                           | 1.8                                              |             |
|                          |                            | 51                     | 2.3                          | 3.8                                           | 1.6                                              |             |
|                          |                            | 60                     | 3.0                          | 4.1                                           | 1.9                                              |             |
|                          |                            | 70                     | 4.7                          | 4.6                                           | 2.2                                              |             |
| Walking using crutches   | 5                          | 21                     | 1.3                          | 2.8                                           | Not given                                        |             |
|                          |                            | 30                     | 1.4                          | Not given                                     | Not given                                        |             |
|                          |                            | 42                     | 2.6                          | 4.0                                           | Not given                                        |             |
|                          |                            | 51                     | 2.3                          | 3.6                                           | Not given                                        |             |
|                          |                            | 60                     | 3.0                          | 3.6                                           | Not given                                        |             |
|                          |                            | 70                     | 4.7                          | 4.6                                           | Not given                                        |             |
| Walking using stick      | 28                         | 21                     | 1.3                          | 3.6                                           | 1.4                                              |             |
|                          |                            | 30                     | 1.4                          | 3.2                                           | 0.9                                              |             |
|                          |                            | 42                     | 2.6                          | 3.9                                           | 1.4                                              |             |
|                          |                            | 51                     | 2.3                          | 4.6                                           | 2.2                                              |             |
|                          |                            | 60                     | 3.0                          | 4.1                                           | 1.7                                              |             |
|                          |                            | 70                     | 4.7                          | 4.9                                           | 2.3                                              |             |
| Walking using walking frame or rollator | 8    | 21                     | 12.5                         | 5.7                                           | Not given                                        |             |
|                          |                            | 30                     | 12.5                         | 5.2                                           | Not given                                        |             |
|                          |                            | 42                     | 25.0                         | 4.7                                           | Not given                                        |             |
|                          |                            | 51                     | 25.0                         | 6.3                                           | Not given                                        |             |
|                          |                            | 60                     | 25.0                         | 8.9                                           | Not given                                        |             |
|                          |                            | 70                     | 33.3                         | 3.2                                           | Not given                                        |             |
| Manual wheelchair        | 7                          | 21                     | Not tested                   | Not tested                                    | Not tested                                       |             |
|                          |                            | 30                     | 28.6                         | 13.5                                          | Not given                                        |             |
|                          |                            | 42                     | 42.9                         | 12.8                                          | Not given                                        |             |
|                          |                            | 51                     | 42.9                         | 10.5                                          | Not given                                        |             |
|                          |                            | 60                     | 71.4                         | 4.2                                           | Not given                                        |             |
|                          |                            | 70                     | 71.4                         | 4.3                                           | Not given                                        |             |
| Motorized wheelchair     | 2                          | 21                     | Not tested                   | Not tested                                    | Not tested                                       |             |
|                          |                            | 30                     | 100                          | -                                              | -                                                |             |
|                          |                            | 42                     | 100                          | -                                              | -                                                |             |
|                          |                            | 51                     | 100                          | -                                              | -                                                |             |
|                          |                            | 60                     | 100                          | -                                              | -                                                |             |
|                          |                            | 70                     | 100                          | -                                              | -                                                |             |

(Continued)
| Door’s mode of operation | Type of mobility impairment | Number of participants | Closing force of door closer (N) | Percentage of failures to negotiate the closed door | Mean time required to negotiate the closed door in successful cases (second) | Std. of time |
|--------------------------|-----------------------------|------------------------|---------------------------------|--------------------------------------------------|--------------------------------------------------------------------------|-------------|
| Push                     | Walking using no device     | 63                     | 21                               | 1.2                                              | 3.0                                                                      | 0.8         |
|                          |                             |                        | 30                               | 1.1                                              | 3.5                                                                      | 2.2         |
|                          |                             |                        | 42                               | 2.4                                              | 3.7                                                                      | 1.5         |
|                          |                             |                        | 51                               | 3.8                                              | 4.1                                                                      | 2.4         |
|                          |                             |                        | 60                               | 4.0                                              | 4.0                                                                      | 1.9         |
|                          |                             |                        | 70                               | 6.4                                              | 4.3                                                                      | 2.0         |
|                          | Walking using crutches      | 5                      | 21                               | 1.2                                              | 3.7                                                                      | Not given   |
|                          |                             |                        | 30                               | 1.1                                              | 3.0                                                                      | Not given   |
|                          |                             |                        | 42                               | 2.4                                              | 3.8                                                                      | Not given   |
|                          |                             |                        | 51                               | 3.8                                              | 3.6                                                                      | Not given   |
|                          |                             |                        | 60                               | 4.0                                              | 3.8                                                                      | Not given   |
|                          |                             |                        | 70                               | 6.4                                              | 3.9                                                                      | Not given   |
|                          | Walking using stick         | 28                     | 21                               | 1.2                                              | 3.7                                                                      | 1.5         |
|                          |                             |                        | 30                               | 1.1                                              | 3.8                                                                      | 1.5         |
|                          |                             |                        | 42                               | 2.4                                              | 4.0                                                                      | 1.6         |
|                          |                             |                        | 51                               | 3.8                                              | 4.3                                                                      | 2.4         |
|                          |                             |                        | 60                               | 4.0                                              | 3.7                                                                      | 1.5         |
|                          |                             |                        | 70                               | 6.4                                              | 4.6                                                                      | 2.1         |
|                          | Walking using walking frame or rollator | 8          | 21                               | 12.5                                             | 7.9                                                                      | Not given   |
|                          |                             |                        | 30                               | 12.5                                             | 6.3                                                                      | Not given   |
|                          |                             |                        | 42                               | 25.0                                             | 5.2                                                                      | Not given   |
|                          |                             |                        | 51                               | 25.0                                             | 7.9                                                                      | Not given   |
|                          |                             |                        | 60                               | 25.0                                             | 5.2                                                                      | Not given   |
|                          |                             |                        | 70                               | 25.0                                             | 6.2                                                                      | Not given   |
|                          | Manual wheelchair           | 7                      | 21                               | Not tested                                       | Not tested                                                               | Not tested  |
|                          |                             |                        | 30                               | 14.3                                             | 13.1                                                                      | Not given   |
|                          |                             |                        | 42                               | 14.3                                             | 13.3                                                                      | Not given   |
|                          |                             |                        | 51                               | 28.6                                             | 10.0                                                                      | Not given   |
|                          |                             |                        | 60                               | 28.6                                             | 10.5                                                                      | Not given   |
|                          |                             |                        | 70                               | 28.6                                             | 11.6                                                                      | Not given   |
|                          | Motorized wheelchair        | 2                      | 21                               | Not tested                                       | Not tested                                                               | Not tested  |
|                          |                             |                        | 30                               | 50                                               | 7.2                                                                      | -           |
|                          |                             |                        | 42                               | 50                                               | 7.0                                                                      | -           |
|                          |                             |                        | 51                               | 50                                               | 7.3                                                                      | -           |
|                          |                             |                        | 60                               | 50                                               | 10.0                                                                     | -           |
|                          |                             |                        | 70                               | 50                                               | 8.6                                                                      | -           |
A total of 86 student subjects, 8 female and 78 male, aged between 17 and 21 and all in good health, were used in an evacuation drill performed in a four-story building by Chen, Pan, Zhang, Narayanan, and Soldner (2013). All evacuees were distributed on the fourth floor of the building and were asked to evacuate the building as soon as they heard the alarm. The results showed that: (a) when evacuees are familiar with all egress routes, 57.7% of them take the fastest route (fastest route can be either the shortest or the least congested one), 23.1% follow the crowd, and 19.2% take the route that they took to enter the building last time, (b) if evacuees are familiar only with one route/stairwell/exit door, 74.2% take that route/stairwell/exit door and do not try to find any alternative even if it is very congested, 16.1% follow the crowd, and 9.7% try to find alternative egress routes, (c) evacuees are forced to follow the crowd even if they prefer another egress route, (d) the exit door’s width is the most influencing factor on congestion and evacuation time, and (e) the evacuation speed is almost inversely proportional to the density of evacuees.

Bode and Codling (2013) virtual reality evacuation drills showed that when occupants are stressed and panicked: (a) they prefer the route with which they are familiar, (b) they are more willing to follow the crowd even if it increases their evacuation time, and (c) they are not willing to avoid congested egress routes. Kobes et al. (2010b) inspected the effect of smoke and exit signs on evacuees’ route choice in 83 emergency evacuation drills in a hotel building at night. The results showed that in the absence of smoke most people take the main exit door and when smoke blocks the route toward the main exit door, most people take the fire exit. Moreover, evacuees use the exit signs more often when these signs are placed lower than ceilings.

3. Computer evacuation models

Many researchers have used agent-based models to investigate different evacuation scenarios. Agents are software constructs or classes in an object-oriented programming which encapsulate characteristics and behaviors of an entity in the real world which is human being in case of evacuation scenarios. Behaviors are if-then rules which allow agents to interact with each other or with their environment and attempt to reach a goal (Manley & Kim, 2012; Watson & Wixom, 2007). Gwynne, Galea, Owen, Lawrence, and Filippidis (1999) reviewed 22 indoor emergency evacuation models by 1999 and recognized that the most significant drawbacks in evacuation models were ignoring individuality of evacuees in decision-making and considering a homogeneous population which were mostly due to low computational capabilities. Computer simulations have been used to investigate emergency evacuation from various aspects such as the effect of occupants’ density (Thompson & Marchant, 1995), smoke (Jeon, Kim, Hong, & Augenbroe, 2011; Jin & Yamada, 1989; Nguyen, Ho, & Zucker, 2013), movement type, e.g. crawling or walking (Kady & Davis, 2009), gender and body mass index (Kady & Davis, 2009), surface type, e.g. hallway or stairs (Chen, Song, Fan, Lu, & Yao, 2003), and disability (Boyce et al., 1999a) on movement speed, the effect of social forces, e.g. friction and compression between evacuees, room door size, exit door size (Ha & Lykotrafitis, 2012), and smoke (Jeon et al., 2011) on evacuation time, and the effect of smoke on wayfinding and evacuation routes (Jeon et al., 2011; Kobes et al., 2010b).

Min and Yu (2013) and Jian, Juan, Yao-Jian, and Lo (2013) showed that a mixed usage of stairwells and elevators can considerably reduce the evacuation time. Min and Yu (2013) found the shortest evacuation time for 100 people on the 10th floor of a building with one stairwell and one elevator when 60% of occupants use the stairwell and the rest use the elevator. By decreasing or increasing the population, the stairwell usage percentage in the optimal plan also decreases and increases. Zu-Ming, Jin, and De-Pin (2011) investigated issues and risks associated with using elevators for evacuation of high-rise buildings in case of fire and suggested using only stairwells to evacuate the low floors (under the 10th floor) and using both elevators and stairwells to evacuate the high floors (above the 10th floor).

Table 5 shows the size and speed of different agents on different surface types in Koo, Kim, and Kim (2012), (2013), (2014) and Manley and Kim (2012). In all these studies:
residents are uniformly distributed among the floors,

- residents respond to the alarm after some random delay, following a normal distribution with a mean value of 29 s and a standard deviation of 9 s,

- six different agent types: able-bodied agents, motorized wheelchair agents, non-motorized wheelchair agents, visually impaired, hearing impaired, and stamina impaired agents, are considered, where the only differences among them are their speed and size,

- stairs and obstacles reduce agents’ speed, and

- wheelchair agents can evacuate through stairs only with the help of a person without disabilities at half his/her speed.

Following are Koo et al. (2012) findings for a 24-story building. (a) Including 14% PWD in the population increases the total evacuation time by 28%. PWD slowed down the evacuation speed of residents without disabilities to the speed of PWD by blocking their routes in narrow hallways and stairwells due to their larger space requirements and lower speeds, also confirmed by Lena et al. (2012). (b) Increasing the population of the building increases the total evacuation time because of congestions. (c) Bottlenecks in the building such as doors and tight stairwells are more responsible for congestions than other parts of the building. (d) Since evacuees travel from upper floors to lower floors, the flow rate and density of stairwells in higher floors reaches its highest level right after the beginning of the simulation, then immediately drops, but the flow rate and density of stairwells in lower floors remain at full capacity for a longer time. (e) Evacuating residents on lower floors earlier than residents on higher floors results in a faster evacuation of all residents on average. However, Koo et al. (2013) later showed that this reduction in evacuation time is negligible. Koo et al. (2013) also investigated two other scenarios. In the first scenario, evacuation of PWW was delayed because they move slower and require larger space and may block the evacuation route of other residents. In the second scenario, PWW took elevators and other people took stairs but they were evacuated simultaneously. The first scenario steadily reduced the overall evacuation time but delaying the evacuation of PWD is not realistic. The second scenario significantly reduced the overall evacuation time (by 21.5%) and was the fastest evacuation plan. This is not only because PWW took elevators instead of stairs but also because they did not impede other residents on stairwells. Koo et al. (2014) increased the movement speed of agents in Table 1 by 50% (arguing that people run faster when they are panicked) and observed that the overall evacuation time decreases to 67%. They also defined a 40% probability that the next cell that

| Agent type                   | Size (m × m) | Speed (m/s) (Koo et al., 2012) | Speed (m/s) (Koo et al., 2013, Koo et al., 2014; Manley & Kim, 2012) |
|------------------------------|--------------|---------------------------------|---------------------------------------------------------------|
|                              | (Koo et al., | Default | Stairs | Obstacle | Default | Stairs | Obstacle |
|                              | 2012, 2013,  |         |        |          |         |        |          |
|                              | 2014; Manley & Kim, 2012) |         |        |          |         |        |          |
| People without disabilities | 0.46 × 0.46  | 1.25   | 0.70   | 0.70     | 1.22    | 0.61   | 0.61     |
| Motorized wheelchair         | 0.61 × 0.61  | 0.69   | -      | -        | 0.67    | -      | -        |
| Non-motorized wheelchair     | 0.61 × 0.61  | 0.89   | -      | -        | 0.61    | -      | -        |
| Visually impaired            | 0.46 × 0.46  | 0.86   | 0.61   | -        | 0.98    | 0.49   | -        |
| Hearing impaired             | 0.46 × 0.46  | 1.25   | 0.70   | 0.70     | 1.22    | 0.61   | 0.61     |
| Low stamina                  | 0.46 × 0.46  | 0.78   | 0.36   | -        | 0.67    | 0.24   | -        |
an agent takes does not get them closer to the exit door (arguing that people make mistakes when they are panicked). This probability is 50% for residents with low stamina and 0 for people with physical impairment because they are well aware of the exit route. This probability is 0 for all residents when they are on stairwells because there is only one option as the next cell in these areas. Adding this mental disorientation in selecting the next cell to the simulation increased the overall evacuation time by 1% (from 789.1 to 797.0 s). However, they showed that the effect of mental disorientation in a wider building can increase the evacuation time up to 26%. They also considered the effect of accumulated physical fatigue during evacuation by decreasing the movement speed of agents gradually after each 100 m movement interval. The movement speed of PWW and with low stamina was decreased twice as other people due to fatigue. The fatigue effect increased the overall evacuation time by 5.5% (from 832.6 to 789.1 s). Considering the effects of all these three factors together (running faster due to panic, mental disorientation, and fatigue), increased the overall evacuation time by 4.4% (from 789.1 to 823.8 s).

Manley and Kim (2012) considered 65 people without disabilities, 1 with visual impairments, 1 who uses a motorized wheelchair, and 4 people with low stamina in a 4-story building with three exit doors on the second and ground floor, of which only the main exit door is accessible to people with mobility impairments. Their simulation results showed that PWW and those with lower stamina are the last to evacuate the building. They also showed that PWD tend to block the progress of people without disabilities due to larger space requirements and slower speeds. The average evacuation time of all evacuees dramatically increases with the number of PWW in the building. In another scenario, they paired each motorized and non-motorized wheelchair user with two persons without disabilities to assist them. The speed for the person who uses a wheelchair and his/her assistants was set to the average of their original speeds and their new size was set to the sum of their original sizes. The mean evacuation time of all residents increased by 8 s in the assisted evacuation scenario but more PWW could evacuate the building successfully. Finally, they indicated that allowing PWW to take the elevators considerably decreases both the clogging phenomenon and the mean evacuation time.

Fahy (1995) considered the congestion effect in their simulation by not allowing more than a specific number of people to occupy a node at the same time and adjusting the walking speed on each node based on the number of people on it. The walking speed is also decreased by a constant coefficient for PWD. During the simulation, the smoke expands and blocks some nodes. If a resident reaches a blocked node, an alternative egress route is computed and allocated to him/her. The program continues until everyone has exited the building or trapped among blocked nodes. Fahy (1995) tested his simulation with a total of 26 residents including 22 people without disabilities and 4 PWD. The evacuation times ranged from 16.6 to 60.0 s with an average of 37.1 s. The results showed that adding PWD to the fire-induced emergency evacuation simulation does not reduce the average evacuation time of residents without disabilities, which can be justified by the small number of residents (a total of 26 occupants) in their simulation.

Golmohammadi and Shimshak (2011) categorized hospital patients in walking wounded, less critical such as patients who use a wheelchair, and critical such as patients confined to beds in a hospital’s evacuation simulation. Less critical and critical patients must use the elevators and walking wounded patients must take the stairwells. The congestion effect is not taken into account. Two staff members are assigned to each critical patient and one staff member to each less critical patient. The least evacuation time was obtained when walking wounded and less critical patients were evacuated before critical patients because they are faster and need lesser number of staff for evacuation.

4. Indoor accessibility and egressibility
The term accessibility refers to every citizen’s right to move throughout a built environment safely and independently or in brief the ability to access everywhere (Department of Justice, 2010; Evcil, 2012). PWW, people who are blind, or elderly are mobility challenged because the structure is not
designed based on their limitations (Goldsmith, 1997). Two types of accessibility are specific accessibility of a special service and general accessibility of a building. In specific accessibility, the accessibility measures of a particular service or location (e.g. bathroom) from different parts of a building are combined to calculate its accessibility (Church & Marston, 2003). The specific accessibility measures of different services inside a building are combined to produce a number that represents that building’s general accessibility (Sakkas & Perez, 2006). Each of these accessibility definitions can be measured in an absolute (Sakkas & Perez, 2006) or relative (Church & Marston, 2003) form. While an absolute measure only specifies whether a service, location, or building is accessible or not, a relative measure determines the distance, time, and/or effort required to access that location or building (Church & Marston, 2003). In addition, both definitions (general and specific accessibilities) can be narrowed down to a specific group of people such as those with mobility impairments.

Sakkas and Perez (2006) combined two criteria, the length and quality of all paths from all the other interest points (e.g. bathroom, kitchen, telephone kiosks), to measure the accessibility of a specific interest point. However, path quality is not well defined in their study. They assigned a number between 0 and 1 to a building as its accessibility to public, which does not provide much information about its accessibility issues. In a similar effort, Thill, Dao, and Zhou (2011) measured the accessibility of a room inside a building as the total travel cost required to get from different specific places across the city to that room.

Bendel and Klüpfel (2011) identified the following items as influencing factors on the accessibility of a passage: length, width, surface type (e.g. carpet, slippery surface, uneven surface), slope, existence of doors or ramps, and elevation changes. It is the accessibility of exit doors from different parts of the building, referred to as exitability (Vanclooster, Neutens, Fack, Weghe, & Maeyer, 2012), egressibility (Proulx, 1995), or evacuability (Bendel & Klüpfel, 2011), which is of concern for emergency evacuation of PWD. Vanclooster et al. (2012) defined egressibility of a room as the time required for a person without disabilities to reach the nearest exit door, accounting for the speed reductions due to congestions. They found the best egressibility values for rooms adjacent to exit doors and stairwells and worst egressibility values for top floors and highly populated rooms because of the congestion effect at doorways. However, such an egressibility measure assumes that the building is intact while hallways, stairwells, or doors may be damaged or blocked due to disasters. Kim, Jun, Cho, and Kim (2008) developed a similar measure of egressibility, but for PWD, taking into account only the distance and surface type. Instead of focusing on a specific type of disability, they considered them all in one group of people with mobility impairments. Although developing an egressibility measure for a specific room or a building helps to realize whether or not that place is egressible for the target group, it does not solve the wayfinding problem.

Next section discusses research gaps in developing indoor spatial models, accessible, personalized, and collaborative wayfinding, and real-time dynamic navigation systems for evacuation with accessible user-interfaces.

5. Future research directions

5.1. Indoor spatial models

Evacuation simulations usually model the building as a two-dimensional grid, as shown in Figure 2. The first concern with a raster model is the cell size because a small cell size is computationally expensive to process and a large cell size misses details and reduces the accuracy. Additionally, the boundaries of rooms and other components of the building may not match with cell boundaries which could be worse for larger cells. On the other hand, the raster model limits the movement to four or eight directions while neither people are bound by this limitation nor hallways and stairwells are always of regular shapes and directions. Vector models or graphs are a more suitable choice, as shown in Figure 3. Despite graphs are widely used for outdoor wayfinding, they cannot easily be extended to indoor environments because many indoor constraints such as walls,
The first question about a vector model for indoors is that which components of the building should form the graph nodes, which the graph edges, and which should be excluded from the graph. Modeling building components as nodes or edges must be more than arbitrary. An approach is to consider all building components that require effort for passing as graph edges (Hashemi & Karimi, 2016), since this facilitates the application of wayfinding algorithms such as Dijkstra. Another concern is that indoor spatial models, e.g. graphs, used in simulations and evacuation plans do not consider the specific requirements of PWD. For example, while elevators, stairwells, doors, and hallways may all form the edges of the graph, stairwells are not easily accessible to PWW, doors are very demanding, and turns take much more effort from PWW than people without disabilities. While many indoor spatial models do not record the opening mechanism of doors, such information plays a crucial role in wayfinding for PWD. There needs to be an indoor spatial model including all building components that are part of the evacuation routes and containing all their attributes that might affect their accessibility to PWD (e.g. dimension and width). An example is the weighted graph developed by Hashemi and Karimi (2016) where hallways, stairwells, elevators, doorways, and ramps form the graph edges and rooms and intersections form the graph nodes. They assigned a weight to each edge, indicating how demanding that edge is for PWD to pass. The edge weights can be used to find the most accessible egress route. However, the weights assigned to edges are based on their accessibility to PWD, falling short of distinguishing among different disability types or individual physical limitations. Further research is required to address this issue by defining personalized accessibility indexes for different PWD. Finally, manual construction of the graph is very cumbersome for large buildings and needs to be automatically constructed from building floor plans.

5.2. Indoor accessible wayfinding

While finding the shortest, fastest, least congested, or most familiar egress route has been the focus of computer simulations and evacuation plans, none works for PWD. For instance, a very
narrow hallway can make the shortest route inaccessible and useless to a person who uses a wheelchair. There are few studies on egressibility of a building and there are even fewer studies on egressibility of a building for PWD. There should be studies not only to measure the egressibility of a building for PWD, but also to plan their emergency evacuation through accessible routes. An example of an accessible wayfinding algorithm for PWD is developed by Hashemi and Karimi (2016). They apply accessibility indexes of different building components in Dijkstra’s algorithm to find the most accessible egress route for PWD. However, accessible routes should match individuals’ physical limitations where the optimal egress route might not be the same for two people with different disabilities.

5.3. Personalized wayfinding

While accessible wayfinding assures that the route is feasible for the user considering his/her disabilities, personalized wayfinding takes a step further in considering each user’s personal preferences in wayfinding (Hashemi & Karimi, 2017). While for accessible wayfinding we need to investigate the characteristics of each building component, e.g. width, length, and surface type (Hashemi & Karimi, 2016), for personal wayfinding we have to find out what building components are preferred by a specific user, what attributes of each building component are more important to that user, and how comfortable that user is with pedestrian congestion or taking turns. All these factors must be taken into account when finding the optimal egress route for each individual.

5.4. Collaborative wayfinding

The indoor spatial model and its associated attributes might not be accurate, correct, and/or adequate. Users’ personal preferences and physical limitations might be very diverse and exhaustive which makes it very difficult to capture them all. In addition, people might not be accurate in expressing their limitations and preferences. For such reasons the accessible personal egress route might not fully satisfy the user. A partial remedy for this shortcoming is to let users contribute in updating the indoor spatial model and its associated attributes on a daily base. Collaborative wayfinding (Hashemi & Karimi, 2017) lets occupants rate a suggested egress route after taking it. These feedbacks could be reflected in future wayfinding processes for that specific user or similar users.

5.5. Real-time dynamic navigation system for evacuation

Lack of flexibility and speed among PWD to cope with uncertainties in predetermined evacuation plans and rapidly changing conditions may frustrate them during the evacuation. While emergency evacuation simulations are useful to reveal challenges and prepare for them, an emergency evacuation plan cannot be designed solely based on the results of a computer simulation because it will not reveal the same results in reality as in the simulation. In other words, a scenario that resulted in the least evacuation time during the simulation does not necessarily result in the least evacuation time in reality. Expecting people to follow a static evacuation plan when the emergency alarm goes off is far from real. Due to the unknown characteristics of the building and people at the time of the event and people’s unpredictable behavior in emergency situations, an evacuation plan needs to be developed in situ when and where an emergency evacuation needs to be carried out. Such a plan must navigate each evacuee from his current location based on his/her physical capabilities, personal preferences, number of turns, length, and accessibility of the entire route to him/her, real-time human traffic, blockages, and power outages in different parts of the building, etc. The evacuation route needs to be dynamic, i.e. it needs to be updated if any of the assumptions in calculating the route is changed. Hashemi (2018) developed a wayfinding algorithm that not only takes into account the accessibility of building components to people who use a wheelchair but also minimizes the number of turns, avoids blockages, avoids congestions by distributing the evacuees on different egress routes, and dynamically updates the egress route if any of the assumptions in calculating the best route change. Implementing such wayfinding algorithms in a real-time navigation system requires comprehensive and real-time data about the building and people which can be gathered by embedding sensors in different parts of the building and collecting information about evacuees through their phones, mostly automatically.
Last but not least, research needs to be done on designing user-interfaces that best communicate the evacuation route to each group of PWD.

6. Conclusions
We categorized current studies in: evacuation drills, computer evacuation models, and indoor accessibility measures for PWD. We showed that evacuation drills are mostly focused on assessing the ability of PWD to negotiate different surface types and bottlenecks, but none on understanding their behavior and decisions during an emergency evacuation. Computer simulations are focused on developing evacuation plans by minimizing the overall evacuation time, but fail to capture the dynamics, uncertainties, and complexities in a real-world evacuation scenario. Only few studies are devoted to measuring the accessibility of indoor environments to PWD, most of which not suitable for wayfinding purposes.

Evacuation drills can shed light on facts that can be used in developing evacuation plans and wayfinding. Examples of such useful facts are: PWD have longer pre-evacuation times, they move slower than people without disabilities on all surface types, or the most influencing factor on congestion and average evacuation time is the exit door’s width. We can summarize the exit choice behavior of evacuees reported in evacuation drills as follows. If an evacuee is familiar with the structure of the building, he/she chooses the nearest exit door and in case of congestion switches to the fastest egress route. If the evacuee is not familiar with the building structure, he/she takes the same route that he/she took to enter the building or follows the crowd. Evacuation drills focusing on PWD, mostly investigate their ability in negotiating different surface types and building components. There is no study on how the disability type, surface type, passage width, exit door width, distance, familiarity with the building and exit doors, congestion, crowd, exit signs, and smoke affect the PWD’s route selection behavior.

Computer simulations outnumber evacuation drills in the literature because their implementation only needs a computer program. Computer evacuation models report the evacuation time for different scenarios. Their main purpose is to find which scenario produces the least evacuation time which can be used to design an evacuation plan for real events. While there is no issue with minimizing the evacuation time, the main problem is that simulations are naïve abstracts of reality. Many details of the buildings and individual characteristics of people such as physical abilities, wheelchair size, behaviors, and feelings are ignored in a computer model (Pelechano & Malkawi, 2008). Even if a computer simulation considers all details of the building and people, those characteristics do not remain constant during evacuation, we do not know how many people will be inside the building and where in the building they will be, different parts of the building might collapse, water pipes might break, electricity might go out, fires might ignite, people may panic, run, get hurt, some might not wait for PWD or people on the lower floors to evacuate first and some might help PWD, some might ignore the no elevator or elevator only for PWD rules, people do not move with a fixed speed and do not occupy a fixed area during evacuation, some might not move in order and rush into the crowd saving themselves but hurting others and causing more congestion, some might not take the shortest route to the nearest exit, etc. It is simply impossible for a computer simulation to fully imitate the reality.

References
ABS Disability. (2009). ABS: 4430.0 - Disability, aging and carers Australia - summary of findings. Canberra: Australian Bureau of Statistics.

Bendel, J., & Klüpfel, H. (2011). Accessibility and evacuation planning—Similarities and differences. In D. P. Richard, D. K. Erica & D. A. Jason (Eds.), Proceedings of pedestrian and evacuation dynamics (pp. 701–712). Springer US: Boston, MA.

Bode, N. W., & Codling, E. A. (2013). Human exit route choice in virtual crowd evacuations. Animal Behaviour, 86(2), 347–358. doi:10.1016/j.anbehav.2013.05.025

Boyce, K. E., Shields, T. J., & Silcock, G. W. (1999a). Toward the characterization of building occupancies for fire safety engineering: Capabilities of disabled people
moving horizontally and on an incline. Fire Technology, 35(1), 51–67. doi:10.1023/A:1015399216366
Boyce, K. E., Shields, T. J., & Silcock, G. W. (1999b). Toward the characterization of building occupancies for fire safety engineering: Capability of disabled people to negotiate doors. Fire Technology, 35(1), 68–78. doi:10.1023/A:1015391217275
Boyce, K. E., Shields, T. J., & Silcock, G. W. (1999c). Toward the characterization of building occupancies for fire safety engineering: Presence, type, and mobility of disabled people. Fire Technology, 35(1), 35–50. doi:10.1023/A:1015351322996
Chen, T., Pan, L., Zhang, H., Narayanan, S., & Soldner, N. (2013). Experimental study of evacuation from a 4-story building. Procedia Engineering, 62, 538–547. doi:10.1016/j.proeng.2013.08.098
Chen, T., Song, W., Fan, W. C., Li, S., & Yao, B. (2003). Pedestrian evacuation flow from hallway to stairs. In Proceedings of the CIB-CTBUH conference on tall buildings: strategies for performance in the aftermath of the World Trade Centre, CIB T150, (pp. 79–86). Malaysia.
Christensen, K. M., Collins, S. D., Holt, J. M., & Phillips, C. N. (2006). The relationship between the design of the built environment and the ability of egress of individuals with disabilities. Review of Disability Studies, 2 (3), 24–34.
Church, R. L., & Marston, J. R. (2003). Measuring accessibility for people with a disability. Geographical Analysis, 35(1), 83–96. doi:10.1111/gean.2003.35.issue-1
Daamen, W., & Hoogendoorn, S. (2010). Capacity of doors during evacuation conditions. Procedia Engineering, 3, 53–66. doi:10.1016/j.proeng.2010.07.007
Department of Justice. (2010). ADA standards for accessible design. USA: Author.
Evcl, A. N. (2012). Raising awareness about accessibility. Procedia-Social and Behavioral Sciences, 47, 490–494. doi:10.1016/j.sbspro.2012.06.686
Fathy, R. F. (1995). EXIT 89 - An evacuation model for high-rise buildings - recent enhancements and example applications. Proceedings of International Conference on Fire Research and Engineerin. Orlando, FL: National Institute of Standards and Technology (NIST) and Society of Fire Protection Engineers (SFPE).
Fang, Z.-M., Song, W.-G., Li, Z.-J., Tian, W., Lv, W., Ma, J., & Xiao, X. (2012). Experimental study on evacuation process in a stairwell of a high-rise building. Building and Environment, 47, 316–321. doi:10.1016/j.buildenv.2011.07.009
Goldsmith, S. (1997). Designing for the disabled: The new paradigm. Routledge.
Golmohammadi, D., & Shimshak, D. (2011). Estimation of the evacuation time in an emergency situation in hospitals. Computers & Industrial Engineering, 61(4), 1256–1267. doi:10.1016/j.cie.2011.07.018
Gwynne, S., Galea, E. R., Owen, M., Lawrence, P. J., & Filippidis, L. (1999). A review of the methodologies used in the computer simulation of evacuation from the built environment. Building and Environment, 34 (6), 741–749. doi:10.1016/S0360-1323(98)00057-2
Ho, V., & Lyktotrafits, G. (2012). Agent-based modeling of a multi-room multi-floor building evacuation emergency. Physica A: Statistical Mechanics and Its Applications, 391(8), 2740–2751. doi:10.1016/j.physa.2011.12.034
Hashemi, M. (2018). Dynamic, stream-balancing, turn-minimizing, accessible wayfinding for emergency evacuation of people who use a wheelchair. Fire Technology. doi:10.1007/s10694-018-0735-x
Hashemi, M., & Karimi, H. A. (2016). Indoor spatial model and accessibility index for emergency evacuation of people with disabilities. Journal of Computing in Civil Engineering, 30(4), 04015056. doi:10.1061/(ASCE)CF.1943-5487.0000536
Hashemi, M., & Karimi, H. A. (2017). Collaborative personalized multi-criteria wayfinding for wheelchair users in outdoors. Transactions in GIS, 21(4), 782–795. doi:10.1111/tgis.2017.21.issue-4
Jeon, G.-Y., Kim, J.-Y., Hong, W.-H., & Augenbroe, G. (2011). Evacuation performance of individuals in different visibility conditions. Building and Environment, 46(5), 1094–1103. doi:10.1016/j.buildenv.2010.11.010
Jian, M., Juan, C., Yao-Jian, L., & Lo, S. (2013). Efficiency analysis of elevator aided building evacuation using network model. Procedia Engineering, 52, 259–266. doi:10.1016/j.proeng.2012.12.073
Jiang, C. S., Zheng, S. Z., Yuan, F., Jia, H. J., Zhan, Z. N., & Wang, J. J. (2012). Experimental assessment on the moving capabilities of mobility-impaired disabled. Safety Science, 50(4), 974–985. doi:10.1016/j.ssci.2011.12.013
Jin, T., & Yamada, T. (1989). Experimental study of human behavior in smoke filled corridors. In Proceedings of the Second International Symposium on Fire Safety Science, (pp. 511–520). Tokyo, Japan.
Kady, R. A., & Davis, J. (2009). The effect of occupant characteristics on crowding speed in evacuation. Fire Safety Journal, 44(4), 451–457. doi:10.1016/j.firesaf.2008.09.010
Kim, H., Jun, C., Cho, Y., & Kim, G. (2008). Indoor spatial analysis using space syntax. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 37(B2), 1065–1070.
Kobes, M., Helsloot, I., Vries, B. D., Post, J. G., Oberijé, N., & Groenewegen, K. (2010). Way finding during fire evacuation; an analysis of unannounced fire drills in a hotel at night. Building and Environment, 45(3), 537–548. doi:10.1016/j.buildenv.2009.07.004
Koo, J., Kim, B.-I., & Kim, Y. S. (2014). Estimating the effects of mental disorientation and physical fatigue in a semi-panic evacuation. Expert Systems with Applications, 41(5), 2379–2390. doi:10.1016/j.eswa.2013.09.036
Koo, J., Kim, Y. S., & Kim, B.-I. (2012). Estimating the impact of residents with disabilities on the evacuation of a hospital building: A simulation study. Simulation Modelling Practice and Theory, 24, 71–83. doi:10.1016/j.simpat.2012.02.003
Koo, J., Kim, Y. S., Kim, B.-I., & Christensen, K. M. (2013). A comparative study of evacuation strategies for people with disabilities in high-rise building evacuation. Expert Systems with Applications, 40, 408–417. doi:10.1016/j.eswa.2012.07.017
Kuligowski, E., Peacock, R., Wiess, E., & Hoskins, B. (2013). Stair evacuation of older adults and people with mobility impairments. Fire Safety Journal, 62, 230–237. doi:10.1016/j.firesaf.2013.09.027
Lavender, S. A., Hedman, G. E., Mehta, J. P., Reichelt, P. A., Conrad, K. M., & Park, S. (2014). Evaluating the physical demands on firefighters using hand-carried stair descent devices to evacuate mobility-limited occupants from high-rise buildings. Applied Ergonomics, 45(3), 389–397. doi:10.1016/j.apergo.2013.05.005
Lena, K., Kristin, A., Stoffen, B., Sara, W., & Elena, S. (2012). How do people with disabilities consider fire safety and evacuation possibilities in historical buildings?—A Swedish case study. Fire Technology, 48(1), 27–41. doi:10.1007/s10694-010-0199-0
Liu, B., Liu, Y.-B., & Wu, X.-C. (2013). Software design principles of intelligent evacuation indication system. Procedia Engineering, 52, 214–219. doi:10.1016/j.proeng.2013.02.129

Luo, M., & Wong, K. H. (2006). Evacuation strategy for super highrise building. In Proceedings of 5th Annual Seminar on Tall Building Construction and Maintenance. Hong Kong.

Manley, M., & Kim, Y. S. (2012). Modeling emergency evacuation of individuals with disabilities (exitus): An agent-based public decision support system. Expert Systems with Applications, 39(9), 8300–8311. doi:10.1016/j.eswa.2012.01.169

Min, Y., & Yu, Y. (2013). Calculation of mixed evacuation of stair and elevator using EVACNET4. Procedia Engineering, 62, 478–482. doi:10.1016/j.proeng.2013.08.090

Nguyen, M. H., Ho, T. V., & Zucker, J.-D. (2010). Integration of smoke effect and blind evacuation strategy (SEBES) within fire evacuation simulation. Simulation Modelling Practice and Theory, 18(3), 395–418. doi:10.1016/j.simpat.2010.12.001

Peacock, R. D., Reneke, P. A., Kuligowski, E. D., & Hagwood, C. R. (2017). Movement on stairs during building evacuations. Fire Technology, 53(2), 845–871. doi:10.1007/s10694-016-0603-5

Pelechano, N., & Malkawi, A. (2008). Evacuation simulation models: Challenges in modeling high rise building evacuation with cellular automata approaches. Automation in Construction, 17(4), 377–385. doi:10.1016/j.autcon.2007.06.005

Proulx, G. (1995). Evacuation time and movement in apartment buildings. Fire Safety Journal, 24(3), 229–246. doi:10.1016/0379-7112(95)00023-M

Rehabilitation Research and Training Center on Disabilities Demographics and Statistics. (2005). 2005 disabilities status reports. Ithaca, NY: Cornell University.

Sagun, A., Bouchlaghem, D., & Anumba, C. J. (2011). Computer simulations vs. building guidance to enhance evacuation performance of buildings during emergency events. Simulation Modeling Practice and Theory, 19(3), 1007–1019. doi:10.1016/j.simpat.2010.12.001

Sakkas, N., & Perez, J. (2006). Elaborating metrics for the accessibility of buildings. Computers, Environment and Urban Systems, 30(5), 661–685. doi:10.1016/j.compenvurbsys.2005.06.002

Shi, L., Xie, Q., Cheng, X., Chen, L., Zhou, Y., & Zhang, R. (2009). Developing a database for emergency evacuation model. Building and Environment, 44(8), 1724–1729. doi:10.1016/j.buildenv.2008.11.008

Spence, P. R., Lochtian, K., Burke, J. M., & Seeeger, M. W. (2007). Media use and information needs of the disabled during a natural disaster. Journal of Health Care for the Poor and Underserved, 18(2), 394–404. doi:10.1353/hpu.2007.0047

Thill, J.-C., Doo, T. H., & Zhou, Y. (2011). Traveling in the three-dimensional city: Applications in route planning, accessibility assessment, location analysis and beyond. Journal of Transport Geography, 19(3), 405–421. doi:10.1016/j.jtrangeo.2010.11.007

Thompson, P. A., & Marchant, E. W. (1995). A computer model for the evacuation of large building populations. Fire Safety Journal, 24(2), 131–148. doi:10.1016/0379-7112(95)00019-P

Turhanlar, D., He, Y., & Stone, G. (2013). The use of lifts for emergency evacuation - a reliability study. Procedia Engineering, 62, 680–689. doi:10.1016/j.proeng.2013.08.114

The United Nations Office for Disaster Risk Reduction (UNISDR). (2013). UN global survey explains why so many people living with disabilities die in disasters. Geneva: The United Nations Office for Disaster Risk Reduction.

U.S. Census Bureau. (2011). American community survey 1-year estimates. Suitland: U.S. Census Bureau

Vanclouster, A., Neutens, T., Fack, V., Wiehe, N. V., & Maeyer, P. D. (2012). Measuring the exitability of buildings: A new perspective on indoor accessibility. Applied Geography, 34, 507–518. doi:10.1016/j.apgeog.2012.02.006

Watson, H. J., & Wixom, B. H. (2007). The current state of business intelligence. IEEE Computer, 40(9), 96–99. doi:10.1109/MC.2007.331

Williamson, B. J., & Demirbilek, N. (2010). Use of lifts and refuge floors for fire evacuation in high rise apartment buildings. In Proceedings of The 44th Annual Conference of the Australian and New Zealand Architectural Science Association. Auckland, New Zealand.

Zu-Ming, C., Jin, Z., & De-Pin, L. (2011). Smoke control – Discussion of switching elevator to evacuation elevator in high-rise building. Procedia Engineering, 11, 40–44. doi:10.1016/j.proeng.2011.04.624
