5-22-2012

Agent-based Modeling of Emergency Building Evacuation

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Agent-based Modeling of Emergency Building Evacuation

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B.S., University of Connecticut, 2010

A Thesis
Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science at the University of Connecticut 2012
APPROVAL PAGE

Master of Science Thesis

Agent-based Modeling of Emergency Building Evacuation

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2012
ACKNOWLEDGEMENTS

First and foremost, I would like to express my deepest gratitude to my advisor Dr. George Lykotrafitis, who was abundantly helpful and offered invaluable assistance, support, and guidance. I would also like to thank the members of my advisory committee Dr. Hanchen Huang and Dr. Nejat Olgac for their guidance and suggestion.

I also like to thank all my graduate friends and lab members for providing me invaluable support. Special thanks to Mr. He Li for providing me supervision and mentoring on my research the whole time. Also I owe much thanks to Miss Jamie Maciaszek for all her helpful advice and assistance.

Lastly, I would like to express my love and gratitude to my family, friends, and roommates for all their encouragements and moral support. I want to give my special thanks to my father for initiating my interest and appreciation for engineering. I also like to give my deepest thanks to my caring mother and my two wonderful sisters for all their emotional support, understanding, and endless love.
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ABSTRACT

Panic during emergency building evacuation can cause crowd stampede, resulting in serious injuries and casualties. Agent-based methods have been successfully employed to investigate the collective human behavior during emergency evacuation in cases where the configurational space is extremely simple - usually one rectangular room - but not in evacuations of multi-room or multi-floor buildings. This implies that the effect of the complexity of building architecture on the collective behavior of the agents during evacuation has not been fully investigated. Here, we employ a system of self-moving particles whose motion is governed by the social-force model to investigate the effect of complex building architecture on the uncoordinated crowd motion during urgent evacuation. In particular, we study how the room door size, the size of the main exit, the desired speed and the friction coefficient affect the evacuation time and under what circumstances the evacuation efficiency improves.
Chapter 1. Introduction

Empirical data have shown that the main cause of casualties during an emergency evacuation is usually not the actual disaster, but the angst and the impulsive behavior of the crowd under panic [1, 2]. To minimize casualties, it is important that architects and engineers design buildings optimized for panic evacuation [3]. The behavior of individuals under stress is very difficult to predict since different people react differently to the same situation. This is due to the variation in age, gender, cultural differences, athletic abilities and past experiences [4]. However, during emergency, the behavior of the crowd tends to follow some common characteristics independent of the specific case [5-9]. This has been observed during egress situations where people trample and ram others with the sole goal of ensuring their own safety [1, 2]. This ultimately makes emergency evacuations more dangerous than coordinated evacuations and slows down the evacuation rate [1, 2, 4, 10].

Traditionally, crowd management and building evacuation are assessed and analyzed through observation of pedestrians traveling in a controlled space. The recorded motion of these pedestrians is then examined to produce analytical mathematical models that explain the behavior of the crowd [1, 3, 6, 11-21]. These analytical models provide insights to engineers and architects, aiding them in decision making during the process of building design and devising evacuation procedures. However, analytical models are limited by the complexity of building design. The increased power of modern computers makes it possible to study large crowd behavior during an ingression or egression of grand scale buildings via numerical simulations.
Microscopic crowd simulations treat all individual “agents” as discrete entities with a level of artificial intelligence [5, 22-25]. This agent-based modeling (ABM) employs methods of cellular automata (CA) [23, 26-36] and of molecular dynamics (MD) [4, 25, 37-43]. One of the ABM approach based on MD is the social-force model. It considers each pedestrian as a particle without structure whose motion is governed by the Newton’s equations [4, 25, 40, 42, 44]. Studies have been performed to inspect the individual-level interactions among agents in a complex system to thoroughly explore the mechanisms involved in the collective behavior of a large number of people [1, 2, 4] and animals [45, 46]. Emergency evacuation simulations based on the social-force model have been mostly conducted for only simple rectangular rooms. This work proposes the use of the social-force model to study the evacuation of buildings with complicated floor plans to explore how the complexity of the building design affects the overall evacuation process. The concept of wall elements is introduced to allow for designing complicated floor plans that contain rooms, hallways, staircases, and door exits. The simulations examine the behavior of a crowd under panic exiting a large scale building during an emergency evacuation. The obtained results can provide suggestions to engineers and architects about building design and evacuation procedures, and assist in maximizing safety during building evacuations.
Chapter 2. Problem description

In this work, the effects of floor design and panic level on the evacuation time are explored. To represent panic, a desired speed for each agent is introduced. The desired speed is a measure of how fast the pedestrians wish to move. The more alarmed the individuals are, the higher their desired speeds are. To explore the effect of the floor plan complexity on the evacuation time, four different configurations are used: (i) a single room with only one exit. The room is considered as a 20x20 m square that contains 200 pedestrians. The door-size varies from 0.8 m to 3.0 m (see Figure 1a and b). (ii) Two rectangular rooms with a hallway in between leading to an exit of the building are considered. Each one of the two rooms is 30x12 m. The rooms are joined by a hallway 6 m wide directed towards the main exit. 50 pedestrians are placed in each room. The size of the room doors is the same for both rooms ranging from 0.8 to 3m. The size of the main exit at the end of the hallway is also an independent variable ranging from 0.8 to 3 m (Figure 4a and b). (iii) Six rooms are joined by a long 6 m wide hallway leading to a common room with the main exit. Each room has a rectilinear shape of 15x17 m with a single exit. The door sizes are equal in every room and vary from 0.8 m to 5 m. The size of the main exit also varies from 0.8 m to 5 m while it is independent of the size of the room exits. There are 49 pedestrians in each room summing up to a total of 294 pedestrian in the entire floor (Figure 7a and b). (iv) Three copies of the 6 room floor, which is described in case (iii) represent a three-floor building. The floors are placed next to each other, with the common areas connected by stairs. The stairways connecting the floors are 2 m wide and the main exit is located on the ground floor. There are 49
pedestrians in each of the 18 rooms, summing up to a total number of 882 pedestrians in the entire building (Figure10).
Chapter 3. Simulation model

Agent Based modeling (ABM)

ABM has been used to simulate the interactions between multiple autonomous agents in complex systems [47-50]. Here, we implement ABM based on MD to simulate building evacuation. The principles of the simulation follow closely the social-force model introduced by Helbing, Molnar, Farkas, Vicsek (HMFV) [4, 18, 51].

An agent’s motion is determined by the Newtonian equations:

\[
\frac{d\vec{r}_i}{dt} = \vec{v}_i, \tag{31}
\]

\[
m_i \frac{d\vec{v}_i}{dt} = \sum \vec{F}_i, \tag{3.2}
\]

where \( \vec{r}_i \) denotes the position of the \( i^{th} \) particle at any time. \( \vec{v}_i \) represents the velocity of that particle and \( m_i \) is its mass, which is assumed to be 80 kg for all pedestrians. \( \vec{F}_i \) represents the sum of all the physical and social forces acting on the pedestrian \( i \). The position and velocity are obtained via the leapfrog integrator algorithm:

\[
\vec{v}(t + h / 2) = \vec{v}(t - h / 2) + h \cdot \vec{a}(t)
\]

\[
\vec{r}(t + h) = \vec{r}(t) + h \cdot \vec{v}(t + h / 2)
\]

\[
\vec{v}(t) = \vec{v}(t - h / 2) + (h / 2) \cdot \vec{a}(t)
\]

In this simulation, the pedestrians are represented by spherical agents [4, 5, 25, 40]. Each agent has a diameter \( d_i \) ranging from 0.5 to 0.7 m. The diameters are chosen randomly and they follow a uniform distribution. Two agents are considered to be in contact if the
Figure 1. Study of the evacuation of one room with only one exit. (a) The pedestrians are initially in random positions with zero initial velocities (b) The congestion starts when pedestrians are trying to leave the room. (c) The resulting evacuation time as a function of the main exit size and the desired speed is presented as a 3D plot. (d) A cross section of figure (c) depicts the evacuation time versus the desired speed when the room door size is 0.8m.

distance between them is less than the sum of their body radii. The simulation is conducted in a two dimensional (2D) space. In addition, we introduce wall elements to facilitate the construction of complicated floor plans. The walls are represented as line
agents that apply an increasing force to approaching pedestrians. A wall element $i$ is fully characterized by its thickness $h_i$, middle point position $\vec{c}_i$, orientation unit vector $\hat{e}_i$ which is perpendicular to the direction of the wall element, and length $l_i$. In essence, the vector $\hat{e}_i$ is an additional degree of freedom that is used to represent the orientation of the wall element and to differentiate between its two sides. This is useful when we simulate the interaction between pedestrians and wall elements in complex floor structures where pedestrians can be repelled by both sides of a wall element.

Human behavior under panic is generally accepted as chaotic [1]. To simplify the model, a few assumptions are made for the behavior of the crowd under distress. The motion of the pedestrians in this simulation is affected by two types of forces: social forces and physical forces. If the force employed is the result of a choice made by the pedestrian, then it is defined as a social force [18]. Social force is not directly exerted by the pedestrian’s environment, but it is a measure of the motivation and the decision of the pedestrian to perform certain movements. A social force describes the psychological tendency of a pedestrian to have a personal space, or a pedestrian’s desire to move to a certain location or to avoid certain objects or other pedestrians. Because the social-force model [4, 15, 18, 25] essentially belongs in the broad family of particle dynamics models the coupling constants and proportionality factors have Newtonian units. In contrast to social force, a pedestrian may also be subjected to physical forces. A physical force is described as the interaction between the pedestrian and another physical object.

The various forces employed in this work are the following:
3.1 Motivational Force

Motivational force is self-induced by the pedestrians and it is responsible for the acceleration of the pedestrians towards a desired direction [18]. It is categorized as a social force. Because it has been observed that pedestrians tend to move toward their desired destination, even if the path is blocked, individuals under panic are assigned to walk in a straight path toward the room exit during simulated evacuations [1]. If a pedestrian’s motion is uninterrupted, they would continue to accelerate toward their desired location in a straight line under the action of the motivational force. The individuals under panic also prefer to walk at a speed that is adequate based on the status of the surrounding environment [5]. A calm person would walk at a slower pace, while a person under panic would walk at a higher speed. Therefore, the individuals’ desired speed is set to represent their panic level. Their direction of motion is defined by a unit vector pointing to the exit of the room. The force is defined as:

$$\vec{f}_{i, \text{desired}} = \frac{m_i}{\tau} v_{\text{desired}} \frac{\vec{r}_{\text{door}} - \vec{r}_i}{|\vec{r}_{\text{door}} - \vec{r}_i|},$$ (3.3)

where $m_i = 80 kg$ is the mass of pedestrian $i$, $\tau = 0.5 s$ is the relaxation time corresponding to the viscosity force described in a latter section, $v_{\text{desired}}$ is the desired speed, $\vec{r}_{\text{door}}$ is the position of the door, and $\vec{r}_i$ is the position of the pedestrian.

3.2 Psychological Repulsive Tendency

In normal circumstances, pedestrians keep a distance from other pedestrians to maintain a personal space or from objects to avoid collisions and potential harm. To represent this tendency, we employ a social force which is repulsive when the personal space is invaded...
or for short distances between pedestrians and objects [1, 4, 5, 18, 25, 40]. This force is represented by an exponential function and it follows the direction of a normalized vector pointing away of the invader or perpendicular to the wall in the case of pedestrian-wall interactions [4, 40]. It is expressed as

\[
\vec{f}_{ij}^{\text{repulsive}} = \left\{ A_i \exp \left( r_{ij} - d_{ij} \right) \right\} \hat{n}_{ij}, \tag{3.4}
\]

where \( A_i = 2 \times 10^3 N \) and \( B_i = 0.08 m \). The distance between a pedestrian \( i \) and an invader pedestrian \( j \) is \( d_{ij} = \| \vec{r}_i - \vec{r}_j \| \), where \( \vec{r}_i \) and \( \vec{r}_j \) are the position of the pedestrians \( i \) and \( j \) respectively. The sum of their radii is defined as \( r_{ij} = (d_i + d_j) / 2 \), and the force direction is \( \hat{n}_{ij} = (\vec{r}_i - \vec{r}_j) \times d_{ij} \). In the case of interaction between a pedestrian \( i \) and a wall element \( j \) with center at \( \vec{c}_j \) and orientation \( \hat{e}_j \), \( d_{ij} \) is the distance between the pedestrian and the wall element, \( r_{ij} = (d_i + h_j) / 2 \) is the sum of the radius of the particle and half of the wall thickness, and \( \hat{n}_{ij} = (\hat{r}_i - \vec{c}_j) \times \hat{e}_j \), is the unit vector which is perpendicular to the wall element pointing toward the pedestrian and away of the wall.

### 3.3 Compression

The compressive force represents the physical contact between a pedestrian and another pedestrian or the wall. Two pedestrians are considered to be in contact if the distance between them is less than the sum of their body radii. A pedestrian and a wall element are considered to be in contact when the distance between the center of the agent and the closest point on the wall element is smaller than the sum between the pedestrian radius
and half of the wall thickness. Unlike physiological repulsiveness, compression is much larger in comparison. This is due to the considered rigidity of the human body by the HMFV model [4, 18, 51]. If the compressive force exceeds a certain value, one may use this as a criterion for pedestrian injuries or incapacity [4, 40]. In this work however, we do not consider injuries even when the compression forces are large. The direction of this physical force is along the line between the centers of the agents in the case of agent-agent interactions or perpendicular to the wall in the case of agent-wall interactions.

\[ \vec{f}_{ij}^{\text{compression}} = \left\{ k g (r_{ij} - d_{ij}) \right\} \hat{n}_{ij} \]  

(3.5)

where \( k = 1.2 \times 10^7 \text{kg} \cdot \text{s}^{-2} \), and the function \( g(x) = 0 \) when \( x < 0 \) and \( g(x) = x \) otherwise.

The scalar variables \( r_{ij} \) and \( d_{ij} \), and the unit vector \( \hat{n}_{ij} \) have been defined in the previous section 3.2.

### 3.4 Viscous Damping/Personal Force

Under the application of a constant motivational force, the pedestrians continuously accelerate and eventually reach unrealistic speeds. In addition, the psychological repulsive and compression forces provide elastic interactions between the agents. Under the influence of these forces, the pedestrians tend to collide violently resulting in large accelerations and yield unrealistic motions. Therefore viscous damping is introduced to prevent these effects. The viscous force applied in this case is not a physical force but it is categorized as another social force. It is expressed as

\[ \vec{f}_{i}^{\text{viscous}} = -\frac{m_i}{\tau} \vec{v}_i , \]  

(3.6)
where \( m_i = 80\, \text{kg} \) is the mass of pedestrian \( i \), \( \tau = 0.5\, \text{s} \) is the relaxation time and \( \bar{v}_i \) is the velocity of the pedestrian \( i \). It is induced by the individuals with the motivation to follow their desired direction and speed as it is expressed by the motivational force in section 3.1. The term “viscosity” is adopted because the magnitude of the damping force is proportional to the velocity of the individual.

### 3.5 Sliding Friction

Sliding friction represents the granular frictional sliding between pedestrians or between pedestrians and the walls when they are in contact range [52]. As with compression, friction is applied when the distance between two pedestrians is less than the sum of their body radii or when the distance between a pedestrian and the wall is less than the sum between the pedestrian radius and half of the wall thickness. The magnitude of the frictional force is considered proportional to the tangential relative velocity of the two agents. The simulations show that the frictional force is the main component responsible for jamming at the exits during emergency evacuations. The force takes the direction of the tangent between the individual and the object of contact in the two dimensional plane.

\[
\bar{f}_{ij}^{\text{friction}} = \kappa \frac{\Delta \bar{v}_i}{\bar{r}_{ij}} \cdot \bar{t}_{ij}
\]  

(3.7)

where \( \kappa = 2.4 \times 10^5 \, \text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \), \( \Delta \bar{v}_i = \bar{v}_i - \bar{v}_j \), defining \( \bar{r}_{ij} = \bar{r}_i - \bar{r}_j \), therefore \( \hat{r}_j = \bar{r}_j / |\bar{r}_j| = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \), where \( x_1, x_2 \) are the components of \( \hat{r}_j \). Its tangent unit vector can be written as \( \hat{t}_j = [-x_2 \quad x_1] \). We note that since the friction parameter \( \kappa \) is large, clogging and arching will occur, causing small average speed at the exit [4, 40].
In summary, the total force $\sum \vec{F}_i$ acting on the pedestrian $i$ can be express as the sum of all the physical and social forces by:

$$\sum \vec{F}_i = \vec{f}_{i, \text{desired}} + \vec{f}_{i, \text{viscosity}} + \sum_{j(\neq i)} [\vec{f}_{ij, \text{repulsive}} + \vec{f}_{ij, \text{compressive}} + \vec{f}_{ij, \text{friction}}]$$

(3.8)
Chapter 4. Results and Discussion

In this section we discuss the numerical results of building emergency evacuation in the following cases: (i) one room, (ii) two rooms, (iii) one multi-room floor, and (iv) three multi-room floors.

Figure 2. Evacuation time for one room with respect to the desired speed. Exit size (a) 1.0 m, (b) 1.2 m, (c) 1.6 m, (d) 3.0 m.
4.1 Evacuation of one-room

This simulation is designed to study the impact of the room door size, the desired speed, and the friction coefficient between agents on the evacuation time. Another goal of this section is to validate our numerical approach by comparing our results with results from Helbing et al. [4]. In this work, they conducted a simulation of 200 pedestrians evacuating a square room with a 1.0 m exit at various desired speeds and with a friction coefficient of $\kappa = 2.4 \times 10^5 \, kg \cdot m^{-1} \cdot s^{-1}$. For validation, we construct a similar scenario with various desired speed values from 0.5 m/s to 10 m/s while the door size varies from 0.8 m to 3.0 m (see Figure 1a and b). All the other parameters are the same as in [4, 25]. The 3D plot in Figure 1c shows the variation of the evacuation time for different desired speeds and door sizes. The evacuation time reaches its maximum value when both the size of the door and the desired speed attain their lowest values. As the room door size and the desired speed increase, the evacuation time quickly decreases and reaches an almost constant value.

For small exit sizes, where no more than one pedestrian is allowed through the door each time, the crowd is accumulated at the exit during the evacuation (Figure 1b). Because of increased pressure at the exit, the friction among the pedestrians increases resulting to an impaired mobility of the crowd. As a result, pedestrians would be clogged at the exit causing delay. This means that under these circumstances, the increase in the desired speed slows down the evacuation. For the case of 0.8 m door size, a plot of the evacuation time versus the desired speed is generated (Figure 1d). At low panic level, a large evacuation time is required for the evacuation of the building. As the desired speed increases, the evacuation time decreases drastically. The evacuation time has a minimum
when the desired speed is approximately 2 m/s. If the pedestrians are to reach a higher desired speed, the evacuation flow would decrease resulting in longer evacuation times. This illustrates the concept of “faster is slower” congestion effect as it is explained in [4].

The resulting graph (Figure 1d) in the case for room door size of 0.8 m is very similar to the graph shown in Helbing et al. [4]. For desired speeds greater than 5 m/s, the simulations yield large variation in the results because of large interaction forces (Figure 1d). Averaging of the results over multiple runs produces smaller variations (see Supplementary Material Figure 1). When the exit door size becomes larger, the “faster is slower” effect disappears (see Figure 2) and the minimum vanishes while the evacuation time consistently decreases as the desired speed increases. This is due to the drop in frictional jam at the exit since the larger door results in a lower congestion pressure.

![Figure 3. Evacuation time with respect to the desired speed for one room with low friction. Exit size of 0.8 m for friction coefficient $\kappa = 2.4 \times 10^4 \text{ kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$.
](image-url)

15
To test the impact of sliding friction on the evacuation time, a simulation is conducted for the case where the friction coefficient is $\kappa = 2.4 \times 10^4 \text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$, ten times smaller than the one employed originally while the size of the room door is 0.8. All other parameters are identical with the parameters used in the previous simulations. The results show that the “faster is slower” congestion effect completely disappears. No minimum evacuation time at low desired speed is observed (see Figure 3), while higher desired speeds no longer slow down the evacuation.

4.2 Evacuation of a two-rooms one-floor building

The goal in this case is to study how the evacuation time of a two-room floor is impacted by the exit size, the room door size, and the desired speed (see Figure 4). The sizes of the main exit and of the interior doors vary independently from 0.8 m to 3.0 m (Figure 4a and b) while the desired speed ranges from 0.5 m/s to 10 m/s. A 3D plot (Figure 4c) and its contour lines (Figure 4d) are generated for different values of the main exit size and of room door size at the constant desired speed of 5 m/s. Additional contour plots for constant desired speeds of 1 m/s and 10 m/s are shown in (Figure 5). We divide each of these contour plots into three sections. Region A denotes the area of the plot where the contour lines are relatively perpendicular to the horizontal axis for small main exits. Region B denotes the area where the contour lines are relatively parallel to the horizontal axis for small room door size and for main exit larger than that of region A. Region C is defined as the remaining area on the plot that is not covered by regions A and B. In region A, the size of the room door has negligible effects on the evacuation time which is controlled completely by the exit size. Region A is extended up to the main exit size of approximately 1.7 m for 1 m/s desired speed, 1.5 m for 5 m/s and less than 1.2 m for 10
m/s. In region B the size of the main exit does not affect the evacuation time, which is controlled by the width of the room doors. For region B, the main exit size is greater than

Figure 4. Study of the evacuation of one floor with two rooms. (a) The pedestrians are initially in random positions with zero initial velocities. (b) The congestion starts when pedestrians are trying to leave the room. (c) The resulting evacuation time as a function of the main exit size and room door size for constant 5 m/s desired speed is presented as a 3D plot. (d) The contour lines of figure (c), where the red color signifies higher evacuation time than the blue color.
the maximum exit size of the region A while the room door size is less than 1.0 m for 1 m/s desired speed, less than 0.95 m for 5 m/s and less than 0.9 for 10 m/s.

Figure 4d in conjunction with Figure 5 demonstrates that the size of the main exit is a more important factor than the size of the interior doors when the main exit size is relatively small. The exact value depends on the desired speed. As we see from Figure 4d, where the desired speed is 5 m/s, when the main exit is small (< 1.5 m) all pedestrians are clogged inside the building and changes in room door size do not affect the evacuation time (region A). When the main exit is large (> 1.5 m) and the room door size is less than 1m (region B), the hindrance effect produced by the small room doors decreases the pedestrian flow and as a result the main exit does not cause delay during evacuation. The properties for regions A and B are consistent for all desired speed values. However, the behavior of the evacuation time in region C varies as the desired speed differs. For small desired speeds such as 1 m/s (Figure 5 a), the evacuation time consistently decreases as the size of the main exit or room door size increases. When the desired speed is approximately 5 m/s or greater, then the data behavior change. The evacuation time may actually increase as the size of the room door increases (Figure 4d). This effect is more obvious for large desired speeds (Figure 5b).

As with the one room simulations, the room door is congested when the desired speed is high (>5 m/s). This results in increased pressure and friction causing obstruction of the pedestrians’ mobility. Thus, when the size of the interior doors decreases, the flow of the pedestrians towards the main exit area is hindered. With a smaller crowd rushing to the main exit, the congestion level is greatly reduced, ultimately improving the overall
Evacuation time (Figure 4d). This explains the phenomena of region C for simulations with desired speed 5 m/s or greater. It is concluded that a smaller interior door can play an important role in improving evacuation efficiency.

**Figure 5. Contour lines for the evacuation of one floor with two rooms.** Contour lines of the evacuation time plot against the room door and exit size at constant desired speed (a) 1 m/s (b) 10 m/s. The red lines signify higher evacuation time values and blue lines are of lower. All contour line plots in this work can be divided into three regions of interest. Region A is defined as the area where the contour lines are relatively perpendicular to the horizontal axis for small main exits. Region B includes the area where the contour lines are relatively parallel to the horizontal axis for small room door size and for main exit larger than that of region A. Thus the two regions do not overlap. Region C is defined as the remaining area on the plot that is covered by neither by region A or by region B.

Evacuation time (Figure 4d). This explains the phenomena of region C for simulations with desired speed 5 m/s or greater. It is concluded that a smaller interior door can play an important role in improving evacuation efficiency.
Several plots of evacuation time versus the desired speed are generated to more clearly show the effect of the size of the exit and room doors (Figure 6 and Supplementary Materials Figure 2,3,4). If the main exit size is small and the room door size is large, the behavior of the system is similar to the one room case. However, the “faster is slower” effect is not as prominent as in the one-room simulation because the room doors regulate the flow towards the main exit (Figure 6a and Supplementary Material Figure 2). With an increase in the exit door size, the “faster is slower” congestion effect completely disappears (Figure 6b and Supplementary Materials Figure 3 and 4). When the main exit is large (~3.0m), small room door yields an increase in evacuation time as the contour lines in region B suggest (see Supplementary Materials Figure 4a versus Figure 4b). As the room door size increases the evacuation time is controlled mainly by the main exit size for desired speeds larger than 1 m/s (Supplementary Materials Figure 4c and Figure 4d).
4.3 Evacuation of a multi-room one-floor building

Figure 7. Study of the evacuation of a one-floor building with six rooms. (a) The pedestrians are initially in random positions with zero initial velocities (b) The congestion start when pedestrians are trying to leave the room. (c) The resulting evacuation time as a function of the main exit size and room door size with constant 5 m/s desired speed is presented as a 3D plot. (d) The contour lines of figure (c), where red lines signify higher evacuation time than blue lines.
In this section, we further explore the impact of the building exit size, the room doors size, and the desired speed on the emergency evacuation of a six-room one-floor building (Figure 7a, b). The size of the main exit and the size of the room door vary independently from 0.8 to 5.0 m while the desired speed varies from 0.5 m/s to 10 m/s. The data obtained from the simulation are shown in a 3D plot for 5 m/s desired speed (Figure 7c) while the corresponding contour lines are shown in Figure 7d. For the cases of 1 m/s and 10 m/s desired speed, the contour lines are presented in Figure 8. Region A corresponds to an exit size less than 3.0 m for 1 m/s desired speed, 2.8 m for 5 m/s, and 2.4 for 10 m/s. Region B corresponds to a door size less than 1.2 m for 1 m/s, 0.9 m for 5 m/s, and 0.85 m for 10 m/s (Figure 7d and 8). We note that region A in this simulation is greater in area compared to that obtained in the simulation of the two-room floor. This is mainly due the increase in the agent population which in turn requires a larger door size to relieve the congestion.

For small desired speeds such as 1 m/s (Figure 8a), the contour lines behave similarly to the two room simulation: the evacuation time consistently decreases as the size of the main exit or room door size increases. For large desired speeds, greater than 5 m/s, we notice a drastic shrinkage in region B while the remaining plot behaves as region A (Figure 7d and 8b). Because the agent population in this simulation is much larger than in the case of two-room floor, congestion at the main exit is almost inevitable. The room door size affects the evacuation time only when the main exit is large enough to ease up the massive congestions. Thus we only notice an indication of region B for very large main exit.
Several plots of the evacuation time versus the desired speed are generated to further analyze the results. Similarly with the previous simulations, we note that the main exit is a much more important factor than the room door size. When the exit size is equal to 0.8m (see Figure 9a and Supplementary Materials Figure 5), the “faster is slower” congestion effect becomes very obvious and it correlates well with the case of one room with small exit (Figure 1d). The effect disappears as the size of the exit increases (Figure 9b, and Supplementary Materials 6 and 7). We also observe that the effects of varying room door size are relatively negligible. When the main exit is large (~ 3.0 m), an exceedingly small room door would yields a slight increase in the evacuation time for large desired speeds. (see Supplementary Materials Figure 7a vs. Figure 7b,c,d).

**Figure 8. Contour lines for a one-floor building with six rooms.** Contour lines of the evacuation time plot against the room door and exit size at constant desired speed (a) 1 m/s (b) 10 m/s. The red lines signify higher evacuation time values than the blue lines.
4.4 Evacuation of a multi-room three-floor building

The effect of the size of the exit door, of the size of the room door and of the desired speed on the emergency evacuation of three identical six-room floors connected via staircases is studied in this section (Figure 10a). The sizes of the main exit and of the room doors range between 0.8 m and 5.0 m and the desired speeds between 1 m/s and 10 m/s. For desired speed of 5 m/s, the surface plot and the corresponding contour lines are shown in Figures 10b and c respectively. The entire area of the contour lines graph is of type A, meaning that the evacuation type depends only on the main exit size and not on the room doors width. Our simulations show that this is true for all cases with desired speed higher than 2 m/s (Figures 10c and 11b). This is because the number of pedestrians is large enough to cause congestion at the main exit regardless of the size of the room doors. For desired speed 1 m/s, Figure 11(a) shows that the region A corresponds to
main exit size approximately less than 3.5 m while area B hardly exists. In region C, the evacuation time decreases as either the main exit or the room door size increases.

![Image](image1.jpg)

**Figure 10. Study of the evacuation of a three-floor building with six rooms each.** (a) The pedestrians left the room, entered the hallway and start going through the stairway and initiated congestion at the main exit. (b) The resulting evacuation time as a function of the main exit size and room door size with constant 5 m/s desired speed is presented as a 3D plot. (c) The contour lines of figure (b), where red color signifies higher evacuation time than the blue color.
Several plots of the evacuation time versus the desired speed are generated to analyze the impact of the main exit size and of the room door size (Figure 12 and Supplementary Materials Figures 8, 9 and 10). As with the multi-room one-floor simulations, the size of the main exit is the main factor that controls the behavior of the plots. However, in contrast to the previous simulations, the plots for small main exits show different behaviors than the corresponding plots in the previous section for large desired speeds (Figure 12a and Supplementary Materials Figure 8). The “faster is slower” effect is apparent for exit size of 0.8 m and desired speeds less than approximately 5 m/s. For an exit size of 0.8 m, a minimum is found at the 1 m/s desired speed. As the desired speed increases, the evacuation time increases and reaches a maximum at approximately 5 m/s and it decreases as the desired speed approaches 10 m/s. The initial increase in the

![Figure 11. Contour lines for a three-floor building simulation.](image)

Contour lines of the evacuation time plot against the room door and exit size at constant desired speed (a) 1 m/s (b) 10 m/s. The red lines signify higher evacuation time values than the blue lines.
evacuation time is due to the congestion at the main exit. The decrease afterwards is due to large compression and friction at the exit. We note that this is not a realistic scenario because exceedingly high compression and friction values would result in injuries which are not considered in this work. As the outer exit becomes larger, the shape of the curve slowly changes. When the width of the main exit is 1.2 m, the maximum at 5 m/s becomes relatively smaller but the general behavior remains similar (plot not shown here). As the exit size approaches 1.6 m, the change of the evacuation time is very small as the desired speed increases. For desired speeds larger than 2m/s the evacuation time has an almost constant value (Supplementary Materials Figure 9). As the exit door becomes very large, the evacuation time consistently decreases as the desired speed increases (Figure 12d and Supplementary Materials Figure 10).

Figure 12. Evacuation time of a three-floor building with six rooms per floor with respect to the desired speed. We consider a constant room door size of 0.8 m and exit size of (a) 0.8 m, (b) 3.0 m.
4.5. Conclusion

In this work, we investigate the effect of complicated floor plans on building evacuation by using the social-force model. Introduction of wall elements allows the construction of rooms, hallways, doors, stairs, and exits. We discuss how the exit size, the room door size, and the desired speed affect the evacuation efficiency. The data from the simulations of one room evacuation show that for small exits, large desired speeds result in longer evacuation times because they cause congestion. This result is identical to the result obtained in the work of Helbing et al. [4], where similar parameters are used. We further investigate this case by simulating a large range of different door sizes and found that the congestion effect quickly disappears as the room door becomes larger. Next, we confirm that friction is the main cause of congestion. When a lower friction coefficient value is employed, the congestion effect no longer appears.

For the case of one floor with two rooms and one main exit with hallway defined by the walls of the two rooms, we observe that by decreasing the room door size the evacuation efficiency may improve under certain circumstances. Also, for a small main exit door, the “faster is slower” congestion effect is not as apparent as in the one-room case. The reason for both observations is that the room doors decrease the pedestrian flow from the rooms to the hallway causing a smaller congestion at the main exit. When the exit and the interior doors are large, the evacuation time decreases consistently with an increase in the desired speed. For multi-room one-floor or multi-floor buildings, the size of the main exit is the major parameter that controls the evacuation time. We also observed that the “faster is slower” congestion effect is prominent for small main exits. In summary, the effect of the interior room door size becomes weaker as the building becomes larger,
while the size of the main exit consistently plays a strong role in controlling the evacuation time.
Chapter 5. Evacuation with Obstacles Blocking Exit

To further explore if obstacles close to the exit affect the evacuation time, we constructed floor plans with obstacles placed near the exit. These simulations are performed in a single-room scenario with the obstacles inside the room. The room has a dimension of 20x20m with 0.8m door size while 200 pedestrians are inside. Two types of obstacles were used in the numerical experiment: (1) two cylindrical columns and (2) a triangle made of three walls.

5.1 Columns Obstacles

![Figure 13. Evacuation of one room with a two-column obstacle.](image)

(a) The congestion starts when pedestrians are trying to leave the room. (b) Evacuation time versus desired speed for exit size 0.8m for the case of no obstacles and the cases of various distances from the obstacles to exit: [1.0m, 2.5m, 4.0m, 5.5m, 7.0m, 8.5m].

The obstacles used for this test are two identical cylindrical columns of radii 3m with centers 3.9m mutually apart. The columns are placed at varying distances (from 1.0 to 8.5
m) away from the exit (Figure 13a). The distance is measured form the wall to the perimeter of the column. When the columns are 2.5m or greater distance from the door, the evacuation behavior is similar to the case where there are no obstacles in the room (Figure 13b). When the columns are only 1.0m away from the door however, the plot of the evacuation time versus the desired speed changes behavior. For desired speeds less than 2m/s the evacuation time is larger compared to the evacuation time in the unobstructed case but it is drastically lower for desired speeds greater than 2 m/s. This shows that round-shape obstacles close to the exit break up the congestions when the crowd is in high panics because the obstacles divide up the crowd and reduce the pressure among them.

5.2 Triangular Obstacle

The obstacle used for this test is an isosceles triangle with base 5m facing the exit and two congruent sides of 5.6m (Figure 14a). The numerical experiments were performed with various distances between the triangle base and the exit. The distances were chosen from 1.5 to 4.5 m. When the obstacle is 2.0 m and farther from the exit, the evacuation behavior is similar to the case where there are no obstacles in the room (Figure 14b). When the obstacle is located at 1.5 m from the exit, it was observed that the evacuation time is lower for all desired speed in comparison to the case with no obstacles. It can be concluded that under certain circumstances, having obstacles close to the exit door can decrease the evacuation time and improve the evacuation process.
Figure 14. Evacuation of one room with a triangular obstacle. (a) The congestion starts when pedestrians are trying to leave the room. (b) Evacuation time versus desired speed for exit size 0.8m for the case of no obstacles and the cases of various distances from obstacle to exit: [1.5m, 2.0m, 2.5m, 3.0m, 3.5m, 4.0m, 4.5m].
Chapter 6. Room Evacuation Based on Path-Finding Algorithm

6.1 Path-Finding model

Past studies have shown that humans can estimate the time to collision with surrounding obstacles by means of specialized neural mechanisms at the retina and brain levels [53, 54]. Here, we use a model developed by Moussaid et al. [55] that allows agents to find an optimized path and at the same time to avoid collisions and to minimize the walking distance.

In this model, each pedestrian $i$ is represented by their position $[x_i, y_i]$, velocity $egin{bmatrix} \frac{dx_i}{dt}, \frac{dy_i}{dt} \end{bmatrix}$, body diameters $d_i$, desire speed $v_{desired}$ and their destination defined by the angle $\alpha_0$. We assume that a pedestrian has the ability to scan their surrounding for obstacles within their field of view. All pedestrians’ left-to-right field of view is limited by angles of $[-\varphi, \varphi]$, measured from the direction straight ahead of them (perpendicular to the pedestrian’s shoulders, see Figure 15). The obstacles can be either moving or stationary (Figure 15b). After analyzing all obstacles around them, the pedestrian will estimate the distance to collision for every possible path. For all possible directions $\alpha$, the distance to the first collision $f(\alpha)$ with pedestrian $j$ can be calculated as:

$$f(\alpha) = v_{desired} \cdot \Delta t$$  \hspace{1cm} (6.1)

where $\Delta t$ is the time until collision and it is a function of the possible direction $\alpha$. To calculate $\Delta t$, we consider the following:
The sum of the body radii between two pedestrian is:

\[ r_{ij} = (d_i + d_j) / 2 \]  

(6.2)

If the position and velocity of the two pedestrian are given, the time \( \Delta t \) it takes for them to collide can be estimated by solving the equation below

\[ r_{ij} = \sqrt{[x_i(\Delta t) - x_j(\Delta t)]^2 + [y_i(\Delta t) - y_j(\Delta t)]^2} \]  

(6.3)

where

Figure 15. Path Optimization Diagrams. (a) Bird-eye view illustration of pedestrian \( p_1 \) trying to move toward \( \alpha = \alpha_0 \), while observing 2 subjects: \( p_2 \) (stationary) and \( p_3 \) (moving to \( p_3' \)). (b) Illustration of the same situation from pedestrian \( p_1 \)'s perspective. (c) Graphical representation of \( f(\alpha) \) reflecting the distance to collision in direction \( \alpha \).
For the observing pedestrian $i$, \( \frac{dx_i}{dt} = \sin(\alpha) \) and \( \frac{dy_i}{dt} = \cos(\alpha) \). For the obstacle pedestrian $j$, \( \begin{bmatrix} \frac{dx_j}{dt} & \frac{dy_j}{dt} \end{bmatrix} \) is their instantaneous velocity.

To find $\Delta t$, the quadratic formula is employed

\[
\Delta t = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}
\]

where

\[
a = \left( \frac{dx_i}{dt}(t_0) - \frac{dx_j}{dt}(t_0) \right)^2 + \left( \frac{dy_i}{dt}(t_0) - \frac{dy_j}{dt}(t_0) \right)^2
\]

\[
b = 2(x_j - x_i) \left( \frac{dx_j}{dt}(t_0) - \frac{dx_i}{dt}(t_0) \right) + 2(y_j - y_i) \left( \frac{dy_j}{dt}(t_0) - \frac{dy_i}{dt}(t_0) \right)
\]

\[
c = (x_j - x_i)^2 + (y_j - y_i)^2 - r_0
\]

If $\Delta t$ is a complex or a negative solution, it implies that the two pedestrians will not collide. If no collision is expected to occur in direction $\alpha$, \( f(\alpha) \) is set to a default maximum value $d_{\text{max}}$, which represents the horizon distance of the pedestrian (Figure 15). If collision occurs, two solutions $\Delta t$ can be obtained from the quadratic formula.
The smaller $\Delta t$ represents the earlier contact between the two pedestrians. Because we are only interested in the first contact for a single direction $\alpha$, thus we simplified the quadratic formula to:

$$\Delta t = \frac{-b - \sqrt{b^2 - 4ac}}{2a}$$  \hfill (6.9)

Combining equation (6.1) with equation (6.9), we obtain the collision distance $f(\alpha)$ as a function of $\alpha$. Refer to (Figure 15c) for illustration of $f(\alpha)$.

Empirical evidence suggests that pedestrians seek an unobstructed walking direction but avoid deviating too much from the direct path to their destination [56, 57]. The chosen direction $\alpha_{desired}$ can be obtained by minimizing the distance to destination $d(\alpha)$:

$$d(\alpha) = d_{max}^2 + f(\alpha)^2 - 2d_{max} f(\alpha) \cos(\alpha_0 - \alpha)$$ \hfill (6.10)

The path finding algorithm is used to replace the motivational force (section 3.1) and the psychological repulsive tendency (section 3.2) from the social force model. The compression force (section 3.3), viscous damping (section 3.4) and sliding friction (section 3.5) are still applied as the social force model.

### 6.2 Simulation

We investigate the calculation of $\alpha_{desired}$ by conduct a case where the observing pedestrian $p_1$ is stationary at $[x=0, y=0]$m, while a second pedestrian $p_2$ located at $[x=-0.5, y=3.0]$m travels with instantaneous velocity $\vec{v}_2 = [1.0, -0.5]$m/s (Figure 16). The resulting $f(\alpha)$ and $d(\alpha)$ are plotted in Figure 17. $\alpha_{desired}$ is found as the minimum of
Figure 16. Path optimization with one moving obstacles. Observing pedestrian $p_1$ is stationary trying to move toward their destination $\alpha_0$ while a second pedestrian $p_2$ is traveling with velocity $\vec{v}_2$. The optimized path for $p_1$ to reach their destination along angle $\alpha_0$ while avoiding collision with $p_2$ is towards angle $\alpha_{\text{desired}}$.

Figure 17. Plotting of $f(\alpha)$ and $d(\alpha)$. For case of one observing pedestrian and one moving obstacle.
the function $d(\alpha)$ (Figure 17b). This corresponds to the optimized path for $p_1$ to reach their destination along angle $\alpha_0$ while avoiding collision with $p_2$ (Figure 16).

![Path Finding Simulation with stationary obstacles](image)

**Figure 18. Path Finding Simulation with stationary obstacles.** Pedestrian (red) seeks an unobstructed walking direction that evade all stationary obstacles (blue) while avoid deviating too much from the direct path to their destination. The figures project the instantaneous position of the pedestrian and the three obstacles at $t= (a)$ 0s, (b) 2s and (c) 4s.

The objective of this model is to simulate by employing empirical observations the obstacle-evading trajectory of pedestrian agents traveling among obstacles and other pedestrians. In this section, we calculate the path of one pedestrian traveling through three stationary obstacles (Figure 18 a,b,c) and three moving obstacles (Figure 19 a,b,c) while avoiding collisions. The field of view of the pedestrian is set to be from $[-\pi/3,\pi/3]$ radians and the desired speed is set to 2m/s. The pedestrian and the three
obstacles have diameters $d_i$ ranging randomly from 0.5 to 0.7 m. The resultant paths are shown in Figures 16 and 17.

Figure 19. Path Finding Simulation with moving obstacles. Pedestrian (red) seeks an unobstructed walking direction that evade all moving obstacles (blue) while avoid deviating too much from the direct path to their destination. The figures project the instantaneous position of the pedestrian and the three obstacles at $t =$ (a) 0s, (b) 2s and (c) 4s.
Chapter 7. Particle motion under the influence of diffusing “chemical” cues

The spreading of a toxic substance during building emergency evacuation can cause directly and indirectly heavier causalities than a panic-driven stampede. In this section, we study the response of particles to diffusing “chemical” cues that are secreted by the environment or/and by particles. The developed methodology - modified appropriately - can be applied not only in building evacuation problems but also in migration problems e.g., swarm motion, cell migration. For evacuation scenarios, these diffusing substances can represent spreading of a fire or of a poisonous gas.

Here, we represent the continuum environment as a grid of points (node agents) on which we solve 2D diffusion equations for the “chemical” cues that are secreted from the environment or from the moving particles. The nodes interact with neighboring nodes and with moving agents via the diffusion equation which is defined as

\[
\frac{\partial T}{\partial t} = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right)
\]  

(7.1)

where \( t \) is the instantaneous time and \( k \) is the diffusive constant. To solve the above equation numerically, the fully explicit finite differences method is adopted. In particular, we use the center finite-divided difference to approximate the second spatial derivative of the continuum field

\[
\frac{\partial^2 T}{\partial x^2} = \frac{T_{i+1,j}^l - 2T_{i,j}^l + T_{i-1,j}^l}{\Delta x^2}
\]  

(7.2)
The forward finite-divided difference is used to approximate the first time derivative

\[ \frac{\partial T}{\partial t} = \frac{T_{i,j}^{t+1} - T_{i,j}^t}{\Delta t} \]  

(7.4)

Solving for \( T_{i,j}^{t+1} \) from equation (7.4), we obtain

\[ T_{i,j}^{t+1} = T_{i,j}^t + \Delta t \cdot \frac{\partial T}{\partial t} \]  

(7.5)

Substituting the diffusion equation (7.1) into equation (7.5), we obtain

\[ T_{i,j}^{t+1} = T_{i,j}^t + \Delta t \cdot k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \]  

(7.6)

Substituting (7.2) and (7.3) into (7.6), we obtain

\[ T_{i,j}^{t+1} = T_{i,j}^t + \Delta t \cdot k \left( \frac{T_{i+1,j}^{t+1} - 2T_{i,j}^{t+1} + T_{i-1,j}^{t+1}}{\Delta x^2} + \frac{T_{i,j+1}^{t+1} - 2T_{i,j}^{t+1} + T_{i,j-1}^{t+1}}{\Delta y^2} \right) \]  

(7.7)

The gradient of \( T \) is defined as

\[ \nabla T = \left[ \frac{\partial T}{\partial x}, \frac{\partial T}{\partial y} \right] \]  

(7.8)

The gradient can be approximated using the finite-divided difference:
A particle agent traveling in the continuum field will be able to receive information from surrounding node agents. This information includes the concentration value and the gradient vectors. The particle interpolates the data from the 4 closest surrounding nodes to estimate the concentration and the gradient. If the particle is moving towards areas of high concentration of the “chemical” cues or if it flees areas of high concentration, the path is obtained based on the steepest ascent/descent method. We also note that the particle is programmed to move only if the magnitude of the gradient magnitude is greater than a predefined value. We consider two cases: free particles migrate in the continuum field (1) while the environment has locations with an initial concentration of chemical cues and (2) a “leader” particle travels while constantly secretes chemical cues in the previously defined continuum field.

### 7.1 Environment with initial chemical cues

In this section, we observe the motion of the free particles migrating in an environment with spots of initial concentration of chemical cues that diffuse (Figure 20). The underline pattern in Figure 20 shows the position of the grid nodes. The nodes are spaced out evenly on both the x and y axis. The colors of the nodes signify the concentration value that is stored in the grid point memory. The red nodes signify higher concentration values and blue nodes lower values. The free particles are scattered randomly in the field and are attracted towards points with highest concentrations. A particle only travels if it senses a gradient magnitude greater than \( T_0 \). Here, we observe a collective motion of...
particles swarming towards points of higher concentration. Particles at large distances from the initial concentration points are sensing a concentration gradient magnitude lower than $T_o$, therefore they remain stationary.
7.2 Leadership

In this scenario, we assign a single particle the ability to change the information registered in the grid agents’ memory. The particle represents a moving chemical source which constantly excretes a “substance” that is superposed with the local concentration of the field. This is done by distributing the excretion value from the source particle to the 4

Figure 21. Leadership. Free agent following the trail of the diffusing “substance” secreted by the “leader” particle.
surrounding node via linear interpolation. In addition to the source particle, the field is also filled with free particles. Similarly to section 7.1, the free particles are attracted to the location of the highest concentration. The free agents form a comet-like tail following the source agent (Figure 21).
Supplementary Figures

SF 1. Evacuation time for one-room averaged out from 10 runs. The plot shows the change in the evacuation time of one room with exit size of 0.8 m with respect to the desired speed averaged out for 10 experimental runs.
SF 2. Evacuation time of the two-room floor with constant exit size of 0.8 m. Plots showing the variation of the evacuation time of the two-room floor with respect to the desired speed for constant exit size of 0.8 m, and room door size of (a) 0.8 m, (b) 1.2 m, (c) 1.6 m, (d) 3.0
SF 3. Evacuation time of the two-room floor with constant exit size of 1.6 m. Plots showing the variation of the evacuation time of the two-room floor with respect to the desired speed for constant exit size of 1.6 m, and room door size of (a) 0.8 m, (b) 1.2 m, (c) 1.6 m, (d) 3.0.
SF 4. Evacuation time of the two-room floor with constant exit size of 3.0 m. Plots showing the variation of the evacuation time of the two-room floor with respect to the desired speed for constant exit size of 3.0 m, and room door size of (a) 0.8 m, (b) 1.2 m, (c) 1.6 m, (d) 3.0.
SF 5. Evacuation time of the one-floor with constant exit size of 0.8 m. Plots showing the variation of the evacuation time of the two-room floor with respect to the desired speed for constant exit size of 0.8 m, and room door size of (a) 0.8 m, (b) 1.2 m, (c) 1.6 m, (d) 3.0.
**SF 6. Evacuation time of the one-floor with constant exit size of 1.6 m.** Plots showing the variation of the evacuation time of the two-room floor with respect to the desired speed for constant exit size of 1.6 m, and room door size of (a) 0.8 m, (b) 1.2 m, (c) 1.6 m, (d) 3.0.
SF 7. Evacuation time of the one-floor with constant exit size of 3.0 m. Plots showing the variation of the evacuation time of the two-room floor with respect to the desired speed for constant exit size of 3.0 m, and room door size of (a) 0.8 m, (b) 1.2 m, (c) 1.6 m, (d) 3.0.
SF 8. Evacuation time of the three-floor with constant exit size of 0.8 m. Plots showing the variation of the evacuation time of the two-room floor with respect to the desired speed for constant exit size of 0.8 m, and room door size of (a) 0.8 m, (b) 1.2 m, (c) 1.6 m, (d) 3.0.
SF 9. Evacuation time of the three-floor with constant exit size of 1.6 m. Plots showing the variation of the evacuation time of the two-room floor with respect to the desired speed for constant exit size of 1.6 m, and room door size of (a) 0.8 m, (b) 1.2 m, (c) 1.6 m, (d) 3.0.
SF 10. Evacuation time of the three-floor with constant exit size of 3.0 m. Plots showing the variation of the evacuation time of the two-room floor with respect to the desired speed for constant exit size of 3.0 m, and room door size of (a) 0.8 m, (b) 1.2 m, (c) 1.6 m, (d) 3.0.
References