Evacuation Simulation in Indoor Environment Using Social Force Model

Ali Aryaeinezhad, Zahra Bahramian*

College of Engineering, School of Surveying and Geospatial Engineering, University of Tehran, Tehran, Iran – (aliaryaeinezhad, zbahramian)@ut.ac.ir

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Abstract:
The safe evacuation of pedestrian crowds in indoor environments is a key challenge for architects and safety engineers. This study uses the Social Force Model (SFM), as a microscopic model-based approach, to simulate evacuation in a building, incorporating factors such as building layout, furniture arrangement, student distribution and their physical characteristics. Moreover, the evacuation process is based on assigning pedestrians to the nearest exit, and adding decision-making knowledge during the evacuation process. Pedestrians are modeled with individual physical characteristics (e.g., gender, height, and mass) that affect their movement and preferred speed. The simulation evaluates evacuation performance based on total evacuation time, crowd density, and pedestrian speed, using real-world data from the School of Surveying and Geospatial Engineering, University of Tehran. Results show that including gender diversity reduces evacuation time by 15.98% compared to a basic, homogeneous model. The system also identifies congestion hotspots and helps improve evacuation safety and efficiency.

1. Introduction

Nowadays, with the increase in global population and the limited availability of land resources, full utilization of space becomes a must. As a result, larger cities across the world are moving toward the construction of high-rise and complex structures with large population capacities. Furthermore, the emergence of new types of buildings should be attributed to two factors: First, the era has entered decades of rapid economic development; second, technology in civil engineering and architecture has matured at the same time. The variety of designs and building forms has a direct impact on the evacuation of its inhabitants (Thompson and Marchant, 1995). As such, a key challenge faced by designers is the establishment of an effective system for the fast and safe evacuation of crowds from these buildings.

With the population and diversity of buildings growing, escaping the crowds and ensuring safe evacuation has become more complicated. A major problem in such circumstances is the excessive congestion on the routes used for evacuation. In addition, the building architectural design can significantly affect the efficiency and safety of the evacuation (Soltanzadeh et al., 2018). Under these conditions, people who are not aware of alternative escape routes, not knowing the exact position of the exits, or faced with insufficient directional signs might choose the wrong direction, leading to confusion and disorder in the evacuation. Population-related issues highlight the importance of crowd management in enhancing the safety, efficiency, and sustainability of shared urban public spaces. In such conditions, higher crowd density, a limited number of exit routes, and physical obstacles can negatively affect the timing and efficiency of evacuation. Therefore, it is increasingly important to predict crowd behavior and the use of scientific methods to study pedestrian flow in these spaces. This issue is particularly relevant in educational buildings (e.g., universities and schools), which often present a given structure with classrooms, laboratories and narrow corridors. In some cases, environmental conditions and physical obstacles may prevent the evacuation. In addition, the architectural complexity of these buildings (e.g., long corridors), individual and social factors of occupants can have a great impact on the speed and effectiveness of evacuation.

Hence, the challenges associated with building evacuation and the necessity for well-defined strategies to manage this process are clearly evident. An effective evacuation system requires careful planning, technological tools and public preparedness. That is, the engineering of a good evacuation system requires not only the qualification of escape routes according to national and international standards, but also to consider the use of advanced technologies, such as computer-based simulations, dynamic analysis, and intelligent guided systems as a measure for optimizing evacuation and threat reduction. These strategies may also help reduce potential risks, improve evacuation rate, and enhance safety during emergencies.

The existence of gender and physical differences among individuals gives rise to disparities in evacuation times. Furthermore, individuals may inadvertently select incorrect routes, resulting in disorder due to their unawareness of the precise locations of the exits or the absence of directional signs.

There are generally two types of approaches for the investigation and understanding of crowd evacuation: empirical experiments and modeling (simulation). Empirical approaches commonly utilize data derived from real-world drills, field-based scenarios, and the in-situ observation of human behaviour. Yet, for reasons that are complex, it is difficult if not impossible to have a true evacuation drill that encompasses all of the conditions. It should also be noted that such drills are usually performed within controlled situations and may not reflect the actual reactions of people. The ability of the data collected to be generalized to actual usage conditions may be somewhat compromised by the participants' having knowledge of the drill and spatial or logistical constraints. Because of these constraints, simulation has proved to be a very useful tool to study crowd evacuation. Simulations provide a possibility to study the impact of different parameters, and to analyze various alternative scenarios, without the necessity to conduct rather expensive and time-consuming real experiments (Santos and Aguirre, 2004).

More sophisticated models can simulate human behavior in a more realistic manner. Such models can model the effects of

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* Corresponding author

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age, gender, physical capability, knowledge of the exit routes and even social interaction between occupants during an evacuation. For this reason, advanced simulation is an essential factor to improve building design, evacuation strategies and for safety in public places.

On the other hand, pedestrian movement simulation models can be categorized into three distinct classifications: macroscopic, mesoscopic, and microscopic (Lian et al., 2023). The macroscopic model does not consider interactions between individuals and treats pedestrian flow as a gas or fluid. The mesoscopic model is situated between the macroscopic and microscopic approaches and does not account for interactions between individuals. The term is defined in two distinct ways. Firstly, it is understood as a spatial framework that guides pedestrian movement. Secondly, it is regarded as a lower-accuracy simulation model that is particularly favored by information science researchers.

The microscopic model, which treats pedestrians as rational pedestrians Under these conditions and incorporates interpersonal interactions, is suitable not only for accurately describing the complex collective behavior of pedestrian groups but also for quantitatively representing individual interactions. The Social Force Model and Cellular Automata Model are among the most widely used microscopic models (Blue and Adler, 1999; Helbing and Molnar, 1995).

Research on crowd evacuation has been conducted under a variety of conditions, resulting in the emergence of diverse behavioral characteristics during evacuation. The researchers proposed a Social Force Model grounded in Newton's second law. This model is regarded as microscopic and has the capacity to represent a wide range of scenarios involving realistic pedestrian movement. Consequently, it is frequently selected and adapted to simulate different types of evacuations. However, the majority of enhancements to the Social Force Model have centered on incorporating novel forces customized for specific applications, with comparatively less emphasis on comprehending pedestrians' environmental perception and cooperation among individuals during evacuation.

This paper proposes a SFM-based method to simulate the evacuation of pedestrian crowds in indoor environments. It incorporates the building layout, the locations of obstacles, pedestrians' position and gender (height and mass), and awareness (of the nearest exit) into pedestrian movement simulation.

The contribution of this study lies in its accounting for gender diversity among pedestrians, which results in variations in height and mass. These variations lead to differences in desired walking speeds and body masses. These parameters are direct and influential in the model. Also, it considers pedestrians' awareness.

The following sections are organized as follows: The subsequent section delineates the pertinent theoretical concepts. Section 3 offers a comprehensive review of the related researches. Section 4 delineates the proposed methodology. The subsequent section, Section 5, presents the implementation results of the proposed method. Finally, the concluding section summarizes the findings and offers final remarks.

2. Theoretical Background: Social Force Model

The Social Force Model (Helbing et al., 2000) is a force-based model that defines pedestrian movement as a result of the combination of various social forces acting upon an individual. The model delineates the forces influencing an individual, encompassing the driving force, repulsive force and obstacle force, as described following.

2.1 Driving Force

The driving force ($\overrightarrow{F_i^{drv}}$) defines the force that propels pedestrians towards their intended destinations, independent of other people and obstacles:

$$\overrightarrow{F_i^{drv}} = \frac{v_i^0 \overrightarrow{e_i^0} - \overrightarrow{v_i}}{\tau} \tag{1}$$

where v_i^0 = desired speed
$\overrightarrow{e_i^0}$ = desired direction
$\overrightarrow{v_i}$ = current velocity
τ = reaction time

2.2 Repulsive Force

Pedestrians exert an exponentially increasing repulsive force on each other as their proximity decreases. Upon collision, not only do the pushing forces intensify further, but a frictional force also arises. This frictional force acts perpendicularly to the repulsive force, aligning with the direction of the difference in speed. The repulsive force of the pedestrian acts from the originating pedestrian towards the pedestrian on which the forces act. When their distance greater than their combined radius no other forces apply. If the distance between two pedestrians is smaller than their combined radius, the pedestrians collide and a frictional force also occurs. The repulsive force between two pedestrians i and j ($\overrightarrow{f_{ij}}$) is defined as follows:

$$\overrightarrow{f_{ij}} = \underbrace{\left[A_i \exp\left[(r_{ij} - d_{ij})/B_i\right] + kg(r_{ij} - d_{ij})\right]\overrightarrow{n_{ij}}}_{pushing} + \underbrace{\kappa g(r_{ij} - d_{ij})\Delta v_{ji}^t \overrightarrow{t_{ij}}}_{sliding} \tag{2}$$

where $r_{ij} = r_i + r_j$ = combined radius of i and j
d_{ij} = distance between i and j
A_i, B_i, k and κ = constants
g = distance between pedestrians when they are in contact, and is zero when there is no contact
$\overrightarrow{n_{ij}} = (n_{ij}^1, n_{ij}^2) = (\overrightarrow{\mathrm{pos}_i} - \overrightarrow{\mathrm{pos}_j})/d_{ij}$ = normalized vector from position of pedestrian j (pos j) to position of pedestrian i (pos i)
$\overrightarrow{t_{ij}} = (-n_{ij}^2, n_{ij}^1)$ = tangent of $\overrightarrow{n_{ij}}$ which is perpendicular to it, rotated counterclockwise
$\Delta v_{ji}^t = (\overrightarrow{v_j} - \overrightarrow{v_i}) \cdot \overrightarrow{t_{ij}}$ = tangential velocity difference of i and j

The repulsive force of pedestrians i is the sum of repulsive force of pedestrian i and other pedestrians:

$$\overrightarrow{F_i^{rep}} = \sum_j \overrightarrow{f_{ij}} \tag{3}$$

2.3 Obstacle Force

Obstacles exert a force on the pedestrian similar to a static pedestrian. The repulsive force increases exponentially with decreasing distance. When the pedestrian collides with the segment the repulsive forces are increased additionally. When colliding, a frictional force also occurs, which acts orthogonally to the repulsive force in the direction to the velocity of the pedestrian. The repulsive force originating from a segment of an obstacle acts from the point on the wall segment that is closest to the pedestrian. When the minimum distance between a pedestrian and a wall segment falls below the pedestrian's radius, an additional frictional force comes into effect. This frictional force acts orthogonally to the repulsive force in the direction of the velocity of the pedestrian. The obstacle force between pedestrians i and obstacle o is defined as follows:

$$\overrightarrow{f_{\iota o}} = \underbrace{[A_i \exp[(r_i - d_{io})/B_i] + kg(r_i - d_{io})]\overrightarrow{n_{\iota o}}}_{pushing} + \underbrace{\kappa g(r_i - d_{io})(\overrightarrow{v_i} \cdot \overrightarrow{t_{\iota o}})\overrightarrow{t_{\iota o}}}_{sliding} \quad (4)$$

where o = a segment of the obstacle
r_i = radius pedestrian i
d_{io} = distance from closest point on the segment o to i
$\overrightarrow{n_{\iota o}} = (n^1_{io}, n^2_{io}) = (\overrightarrow{\text{pos}_\iota} - \overrightarrow{\text{pos}_o})/d_{io}$ = direction from the closest point on the segment ($\overrightarrow{\text{pos}_o}$) to i
$\overrightarrow{t_{\iota o}} = (-n^2_{io}, n^1_{io})$ = tangent of $\overrightarrow{n_{\iota o}}$ which is perpendicular to it, rotated counterclockwise
v_i = velocity of i
A_i, B_i, k and κ = constants
g = distance between a pedestrian and an obstacle segment when they are in contact, and is zero

The obstacle force of pedestrians i ($\overrightarrow{F_\iota^{obst}}$) is the sum of repulsive force of pedestrian i and obstacles:

$$\overrightarrow{F_\iota^{obst}} = \sum \overrightarrow{f_{\iota o}} \quad (5)$$

2.4 Calculating new velocity and new position from forces

With the definition of the forces affecting an individual, it is possible to calculate its new speed ($\overrightarrow{v_{new}}$) and new position ($\overrightarrow{\text{pos}_{new}}$):

$$\overrightarrow{v_{new}} = \overrightarrow{v_\iota} + \left[\overrightarrow{F_\iota^{drv}} + \frac{\overrightarrow{F_\iota^{rep}} + \overrightarrow{F_\iota^{obst}}}{m_i}\right] \cdot \delta T \quad (6)$$

$$\overrightarrow{\text{pos}_{new}} = \overrightarrow{\text{pos}_\iota} + \overrightarrow{v_{new}} \cdot \delta T. \quad (7)$$

where m_i = denotes the mass of i
δT = denotes the length of one simulation iteration

3. Literature Review

(Zhou et al., 2020) employed simulation tools to develop a model of classroom evacuation. The results of the study indicated that the width of exits, the number of exits, and the classroom layout significantly influence evacuation efficiency. As the population increases, the efficacy of evacuation procedures was diminished. The implementation of double exits, an augmented number of evacuation paths, and the optimization of desk and chair arrangements had been demonstrated to enhance evacuation performance.

(Lian et al., 2023) developed a pedestrian simulation to investigate emergency evacuation behavior in educational buildings. A total of 27 design scenarios were created and simulated, focusing on optimized circulation space by varying corridor width, corridor shape, and stair width. The sensitivity of circulation space design parameters to evacuation time was found to be 31.85%, and the impact of corridor width on evacuation time was 49.06 times greater than that of stair width.

(Delcea and Cotfas, 2019) examined the issue of enhancing awareness in classroom emergency evacuation scenarios through the utilization of agent-based modeling. A two-phase experimental study was conducted on classroom evacuation. In the initial phase of the study, students were furnished with maps of their classroom, delineating various evacuation scenarios. They were then instructed to delineate their intended evacuation routes. In the subsequent phase, the students were presented with various simulations utilizing the model. The knowledge gained from this study led to increased student awareness and resulted in a 22.99% reduction in evacuation time.

(Huang et al., 2023) utilized agent-based modeling and Building Information Modeling (BIM) to simulate the evacuation of a student dormitory. Agent-based modeling represented individual behavior, while BIM represented the physical environment. These models were based on evacuation delay times. Three scenarios were considered for notification time, reaction time, and preparation time: 0–30, 31–60, and 61–90 seconds. The term "evacuation delay times" was used to collectively refer to these metrics. Each scenario was simulated thrice, and the mean safe evacuation time was calculated. The results indicated that the delay time should be restricted to 90 seconds to ensure a safe evacuation.

(Zang et al., 2021) created two simulation models of an educational 19-story building-one with obstructions (desks) in the classrooms and one without. The simulation results also indicated that the obstacles increased the evacuation speed by 23.6% compared to those without obstacles, which reflected the effect of obstacles on the density and flow of walkway crowd. The study suggested that physical obstacles divided the crowd, limited the routes for movement, and stopped panicky stampeding towards exits. High-density areas moved from the exits to the spaces between desks. Evacuees were prone to overuse of some exits rather than others, and the use of exits can be balanced when the exits were assigned and the evacuation time was minimized.

(Adrian et al., 2018) conducted an empirical investigation into the impact of entrance corridor width on crowd behavior and density in entry scenarios. The experimental design involved a sample size of 20 to 75 participants, with corridor widths varying from 1.2 to 5.6 meters. The participants exhibited two distinct levels of motivation: high and low. The results of the study indicated a transition from queuing behavior to crowd pressure occurring at corridor widths between 1.2 and 2.3 meters. The density and area of high-density zones exhibited an increase in proportion with greater corridor width and higher participant motivation. Furthermore, the number of participants had a substantial impact on the occurrence of crowd pressure and the level of density.

(Wang et al., 2020) examined the impact of human interaction with obstacles during classroom evacuations, focusing on two types of behaviors: climbing over obstacles and pushing obstacles. The results showed that climbing over obstacles could reduce evacuation time, whereas pushing obstacles had a negative effect, potentially leading to blocked pathways. The study also examined differences between traditional classrooms and active learning environments, recommending that, to enhance evacuation efficiency, aisles in traditional classrooms should be located along the walls, while in active learning classrooms, sufficient open space should be allocated near the exits.

(Vanumu et al., 2020) conducted a series of 17 experiments involving high school students, undergraduate students, and graduate students to examine emergency evacuation behavior in classrooms with different age groups. The study evaluated the impact of variables such as door width and group size on evacuation time. The findings indicated that the relationship between evacuation time and door width follows a power-law function, suggesting a substantial decrease in evacuation time up to a specific door width. Beyond this threshold, further increases in width yield only a negligible additional benefit.

A review of the extant literature indicates that the majority of previous studies have primarily focused on general evacuation models without giving sufficient attention to individual-specific characteristics. While recent research has attempted to align simulations with reality, the majority of existing models continue to exhibit deficiencies in incorporating the diversity of individuals' physical attributes and lack of consideration of awareness during evacuation scenarios. The objective of this study is to address these gaps by integrating realistic physical characteristics, thereby enhancing the accuracy and applicability of evacuation simulations.

4. Methodology

The objective of this study is to utilize the Social Force Model to develop a simulation of the evacuation of pedestrian occupants from an educational building. To achieve this objective, a comprehensive set of factors must be considered. These include not only the architectural layout of the building, the arrangement of desks and chairs in classrooms, the spatial distribution of students, and the physical characteristics of individuals such as gender, and consequently, their height and mass, but also other relevant factors. Furthermore, the level of awareness among individuals is taken into consideration, and the evacuation of each classroom or site is carried out through the nearest available exit. The subsequent steps of the proposed methodology are illustrated in Figure 1 and described in detail below.

4.1 Database Preparation

In this study, building data, individual data, and classroom data are utilized, each of which is described in detail below.

4.1.1 Building Data

One of the fundamental components in configuring pedestrian dynamics simulations is the definition of walkable area, the area or boundary within which pedestrians are allowed to move. Consequently, all points within this designated area are accessible to pedestrians, while points outside of it are excluded from the simulation environment. It is important that no pedestrian transgress the boundaries of this walkable area. The concept of a walkable area is delineated by a simple polygon, defined as a shape that does not intersect itself, and is characterized by a non-zero area. The building data also includes information on obstacles and exits.

Obstacles such as columns, gates, desks, and chairs are presented in the designated walkable area. These obstacles are circumvented by pedestrians, who refrain from entering these inaccessible regions. Such regions are incorporated into the main polygon as holes. When introducing obstacles, it is important to exercise caution to prevent the walkable area from becoming divided into two or more disconnected sections.

An exit models the designated evacuation points within the simulation. The Exit area defines the area in which pedestrians are removed from the simulation upon entry. This removal process occurs at the beginning of the next simulation step. In other words, pedestrians move toward the center of the exit polygon, and upon reaching the defined exit area, they are eliminated from the simulation.

4.1.2 Individual Data

To enable a more realistic simulation, individuals are categorized based on their gender. According to each individual's gender, their height is first determined, followed by the estimation of their body mass, both of which influence pedestrian speed. Gender is utilized in subsequent stages, while the parameters of mass and speed are directly incorporated into the model.

4.1.3 Classroom Data

Classroom data includes the spatio-temporal schedule of classes and the number of pedestrians present in each class, all of which are stored in the database.

4.2 Triangulation and Graph Construction

In this step, the walkable area is triangulated. In the simulation, each pedestrian is assigned a specific target destination toward which they must move. The subsequent critical step is to determine the optimal path to reach these targets. This process entails the calculating the most efficient or desirable routes from the pedestrian’s current position to the designated destination within the simulation environment. The determination of the path is achieved through the implementation of a geometric triangulation method, which involves computing the distance between two points through triangulation. In this process, the distance between the centers of two adjacent triangles is calculated, and if multiple paths lead to the destination, the shortest path is selected. In complex scenarios, it may be necessary to use multiple sub-journeys to model pedestrian movement. At certain locations, pedestrians may need to switch between these sub-journeys depending on the conditions. This transition occurs at switching points, which can be extracted from the building data, for example from classroom to corridor.

In this context, the switch points are regarded as the vertices of the graph, with the edges of the graph representing the paths taken by each pedestrian. These paths are obtained by performing triangulations.

4.3 Journeys Construction

In the context of pedestrian dynamics simulation, the term "routing" refers to the process of determining how individuals move within a physical environment, such as a street, building, or public space. The process is composed of two fundamental components: path planning and pathfinding. The process of path planning entails the modeling of the decision-making process of pedestrians in determining their routes within the simulation. The destinations of the pedestrians are defined based on the selected path. This process may involve conditional decision-making, whereby the routes of different pedestrians along the same corridor or area may vary.

To model complex scenarios in which pedestrians must pass

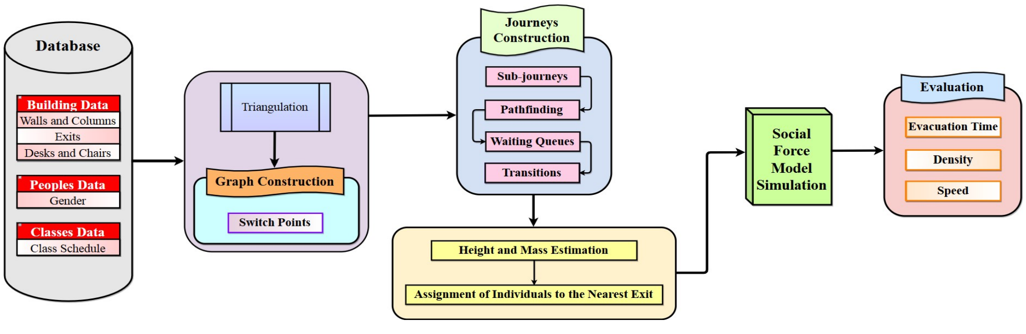

Figure 1. The proposed method

through multiple specified targets, paths can be defined accordingly. These paths are modeled as a network referred to as Journeys, which consist of target points represented as nodes known as Stages and directed connections between these targets that indicate the next destination, referred to as Transitions.

A "Stage" refers to an intermediate target that a pedestrian must reach. When a pedestrian arrives at a given stage, they may wait until that stage is considered complete before proceeding to the next one. A stage may be deemed complete either upon the pedestrian's arrival is satisfied. It is important to note that all stages added to the simulation must lie within the walkable area. This requirement must be upheld whenever modifications are made to the geometry of the environment.

4.3.1 Sub-journeys

Now that the nodes have been added to the network, they must be integrated into a sub-journey. A pedestrian continues along the paths of a sub-journey after completing its current stage. However, before transitions can be added, the sub-journeys must first be defined.

4.3.2 Pathfinding

As previously mentioned, in the context of pedestrian dynamics simulation, the term "routing" refers to the process of determining how individuals move within a physical environment. The process is composed of two fundamental components: path planning and pathfinding. Pathfinding is defined as the process through which pedestrians determine the most effective course of action to achieve their objective. This process generally incorporates various factors, including the pedestrian's objective (i.e., the intended destination), the environmental layout, available routes, and the pedestrian's knowledge of the surrounding environment.

Based on the positions of the pedestrians and their Euclidean distances to the available exits, each individual is assigned to the nearest exit accordingly to carry out the simulation.

4.3.3 Waiting Queues

In the simulation, pedestrian movement can be guided not only through path points but also by incorporating waiting queues. The simulation supports the creation of queues in which pedestrians wait at predefined positions (switch points). These positions are arranged in a specified order, and pedestrians occupy the first available position. As pedestrians leave the queue, others move forward to fill the front positions. In order to exit pedestrians from the queue, a signal must be sent indicating that a specified number of individuals are permitted to proceed. If the number of pedestrians arriving at the queue exceeds the capacity of the designated waiting positions, the additional pedestrians remain in the last defined position of the queue.

4.3.4 Transitions

The Journey is composed of multiple stages that are not yet connected. The establishment of a comprehensive pathfinding structure necessitates the delineation of the connections between these stages, which are designated as Transitions. Transitions are determined by the sequence of stages a pedestrian must complete to progress to the subsequent stage. It is essential to ensure that Exits are placed only at the end of the path; otherwise, pedestrians are removed from the simulation upon reaching the exit and are not proceed to the next stage.

4.4 Pedestrians' Height and Mass Estimation Based on Their Gender

Given that height and mass typically follow a normal distribution, the lower and upper bounds of the height and mass range, encompassing approximately 95.4% of the population, are calculated by subtracting from and adding to the mean twice the standard deviation, as illustrated in the Figure 2. These values, in conjunction with the spatial distribution of individuals, are randomly assigned to the pedestrians.

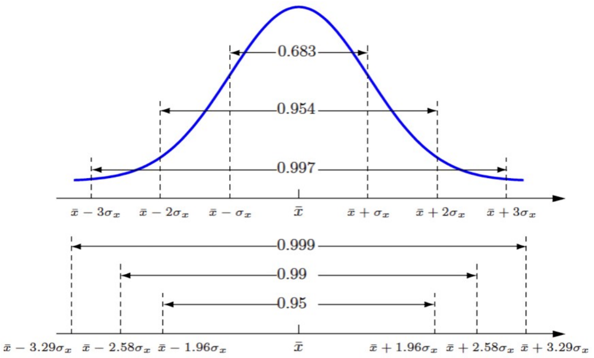

Figure 2. Important probabilities of the normal distribution of pedestrians' height or mass (x)

The desired walking speed is then configured for each pedestrian; specifically, the baseline desired speed is set higher for males than for females. However, in the final step, all speeds are constrained within the defined range.

4.5 Assignment of Individuals to the Nearest Exit

Based on the positions of the pedestrians and their Euclidean distances to the available exits, each individual is assigned to the nearest exit according to carry out the simulation.

4.6 Pedestrian Dynamics Simulation Using the Social Force Model

The proposed method uses the Social Force Model to simulate evacuation in buildings. It is a force-based microscopic approach that describes pedestrian movement by combining various social forces. It is well-suited for capturing individual-level interactions and reproducing pedestrian flow phenomena. It provides a more rational analysis of pedestrian behavior and aligns with the characteristics of pedestrian movement. Furthermore, it represents a comprehensive range of scenarios based on realistic movement dynamics that are selected and adapted.

The paper models pedestrians as particles influenced by forces representing other individuals and environmental factors, including driving, repulsive, and obstacle forces (see Section 2).

4.7 Evaluation of the Proposed Method

In order to evaluate the proposed method, pedestrian movement data is represented as trajectory data. In this study, we work with trajectory data that can be imported through a dedicated import function for specific data files or created from a Data Frame with the following columns:

- "id": a unique numerical identifier for each individual
- "frame": the video frame index from which the positions are extracted

- "x", "y": the individual's position coordinates (in meters)

Before beginning the analysis, it is essential to ensure that all movement trajectories lie within the predefined movement area. Failure to do so may result in errors.

In addition, some regions are specified to be analyzed in greater detail. These regions can be defined as a particular zone or the entire accessible area. Such regions are referred to as Measurement Areas. For example, a measurement area is defined near each exit.

Three indicators are computed from trajectory data to evaluate the proposed method: evacuation time, density, and speed.

4.7.1 Evacuation Time

Evacuation time is typically defined as the total duration required to remove all individuals or pedestrians present within a specified space. In standard models, evacuation time is calculated from the initiation of the evacuation process (e.g., when individuals commence movement) until the final individual exits the designated area (e.g., a building, room, or hazard zone). In essence, evacuation time functions as a metric for evaluating the duration required for a real or simulated population to depart from a designated area. The most critical measure in this process is the total evacuation time.

4.7.2 Density

Density is a fundamental metric in pedestrian dynamics, as it indicates the amount of space available per pedestrian within a specific area. High density can lead to reduced walking speeds, increased congestion, and even safety hazards. The classical method for calculating density $\rho_{classic}(t)$ at a given time (t) involves counting the number of pedestrians ($N(t)$) within a defined space near each exit (M) and dividing that count by the area of the space ($A(M)$).

$$\rho_{classic}(t) = \frac{N(t)}{A(M)} \tag{8}$$

4.7.3 Speed

Another salient metric in pedestrian dynamics, which is conducive to secondary analyses, is walking speed, which is calculated for each pedestrian individually. Low speeds may indicate high density or the presence of obstacles within the crowd.

After calculating the individual speed, the average speed is computed within the measurement area (M) located directly in front of the exit. It should be noted that the average speed can only be calculated if the $v_i(t)$ speed has been determined for each pedestrian within the measurement area. The average speed is defined as follows:

$$v_{mean}(t) = \frac{1}{N} \sum_{i \in P_M} v_i(t) \tag{9}$$

where P_M = set of all pedestrians within the measurement area
N = number of pedestrians inside the measurement area ($|P_M|$).

5. Implementation and Results

The proposed method is implemented in the School of Surveying and Geospatial Engineering, College of Engineering, University of Tehran (Figure 3). This educational building comprises five classrooms, two computer laboratories (sites), and two exits.

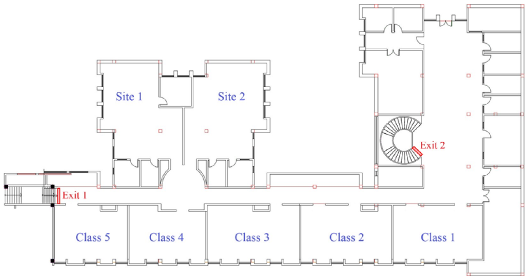

Figure 3. Case Study

This implementation is carried out using Visual Studio Code with the Python programming language. The default parameter values of the Social Force Model (Helbing et al., 2000) are presented in the Table 1.

Param.	A_i	B_i	k	κ	r_i	τ	v_i^0	m
Value	2000	0.08	120000	240000	0.3	0.5	1.0	80
Unit	N	m	$\frac{\mathrm{kg}}{\mathrm{s}^2}$	$\frac{\mathrm{kg}}{\mathrm{m} \cdot \mathrm{s}}$	m	s	$\frac{\mathrm{m}}{\mathrm{s}}$	kg

Table 1. Default values of SFM's parameters (Helbing et al., 2000)

In this study, the factor of gender is incorporated such that, according to the individual and class data, approximately 67% of the population consists of males and the remainder is female. According to official statistics (Mohamadzadeh et al., 2024), the mean height of Iranian individuals aged 20-29 is 177.6±6 cm for males and 162.4±6.3 cm for females. The mean body mass of males 80.5±13.8 kg and females 63.7±10.8 kg is found to be statistically indistinguishable. Accordingly, the height ranges for the mentioned individuals are (165.7–189.6) cm for males and (149.8–175) cm for females, and the mass ranges are (52.9–108.1) kg for males and (42.1–85.3) kg for females, encompassing approximately 95.4% of the population. Finally, the desired walking speed for all pedestrians is randomly assigned within the range of 0.8 to 1 meter per second (Helbing et al., 2000).

The proposed generalized model is also capable of decision-making for exit selection, where the criterion is defined as the shortest Euclidean distance from each class or site to an exit. Consequently, individuals from Classes 1 and 2 (positioned on the right) are instructed to exit through Exit 2. Meanwhile, individuals from Classes 4 and 5 (also positioned on the right) and both sites are instructed to exit through Exit 1. According to the geographical distribution of the population, individuals from Class 3 are divided into two groups: the first group is allocated to Exit 1, and the second group is allocated to Exit 2. The population distribution is as follows: 50% of the population is allocated to Exit 1, and the remaining 50% is allocated to Exit 2. Figure 4 shows two snapshots of the simulation of the proposed method at 0.72 and 24.88 seconds.

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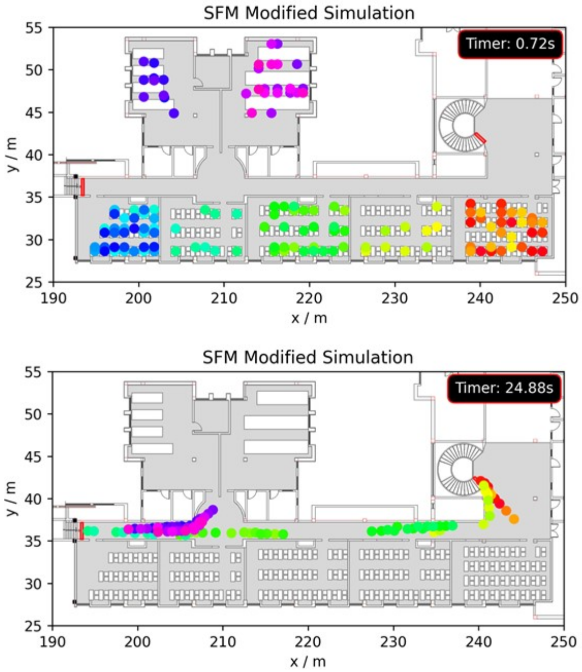

Figure 4. Snapshot of the simulation of the proposed method

The evacuation time is 54.24 second. In this scenario, individuals evacuate according to their proximity to the nearest exit.

The cumulative evacuation curve is fitted with a logistic function that is a mathematical function with widespread applications in the field of social modeling:

$$f(t) = \frac{L}{1 + e^{-k(t-t0)}} \tag{10}$$

where the parameter L is defined as the maximum cumulative value, representing the total number of individuals. The parameter k denotes the growth rate, or the slope of the curve. The parameter t_0 is defined as the time at which half of the cumulative value is reached, also known as the time when half of the individuals have evacuated. Figure 5 shows the cumulative evacuation curve that is fitted with a logistic function.

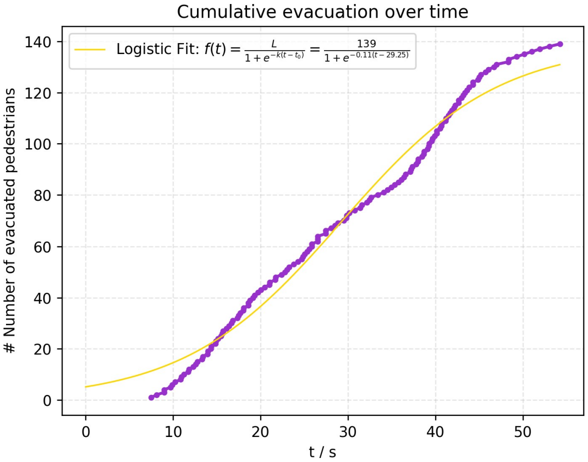

Figure 5. Cumulative evacuation time of the proposed method

Near each exit, a measurement area is defined to calculate the pedestrian density. The figure below illustrates the density of individuals in this area, broken down by each frame. It can be observed that the maximum density at both exits is equal, with a value of 5.5, indicating a perfectly balanced and evenly distributed density.

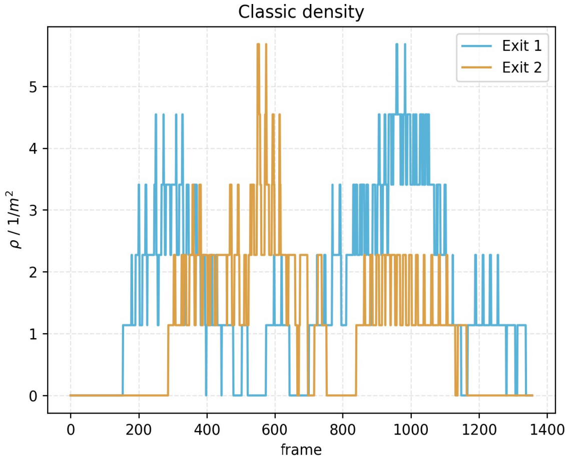

Figure 6. Classic density of the proposed method

Figure 7 shows the average speed of individuals exiting through Exit 1 and Exit 2.

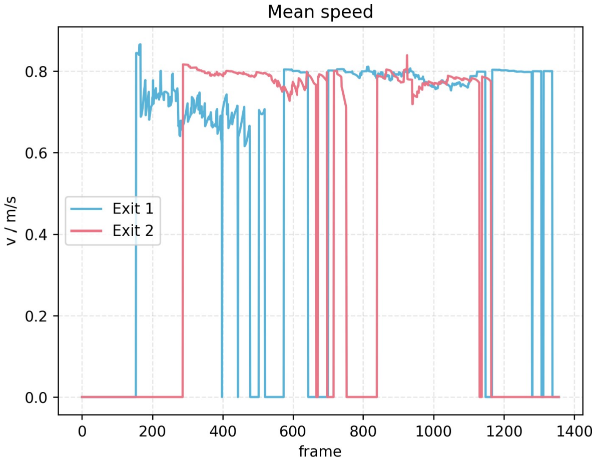

Figure 7. Mean speed of the proposed method

The results of the proposed method are compared with the results of standard SFM. In standard SFM scenario, it is assumed that obstacles such as walls, columns, desks, and chairs exist within the designated study area. However, the gender of the individuals is not taken into account, and all pedestrians are assigned identical speed and mass values. Also, it is not capable of decision-making for exit selection to nearest exit from each class or site. Figure 8 shows two snapshots of the simulation of the proposed method at 0.60 and 24.60 seconds.

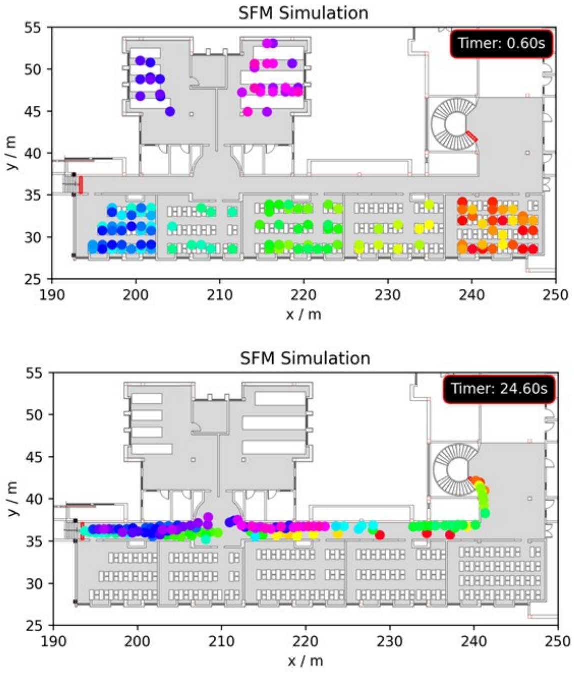

Figure 8. Snapshot of standard SFM simulation

In this particular scenario, the evacuation time is measured at 64.56 seconds. It has been observed that some individuals opt to exit through the farther exit, despite being closer to another exit, which consequently results in a longer evacuation time. This also leads to increased pedestrian interference in the corridor.

The maximum density recorded at Exit 1 is 5.5 persons, while Exit 2 recorded a maximum density of 4.5 persons (Figure 9). This observation suggests a relatively balanced distribution of density between the two exits.

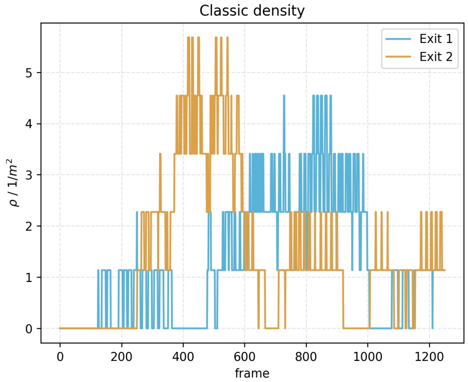

Figure 9. Classic density of standard SFM

Figure 10 shows the average speed of pedestrians in standard SFM scenario.

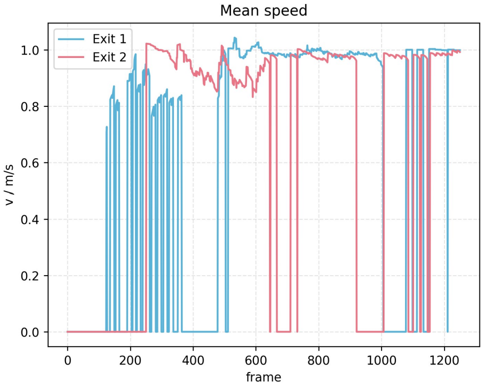

Figure 10. Mean speed of standard SFM

6. Conclusion

The present study focuses on simulating the evacuation of pedestrian crowds in an educational building using the Social Force Model, in which individuals' gender and individual awareness are also taken into account. Consequently, the height, mass, and walking speed of individuals are determined based on their gender, resulting in variations among different pedestrians. The incorporation of gender-related variables, such as height, mass, and speed, into the simulation renders it more realistic by acknowledging the variability in physical characteristics among individuals. Additionally, the model incorporates nearest exit selection as individual awareness and their decision-making during the evacuation process.

The proposed method is evaluated using data from the School of Surveying and Geospatial Engineering at the University of Tehran. The resulting evacuation time is 54.24 seconds, which indicates a 15.98% improvement compared to the standard SFM where gender and individual awareness are not considered resulting in evacuation time of 64.56 seconds.

On the other hand, in terms of density, the proposed method successfully achieves a balanced distribution between the two exits. Therefore, when designing or constructing a building or for the purpose of managing and controlling crowd evacuation, it is essential to pay close attention to exits and the characteristics they must possess (such as sufficient space and accessibility). By utilizing density and speed, congestion hotspots can be identified, allowing class schedules to be organized in a way that enables individuals in each classroom to evacuate the building more easily and with less crowding.

Further studies could investigate the architectural design recommendations to improve the evacuation flow rate. The effects of narrow and long corridors can be evaluated on evacuation. It may also be interesting to analyze the layout of the classrooms across the corridors (en face) as compared to all rooms on one side to see how this arrangement affects pedestrian movement. Moreover, to achieve a more realistic simulation of evacuation, group behaviour, nonlinear characteristics, and collective panic can be incorporated into the model.

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