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RESEARCH ARTICLE

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Modeling pedestrian group behavior in crowd evacuations

Yakup Turgut | **Cafer Erhan Bozdag**

Management Faculty, Industrial Engineering Department, Istanbul Technical University, Macka, Turkey

Correspondence
Yakup Turgut, Management Faculty, Industrial Engineering Department, Istanbul Technical University, Macka, Istanbul 34367, Turkey.
Email: turgut16@itu.edu.tr

SUMMARY

Many models have been developed in recent years to describe pedestrian group behavior. Most prior research on group behavior focuses mainly on small groups and does not provide a general approach for grouping pedestrians with respect to different group sizes. They also analyze pedestrian group dynamics in normal circumstances. However, people's reactions who are aware of an emergency are not the same as how they respond to normal or usual situations. The central focus of this paper is to study pedestrian group behavior during evacuation. To accomplish these objectives, a new model is proposed with some extensions of a social force model in its emergency context. The new extensions are intended to simulate the single leader-centered and group-centered crowd behavior in emergencies. Besides small pedestrian groups, larger ones are also considered, and extensions are added in this direction. The model is calibrated using the results of an existing experimental study. Then, the model is verified by testing for the occurrence of certain emergent patterns. The results indicate that the proposed model can capture these trends. Additionally, the model is validated by comparing the simulation results with experimental results available in the literature. Also, several different evacuation scenarios are used to evaluate the proposed model. The simulation results show that leader-centered behavior performs better than group-centered behavior with respect to the evacuation time for small groups. The number of leaders also affects the evacuation time. Moreover, an increase in the number of leaders positively influences the effect of the width of the door on evacuation time, but the size of this effect depends on the number of leaders. Finally, group-centered behavior results in less evacuation time than leader-centered behavior in the presence of multiple exits, and leader-centered (also called single leader-centered in this study) behavior causes a more unbalanced use of the exits than group-centered behavior.

KEYWORDS
crowd evacuation, pedestrian group behavior modeling, social force model

1 | INTRODUCTION

Investigating crowd behavior in emergencies is a continuing concern for crowd safety. What we know about crowd behavior is largely based upon computer simulations and empirical studies.[1–3] Cocking et al[4] have reported that people are more likely to behave cooperatively and altruistically in emergencies. This evidence suggests that people seek to escape buildings with other people even if they are strangers. This indicates a need to understand the various aspects of these behaviors that the crowd display.

The efforts to find out why people show these behaviors go beyond the scope of this study. This paper seeks to address the effects of these behaviors on the egress behavior of the crowd. As a result of these behaviors, the egress behavior exhibited by pedestrians may be divided into two main categories: group behavior and individual behavior. Moreover, it is inappropriate to exclude group behavior in modeling pedestrian behavior, because people have a tendency to act as a group rather than as an individual during emergency situations.[5] This study, therefore, sets out to assess the effect of group behavior in an emergency.

However, so far, to our best knowledge, the terminology for the term group is not clearly defined in pedestrian dynamics and the meaning varies depending on the background of the authors.[6–9] In this study, we consider the pedestrians, who desire to move together due to at least one of the following factors, as a group: (1) the intimacy level between pedestrians. For instance, the members of a family tend to move together during an evacuation, (2) the perception level of the pedestrians during the evacuation. For instance, some pedestrians may not decide how to act during an evacuation and may follow another pedestrian, (3) the altruism level of pedestrians. For instance, a pedestrian may decide to help an injured pedestrian, and they may move together during an evacuation, (4) the personal interest of pedestrians. For instance, two pedestrians may have a common interest and may move together. But the interests of pedestrians can change throughout the evacuation and they can leave their groups or change their groups.

Planners need evacuation models to develop proactive strategies enhancing crowd safety. Multiple modeling approaches have been developed in the past decades. The most popular are the force-based models,[10–12] some variations of cellular automata,[13–15] agent-based models,[10,16,17] and rule-based models.[18] Force-based models are especially suitable for modeling pedestrian behavior during an evacuation because they successfully demonstrate some emergent phenomena, such as faster-is-slower, freezing by heating, arching, and clogging effects during emergency situations.[11] "Faster-is-slower" indicates that people rushing to get out of the area faster without considering the individuals around them causes traffic jams and bottlenecks and leading to increased congestion at the exit, in turn leading to longer evacuation times. "Rushing" here means that people move quickly toward the exit and also make decisions (eg, which exit to take) at an extreme speed to get out as soon as possible. "Freezing by heating" is a physical metaphor and refers to the disorder in the direction of the movements of the pedestrians, because the pedestrians need to change their direction constantly because of urgency, that is, time pressure, rapid evacuation. "Arching and clogging" refers to pedestrian queues being arch-shaped at the exits, as well as the congestion due to people rushing to get to the exit. These phenomena may occur in real systems[19–21] and lead to the death of people.[22] Therefore, a model should reproduce these effects. But force-based models are still incapable of producing an integrated pedestrian model. The behavioral aspects of pedestrians should also be considered to cover the complexity of pedestrian dynamics.

There are several publications on pedestrian motion models, which combine social and psychological behavior.[9,23–29] These publications largely describe the group behavior and some of the underlying drivers of group behavior such as competitiveness, helping based on some social theories. But most of these studies focus on group (especially small groups) behavior in a normal situation, rather than on group behavior in an emergency. However, the behavior of people when they know an emergency is taking place is not the same as how they react in a normal situation.[30] It can be shaped by social attachment and affiliation,[31] social identity, and self-categorization,[4] which are the social theories that are inextricably linked to group behavior. Moreover, they do not provide a general approach for grouping pedestrians according to different group sizes (see Section 3.4 for further details). Furthermore, to the best of our knowledge, there exists no study in the literature modeling the behavior of a group of pedestrians in terms of being either leader-centered or group-centered.[32] While in leader-centered behavior, the leader guides every group member according to their idea, group-centered behavior concerns the interest of the majority of the group. For example, let us consider a room configuration with two exits. In leader-centered behavior, the leader selects one of the two exits, and all group members follow the leader. On the other hand, in group-centered behavior, each group member moves to the exit, which is the closest to the center of the group and leaves the room using this exit. So the main focus of this study is on modeling leader-centered and group-centered behavior in emergency situations for small groups as well as large groups.

To reach our model goals, we formulated a mathematical model by using AnyLogic 7.2 PLE (http://www.xjtek.com). To properly reflect the urgency of pedestrians, the proposed model is based upon the social force model (SFM) version that was built for emergencies,[11] instead of its regular version.[33]

Three additional forces: (a) group force, (b) leader attractive force, and (c) leader repulsive (path clearing) force are added to the SFM. The group force is added to ensure that persons who are in the same group move closer to each other. This force is designed by describing an imaginary group force from the center of the group, which attracts each group member to the center of the group. Reynold's cohesion rule[34] is used to determine the center of the group. Besides, the leader attractive force is added to the SFM to investigate the impact of leader-centered behavior on evacuation time. A leader repulsive force is also added to clear the leader's path to the target or exit. Additionally, we have provided a comprehensive approach for forming different sizes of groups.

The lessons learned from the history of crowd disasters have demonstrated that crowd management plays a crucial role in eliminating minor and major injuries during an evacuation.[35] Given that in any venue or any public gathering such as the museums, shopping centers, libraries, roles and responsibilities regarding safe evacuation have to be clearly defined and given to each party. This model gives the crowd managers a good insight into developing proactive strategies to enhance crowd safety. It may help to determine, for example, how the tasks can be assigned to personnel on-site to optimize evacuation. Also, it provides practical guidance for people responsible for the crowds' safe exit in an emergency.

The remainder of this paper is organized as follows. Section 2 reviews the related literature on pedestrian group behavior. Section 3 describes our method. Section 4 discusses the simulation experiments and results. Section 5 concludes the study and presents future avenues for research.

2 | RELATED STUDIES

Grouping is a commonly observed behavior in empirical research.[36] Therefore, in recent years, scholars have started to model group behavior to examine how it affects the crowd dynamics using social, psychological, and rational decision-making theories. Von Sivers et al[37] proposes an agent-based model to simulate the helping behavior, one of group behavior triggers, in crowd evacuation based on Tajfel's social identity theory and self-categorization theory. It uses an optimal steps model to model the locomotion of the crowd. According to social identity theory, a person has various social identities, which vary based on the social groups to which they belong. On the other hand, self-categorization theory refers to the state of a person categorizing himself as a group member or not.[38]

“Following” behavior is the most apparent kind of group behavior. Fang et al[10] propose an agent-based model to study the leader-follower behavior in crowd egress and utilizes the scalar field method to simulate the crowd motion. Ma et al[39] extends Helbing and Molnar[33] to simulate leader-follower behavior in crowd evacuation. They examine the effects of leadership on crowd evacuation, taking into account the range of visibility of the evacuation area. They conclude that the impact of leadership on evacuation time depends on the range of visibility of the area and crowd size.

In pedestrian models, grouping the pedestrians is an open question in the simulation of group behavior. Li et al[40] group the pedestrians based on their social relations, such as families, friends, and strangers. They extend Helbing's SFM to simulate group and leader-follower behavior in crowd evacuation. They conclude that group behavior provides a faster evacuation time than Helbing's SFM.

Lemercier and Auberlet[25] develop an agent-based model to investigate how pedestrians' perceptions can influence their attitudes during an evacuation. They use the RVO2 model to model the motion of the crowd. They examine leader-follower behavior, grouping, or not grouping. They conclude that the combination of different types of behavior indicates a more realistic crowd behavior.

Selfishness/Selflessness behavior is critical in forming pedestrian groups, where they determine whether the pedestrians act together with others or not. The individual strategies of the pedestrians are influential in the occurrence of these behaviors. Therefore, the authors propose some pedestrian models to simulate these behaviors based on game theory. Game theory is the mathematical modeling approach designed to model rational decision makers' strategies.[41] Song et al[29] propose a simulation model that combines cellular automata and a lattice-gas model, to simulate the selfishness/selflessness behavior in crowd evacuation. They conclude that if the level of selfishness of the pedestrians is great, the evacuation time will increase. Dossetti et al[23] propose an agent-based model to simulate the effect of cooperative/competitive behavior on crowd evacuation. They conclude that behavior at the middle level of this scale is more effective than completely competitive or cooperative behavior. Zheng and Cheng[9] presented a cellular automaton (CA) model to simulate selfish/collaborative behavior. They conclude that collaborative behavior decreases the evacuation time, unlike selfish behavior.

Some researchers have focused on group size, the interaction between groups and intra-group when simulating group behavior. You et al[42] propose a CA model to simulate small pedestrian groups (1-3 people). They conclude that an increase in the group size increases the evacuation time. Qiu and Hu[28] propose an agent-based model to simulate group behavior, evaluating the influence of group size, intra-group structure, and inter-group relationships on crowd evacuation. They use Reynold's Boids algorithm for the locomotion of the crowd. They conclude that group size, intra-group structures, and inter-group relationships are important in crowd evacuation. Zhou et al[43] propose an agent-based model to simulate the group behavior of two different groups by providing collision avoidance. They use a velocity-obstacle method to simulate the locomotion of the crowd.

Qiu and Hu[44] propose an agent-based model to simulate the dynamics of pedestrian groups based on Festinger's Social Comparison Theory and Utility Theory. It states that after one categorizes oneself as a group member, one needs to compare one's own group with the other groups to enhancing one's self-esteem.[45] Utility Theory was originally an economic concept based on the concept of a rational decision. It states that people come to a decision in terms of the utility received by them.[46]

Ren et al[47] propose an agent-based model to simulate the different type of pedestrian groups, such as social groups, marches, guides, etc. They use the velocity-obstacle method to simulate the locomotion of the crowd. It indicates that the proposed model can model different types of groups and it can also suggest some features of the behavior of the group, such as, group splitting/merging, group switching, etc.

Hu et al[48] present a novel three-dimensional CA model with a ladder factor. They examine the position vacancy degree and group attractions. They show that the evacuation time can be effectively reduced when the mean system velocity and position vacancy have the proper degree, and a bigger group has a negative effect on the evacuation time, so bigger groups should be avoided in an actual evacuation process. Müller et al[49] extend the CA model to simulate pedestrian group behavior. They focus on group interactions and take into account the intimacy between pedestrians in the same group when categorizing the group interactions. They define two types of group interactions based on the intimacy between the group members: (1) symmetric group interactions and (2) asymmetric group interactions. So they model groups with symmetric and asymmetric group interactions and discuss the impact of such groups on the evacuation dynamics. Lu et al[50] propose an extended floor field CA to simulate the pedestrian group behavior during an evacuation. They conclude that the total crowd evacuation time significantly increases with the presence of pedestrian groups in the crowd. In addition, an increase in the density of the crowd enhances the negative impact of the group behavior on crowd evacuation.

Empirical studies have enabled researchers to calibrate their models. Unfortunately, there is only a limited number of empirical studies in the literature on group behavior. von Krüchten and Schadschneider[51] carry out an empirical study to investigate the effect of social groups on an evacuation. They focus on analyzing the following characteristics: The shape of the social groups, the space requirement for the different groups, the evacuation time for the different groups, the shape of the groups on the exits, and explicit cooperative behavior in the presence of groups. So they conclude that social groups may increase the efficiency of the evacuation process if the pedestrian groups exhibit a queue behavior in the exits, and explicit cooperative behavior in the groups may increase the evacuation time according to the normal behavior.

Moreover, the shape of the groups is elliptic during an evacuation, and their motions around the exits are conical. Xi et al[52] carry out an empirical study to investigate the intra-group structures and spatial patterns of complex social groups which have five members or more. They found out that groups with five members have the following spatial patterns: 3-2 pattern (three members in the front, two members in the back), 2-3 (two members in the front, three members in the back) pattern or a "U"-shaped pattern in their walking under normal conditions. These patterns are the cellular groups. Also, the shape of the groups is elliptic. They also determine the size of the private space for each group. The sizes of these spaces are consistent with T.Hall.[53]

Köster et al[54] carry out an empirical study in a classroom to determine the influence of small groups on the amount of time required to leave and enter a classroom. They found out that when the group size increases, egress times increase, but ingress times decrease. In their view, it is because students are positioned in the hallway based on their seating location in the classroom. Bode et al[55] investigate the effect of social groups on the egress time of pedestrians. They conclude that social groups increase the egress time due to delays in their pre-movement and movement time. Also, social groups do not increase the movement time prominently in front of the exits. Chen et al[56] carry out an empirical study to investigate how children behave during evacuation. They found out that group behaviors observed during child evacuation increase the time of evacuation.

In Table 1, we present a summary of examined studies of pedestrian group behavior in the literature. The following research questions are developed based on the literature review to guide this study: (1) how should the groups of different sizes be formed when analyzing group behavior in simulation models? (2) How should SFM be modified to obtain a valid model of pedestrian group behavior in crowd evacuations? (3) What are the differences between group-centered behavior and leader-centered behavior in terms of crowd evacuations?

3 | METHOD

3.1 | Human eye field of view

Humans mostly react to the objects that are in their eye field of view, because of the anisotropic characteristic of their motion.[57]

TABLE 1 Overview of Pedestrian Group Behavior (ABM: Agent-Based Modeling, CA: Cellular Automata, SFM: Social Force Model)

No.	Reference	Type of behavior	Modeling method	Motion model	Theory used in study
1	Fang et al[10]	Leader following	ABM	Scalar field method	-
2	von Sivers et al[37]	Help	ABM	The optimal steps	Social identity and self-categorization
3	Song et al[29]	Selfishness and selflessness	CA and lattice gas	-	Game theory
4	Lemercier and Auberlet[25]	Leader following, Group	ABM	RVO2 Collison Avoidance	-
5	Zhou et al[43]	Group	ABM	Velocity-obstacle	-
6	You et al[42]	Group and leader following	CA	-	Von Neumann
7	Qiu and Hu[28]	Group	ABM	Reynold's Boids algorithm	-
8	Li et al[40]	Leader following	ABM	SFM	-
9	Ma et al[39]	Leader following	ABM	SFM	-
10	Dossetti et al[23]	Group	ABM	-	Game theory
11	Zheng and Cheng[9]	Group	CA	-	Game theory
12	Qiu and Hu.[44]	Group	ABM	-	Utility theory and social comparison
13	Ren et al[47]	Group	ABM	Velocity-obstacle	-
14	Hu et al[48]	Group	CA	-	-
15	Müller et al[49]	Group	CA	-	-
16	Lu et al[50]	Group and leader following	CA	-	-
17	Köster et al[54]	Group and leader following	CA	-	-

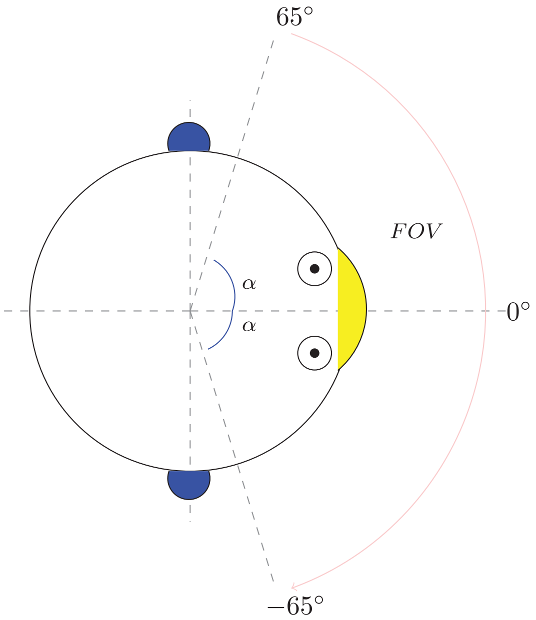

FIGURE 1 Field of view (FOV) for human being's eye

The area that can be perceived by both eyes at the same time is 130°, while the wide field of view of a healthy person is 180°.[58] The field of view of a human being is illustrated in Figure 1. The human eye field of view is briefly mentioned in this subsection because there are some forces in the proposed model, which will be in effect if the objects are in the eye fields of the humans. The reader can see how we use the field of view information in Section 3.6.

3.2 | Social distance theory

Individuals need to maintain some distance from other persons because of social behavior, according to the proxemic theory of Hall.[53] These distances are also known as interpersonal space or interpersonal distance. Hall[53] defines four different types of physical distance, depending on the degree of the relationship between the people (see Figure 2). These relationships are described as follows:

- Intimate distance (A): The distance maintained when we communicate with people to whom we are very close (eg, a lover).
- Personal distance (B): The distance when we communicate with close friends or family members.
- Social distance (C): The distance when we communicate with people we know.
- Public distance (D): The distance when we talk to a member of the community.

Previous studies have reported that these distances are not precise. They change depending on the characteristics of the pedestrians,[59] their gender,[60] cultural norms,[61] social environment,[62] and pedestrian density.[63] On the other hand, to

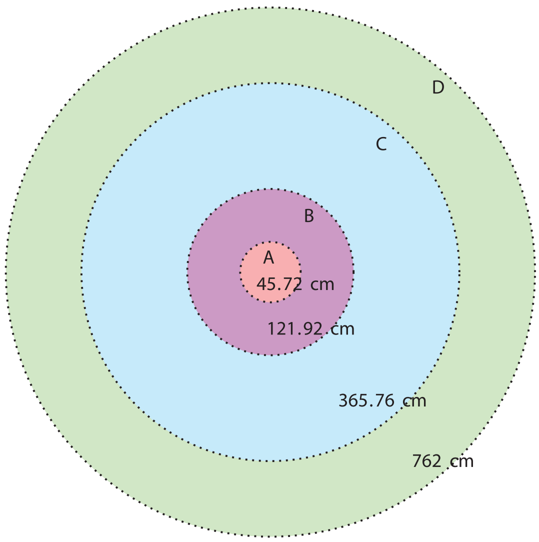

FIGURE 2 Types of proxemics

the authors' best knowledge, these distances are consistent with real life despite a small margin of error. So we consider it quite appropriate to use these distances as a reference point for grouping the pedestrians.

3.3 | Basic concepts for the model

Pedestrian: Pedestrians are defined as agents with a certain mass, initial position and velocity, desired velocity, maximum velocity that can be reached, initial direction, and a target to achieve, and a specific field of view.

Pedestrian set: A pedestrian cluster consisting of n elements containing all the pedestrians to be evacuated. It is denoted by $E = \{\alpha_1, \alpha_2, \alpha_3, \ldots, \alpha_n\}$. A subset of this set is defined as a group.

Group: It is explained is Section 1. They partition the set of pedestrians.

Group size: This is the number of pedestrians in a group. The number of pedestrians in a group is denoted by $|g|$.

Group set: The set of groups: it consists of m elements, each one of which is one of the pedestrian groups. It is denoted by $G = \{g_1, g_2, g_3, \ldots, g_m\}$. The union of these sets gives the set of the pedestrians.

Pedestrian position: The positions of the pedestrians are described in 2D space. It is denoted by $l_\alpha(x, y)$.

Obstacle: The walls or other shapes within the range of motion of the pedestrians are defined as obstacles; they block the moving area of the pedestrians. These objects are depicted in the model by lines.

Pedestrian density: This indicates the number of pedestrians per square meter. It is denoted by ρ.

Evacuation area: It is defined in two-dimensional plane. It is continuous.

Leader: The pedestrian who directs the other pedestrians and attracts them toward themselves. The leader is indicated by the letter "l" in the equations.

3.4 | Grouping pedestrians

The size of a pedestrian group in a public open space generally varies between one and five members, according to empirical observations.[42] These groups are referred to as small groups in the literature. Small groups may unite into large groups of different sizes for a common purpose. In other words, large pedestrian groups are formed by the combination of small pedestrian groups, as illustrated in Figure 3.

Public events such as watching football or attending a concert have high pedestrian densities. According to Oberhagemann,[64] while the maximum pedestrian densities are about 6 people/m^2, pedestrian densities around 2 people/m^2 are assumed to be the average densities in such events. In such high densities, persons cannot maintain their private spaces. Moreover, in high densities above 2 people/m^2, it is not easy to split the crowd into groups, and the crowd seems like one group. Also, it is not easy to analyze the group behavior. Since the pedestrian density of a group of five members positioned inside a circular area with a radius of 1.2 m is 1.1 people/m^2, we consider the pedestrian density 1.1 people/m^2 as the upper limit for grouping pedestrians. So, pedestrian densities above 1.1 people/m^2 are outside the scope of this paper. We group the pedestrians at the beginning of the simulation using the following procedure.

The pedestrians who are members of a small group (the group size varies between 1 and 5), are positioned within the boundaries of a circle with a radius of 1.2 m (approximately personal distance). The distance between each group member's center is identified as at least 0.5 m (approximately intimate distance). For group sizes above 5, the radius of the circle is identified by maintaining the pedestrian density of the groups below 1.1 people/m^2. For example, if the group size varies between 11 and 15, then the radius of the circle is calculated by $\sqrt{\frac{15}{1.1 \times \pi}} = 2.08$ meters. The distance between the centers of two groups is determined as follows: For instance, from Figure 3, the distance between the group centers of Group 1 and Group 3, D_{13}, is set to satisfy the following condition: $D_{13} > r1 + r3 + 1.2$, where 1.2 indicates the group separation distance (approximately personal distance).

After introducing the basic concepts of grouping, the following steps are introduced for grouping the different sizes of pedestrian groups.

1. Determine the number of groups and the size of each group.
2. Choose randomly a group center (m_x, m_y) for each group. The distance between two group centers is determined based on the size of these groups.
3. To simplify the calculation, we establish the shape of the pedestrian groups to be a circle and determine the radius of the circle based on the group size.
4. Position each pedestrian around their group center by keeping the pedestrian within the boundaries of their circle. The distance between two pedestrians' centers is determined based on the above procedure.

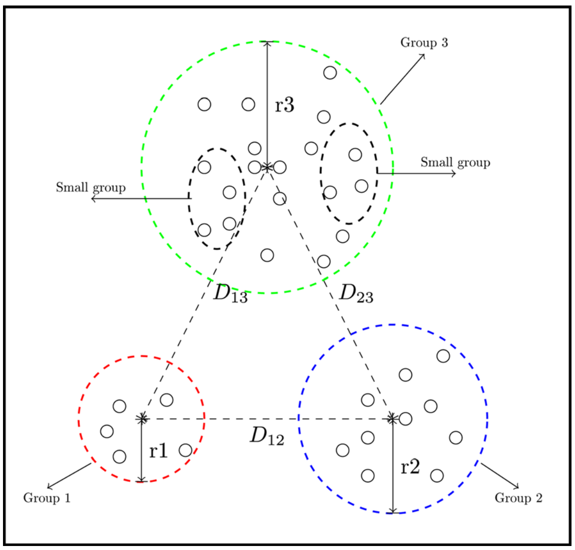

FIGURE 3 Pedestrian groups with different sizes

3.5 | Group force

The most obvious feature of group behavior is the desire of the pedestrians to move together. A group force $\vec{F}_{\alpha\text{group}}$ is added to the SFM to ensure that the pedestrians within the same group keep close to each other. The group forces acting on a pedestrian group in which four pedestrians are present are represented in Figure 4. The definition of the center of the group ((m_x, m_y)) is presented in Equations (1a) and (1b). Equation (1c) shows the calculation of $\vec{n}_{\alpha c}$, where $\vec{n}_{\alpha c}$ is the normalized vector pointing from the center of the group to pedestrian α, and $d_{\alpha c}$ is the distance between pedestrian α and the group center.

Pedestrians tend to move mostly in groups of two or three. Large groups contain small groups. Therefore, the magnitude of the group force that holds the groups together should be strong for small groups, but for large groups, it should be weak. Hence, in order to determine the magnitude of the group force according to the size of the group, the group force was formulated based on the group size. The group force on pedestrian α is calculated through Equation (1d), where K_1 and K_2 are constants and $|g|$ denotes the size of the group.

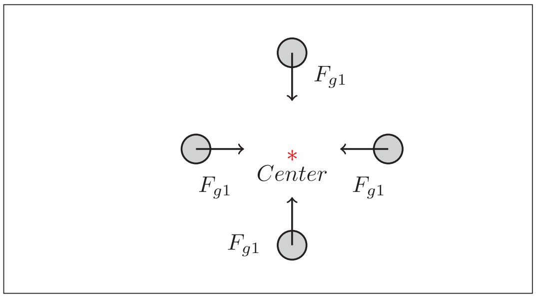

FIGURE 4 Illustration of group force for group 1

$$m_x = \sum_{\alpha \in g} x_\alpha / |g|, \quad \forall g \in G, \tag{1a}$$

$$m_y = \sum_{\alpha \in g} y_\alpha / |g|, \ \ \forall g \in G, \tag{1b}$$

$$\vec{n}_{\alpha c} = \frac{(m_x - x_\alpha, m_y - y_\alpha)}{d_{\alpha c}}, \tag{1c}$$

$$\vec{F}_{\alpha \mathrm{group}}(t) = \vec{n}_{\alpha c}[-(K_1/\exp(|g|)) \exp\left(\sqrt{(m_y - y_\alpha)^2 + (m_x - x_\alpha)^2}/K_2\right)]. \tag{1d}$$

3.6 | Leader force

Pedestrians in a group tend to exhibit leader following behavior when one of their group members is the leader. The leader basically applies two different forces to the members of the leader's own group. They are defined as follows:

- Leader attractive force: With the help of an attractive force applied by the leader to the group, group members can get close to the leader and follow the leader. In Equation (2a), $d_{\alpha l}$ is the distance between pedestrian α and the leader. Equation (2b) shows the calculation of $\vec{n}_{\alpha l}$, where $\vec{n}_{\alpha l}$ is the normalized vector pointing from the leader to pedestrian α. The leader attractive force on pedestrian α is calculated through Equation (2c), where K_3 and K_4 are constants.
- Leader repulsive force: The leader attractive force may lead to the formation by the pedestrians of a barrier around the leader. In order to prevent this, as shown in Figure 5, the leader's path is opened by applying a repulsive force on the path of the leader's field of view. The leader repulsive force on pedestrian α is calculated through Equation (2d), where λ_l shows the anisotropic character of the leader, that is, the leader is mostly affected by the objects within its field of view,[65] $\varphi_{\alpha l}$ indicates the angle between the direction of the motion of the leader and that of pedestrian α, and K_5 is a constant. In Equation (2d), p is a binary variable and is calculated through Equation (2e), where p makes the leaders only apply the repulsive force to the pedestrians in their field of view.

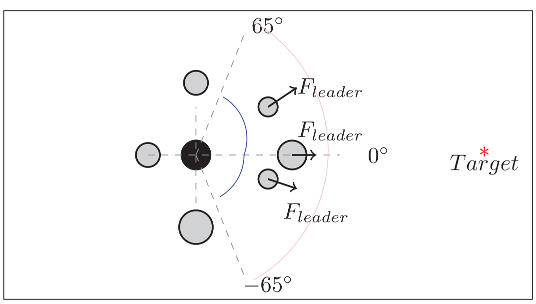

FIGURE 5 Leader repulsive force

The total leader force on pedestrian α is shown in Equation (2f)

$$d_{\alpha l} = \sqrt{(l_y - y_\alpha)^2 + (l_x - x_\alpha)^2}, \tag{2a}$$

$$\vec{n}_{\alpha l} = \frac{(x_\alpha - l_x, y_\alpha - l_y)}{d_{\alpha l}}, \tag{2b}$$

$$\vec{F}_{\alpha \mathrm{leaderattractive}}(t) = \vec{n}_{\alpha l}[-K_3 \exp((r_{\alpha l} - d_{\alpha l})/K_4)], \tag{2c}$$

$$\vec{F}_{\alpha \mathrm{leaderrepulsive}}(t) = \vec{n}_{\alpha l}[K_5 \exp(1/d_{\alpha l})](\lambda_l + (1-\lambda_l)\frac{(1+\cos(\varphi_{\alpha l}))}{2})p, \tag{2d}$$

$$p = \begin{cases} 1 & \text{If} -65^\circ \le \varphi_{\alpha l} \le 65^\circ \\ 0 & \text{otherwise} \end{cases}, \tag{2e}$$

$$\vec{F}_{\alpha \mathrm{leader}}(t) = \vec{F}_{\alpha \mathrm{leaderattractive}}(t) + \vec{F}_{\alpha \mathrm{leaderrepulsive}}(t). \tag{2f}$$

3.7 | Total force

The total force acting on pedestrian α is described in Equation (3). The pedestrian α moves under the influence of this force. A detailed explanation of the basic forces of the SFM is presented in Appendix A.

$$\vec{f}_\alpha^{\,\mathrm{total}}(t) = \vec{F}_\alpha^{\,\mathrm{driving}}(t) + \sum_\beta \vec{F}_{\alpha\beta}^{\,\mathrm{repulsive}}(t) + \sum_W \vec{F}_{\alpha W}^{\,\mathrm{repulsive}}(t) + \sum_\beta \vec{F}_{\alpha\beta}^{\,\mathrm{attractive}}(t) + \vec{F}_{\alpha \mathrm{group}}(t) + \vec{F}_{\alpha \mathrm{leader}}(t) + \xi(t). \tag{3}$$

4 | SIMULATION EXPERIMENTS AND RESULTS

The proposed model has been used to investigate the characteristic features of group behavior in different cases. The parameters of the model have been calibrated, and then the model has been verified and validated. The features, which are common to all the experiments, are as follows:

- AnyLogic, which is a Java-based program, to implement the proposed simulation model;
- All pedestrians are placed randomly in the evacuation environment at the beginning of the simulation, based on the grouping concept;
- All experiments are conducted in an obstacle free environment;
- Due to the stochastic nature of output variables in simulation, the results of any single simulation may not be representative of the variation in nature. The simulation software allows us to test the varying number of runs until a specified confidence level is

reached. Each simulation experiment was repeated a sufficient number of times until a confidence level of 95% was reached. Thus, the number of simulation runs varies among the experiments. And, we have reached the confidence level of 95% for all experiments with at most 100 runs.

Another issue that has to be addressed in the experiments is the time step for the simulation. The SFM describes the pedestrian dynamics by means of nonlinear equations of motion. Therefore, in order to find the position, velocity, and acceleration of a pedestrian, a set of ordinary differential equations (ODEs) must be solved. We used Euler method of numerical integration to find numerical approximations to the solutions. The most critical part of using the Euler method is to determine the time step for the efficiency of the simulation.

We carried out a lot of experiments with different time steps, varying between 0.1 and 0.0001. The large time steps lead to an error related to the magnitude of the forces and result in oscillations or collision. Very small time steps, around 0.0001, provide great accuracy but on the other hand increase the simulation time too much. So the aim is to determine the most appropriate time step that will minimize the errors and not significantly increase the simulation time. For this, we first performed several experiments to determine an upper bound for the time step that does not lead to unacceptable simulation results. Upper bound 0.01 was obtained.

Next, we analyzed the effects of small-time steps on the simulation results using a one-way ANOVA with a 95% confidence interval, followed by Tukey's post hoc test. We compared the total evacuation time for three time steps: 0.009, 0.005, and 0.001. Twenty runs were performed for each time step using different random seeds. The common random numbers (ie, the same random stream) were used for each time step within each run, eliminating the stochastic noise between three groups because of using different random seeds. The ANOVA results showed that the total evacuation times for the three time steps are not significantly different at the 5% significance level.

Finally, we compared the running time of simulation for each time step by following the same procedure. Post-hoc Tukey testing indicated that the running time of simulation for time step 0.001 was significantly higher than that of time step 0.009 and time step 0.005. The time step 0.009 and time step 0.005 are not different in terms of evacuation time, nor are they statistically different in terms of running time. So, we selected the time step $\Delta t = 0.005$ second.

Someone may argue that values between 0.009 and 0.001 or less than 0.001 can be used to get more accurate results. To eliminate this concern, we have carried out many trials for time steps between 0.009 and 0.001, but they did not lead to results statistically different from those obtained with time step 0.005. To analyze whether step sizes smaller than 0.001 would work better, we compared the results of time steps 0.005 and 0.0001. Results showed that a smaller step size results in a longer running time though giving the same simulation results. On the other hand, some studies use variable step size based on forces exerting on agents.[66] The variable step size can be used if

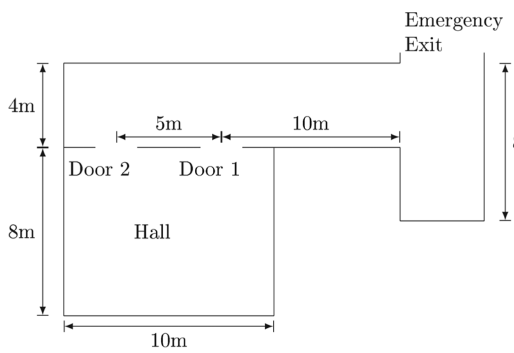

FIGURE 6 A corridor with two open boundaries (Lu et al[50])

TABLE 3 SFM simulation parameters

Parameter	Unit	Value
$v_\alpha^0(0)$	m/s	uniform(1, 3)
v_α^{max}	m/s	5
m_α	kg	uniform(60, 80)
τ_α	s	0.5
A_α	N	2000
B_α	m	0.08
r_α	m	0.25
λ_α	scalar	1
λ_l	scalar	0
C_1	scalar	12
C_2	scalar	24
S	scalar	10
K_1	scalar	0.25
K_2	scalar	10 000
K_3	scalar	0.8
K_4	scalar	20 000
K_5	scalar	0.20

TABLE 2 Comparison of the model with a real experiment from the literature (ET: Evacuation Time)

	Experiment				Simulation			
	1	2	3	4	1	2	3	4
Avg. ET (s)	32	26.5	35.2	36.1	30.3	27.2	33.1	36.5
Min ET (s)	-	-	-	-	28.2	25.7	29.8	30.9
Max ET (s)	-	-	-	-	37.9	28.5	38.4	40.7

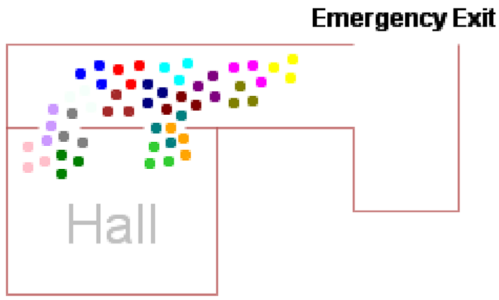

FIGURE 7 Snapshot of pedestrian groups at 9 seconds

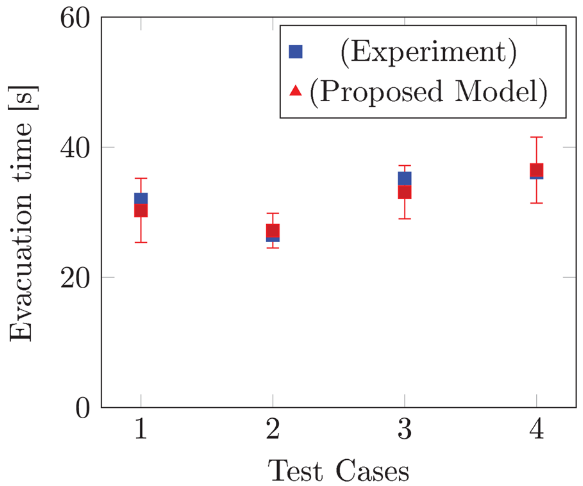

FIGURE 8 Model calibration

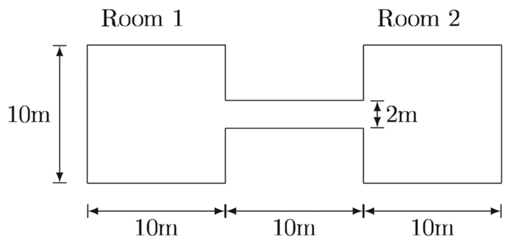

FIGURE 9 Two rooms connected via a corridor

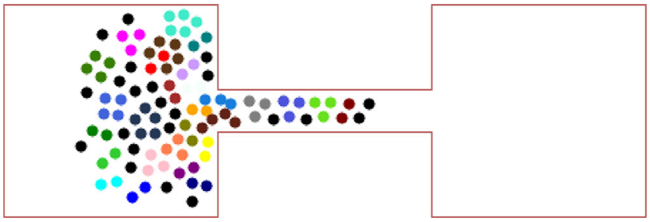

FIGURE 10 Snapshot of pedestrian groups at 7 seconds

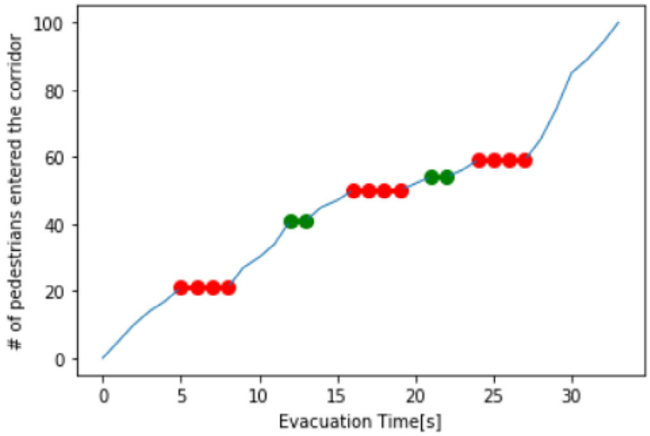

FIGURE 11 The number of pedestrians entering the corridor during the clogging effect (Red and green dotted lines indicate delay time in evacuation due to high pedestrian density in the corridor and the clogging effect around the corridor, respectively)

the forces changed rapidly. But in SFM, forces change slowly based on the interaction among pedestrians. So using variable step size increases the computational requirements unnecessarily.

4.1 | Model calibration

In the model, we can divide the parameters into old and new parameters: (1) old parameters, which have already been studied in the SFM; (2) new parameters, which come from our extension of that model.

All parameters have been systematically calibrated by considering a real experiment of Lu et al.[50] The experiment was conducted in a university hall, as shown in Figure 6. Initially, all the participants were placed randomly in the university hall.

Participants in the same group were asked to stay close to each other. They were directed to evacuate the hall, using the exits, as quickly as possible and to behave naturally as if it was a real emergency. When an initial signal was given, they began to move toward the doors, enter the passage, and escape through the emergency exit. Four different test cases with different group compositions of the 54 participants were designed: (1) 22 isolated individuals, 10 groups of size 2, 4 groups of size 3, (2) 54 isolated individuals, (3) 27 groups of size 2, (4) 18 groups of size 3. The pedestrian movements were monitored and measured for each test case. Each test case was repeated five times and the average evacuation times were obtained, as in Table 2.

We applied the following procedure to calibrate each parameter of the model:

1. Initially, for new parameters, we chose arbitrary numbers for each parameter and observed the animation in order to look for the occurrence of overlapping or oscillations (errors that can arise from the strength of the repulsive forces). On the other hand, the initial values for the old parameters were set by adopting Helbing et al.[57]
2. We changed the values of each parameter until the levels of overlapping and oscillation in the visual animation were brought to a

reasonable level, which would enable pedestrians to evacuate from the evacuation area without displaying undesirable behaviors, for example, hitting the wall and bouncing back.

3. We calculated the proportion of oscillation and the proportion of overlapping as in Chraibi et al[67] for each value of the parameters. Of note, in this study, we represent pedestrians as a circle. However, pedestrians are typically elliptical. So, the percentage (10%) was determined using two anthropometric measures, namely shoulder and standing hip breadth, for approximating the elliptical shape of pedestrians.[68,69] Then, we systematically tried different values of the parameters to reduce the proportions of overlapping and oscillation to 10%.
4. We selected the value that provided a 10% oscillation proportion as the upper limit for the parameter, and the value that provided a 10% overlap proportion its lower limit.
5. After determining the upper and lower limits of the new parameters, we performed many runs with values of the parameters varying between their upper and lower limits and compared the evacuation times obtained from the simulation model with that of the field experiment. We selected the optimal parameter values that showed statistically insignificant differences in evacuation time between the field experiments and the simulation. The model parameters were then set as in Table 3. The parameters of the simulation are expressed in terms of the uniform distribution to ensure heterogeneity between pedestrians.

The test cases have been simulated with the calibrated parameters as presented in Figure 7. And the results are shown in Figure 8, where the red marker shows the calculated average evacuation times from the simulated simulation, and the blue markers denote the experimental data results. We used the confidence intervals to assess the variability of the simulation estimates. Means with 95% confidence intervals were plotted for each test case (see Figure 8). The results indicate that the experimental results and simulation results do not differ significantly because all the mean data falls within the confidence interval. Moreover, the test results are generally consistent with the experiments: the average evacuation time rises when more pedestrians tend to move as a group or the group size increases.

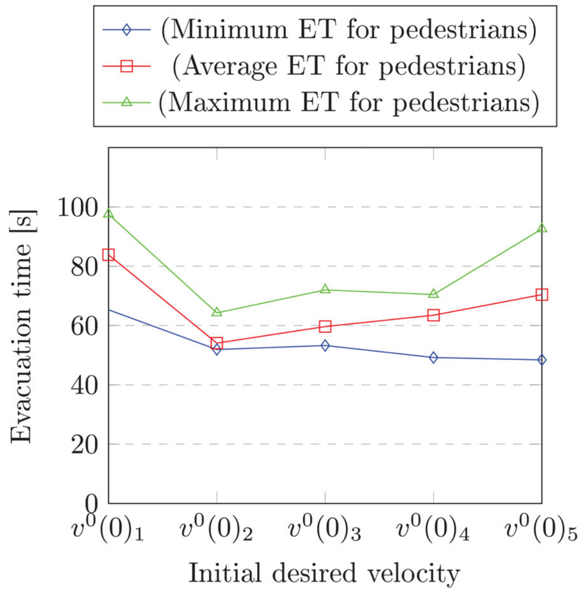

FIGURE 12 "Faster is slower" effect

TABLE 4 Descriptive statistics

Index	$v^0(0)_{index}$ (m/s)	Min ET (s)	Average ET (s)	Maximum ET (s)	STD (s)
1	uniform (0.5, 1)	72.01	83.86	97.54	10.78
2	uniform (1, 1.5)	51.91	54.07	64.26	3.16
3	uniform (1.5, 2)	53.26	59.65	72.01	6.83
4	uniform (2, 2.5)	49.21	63.48	70.45	10.78
5	uniform (2.5, 3)	48.41	70.42	92.6	17.64

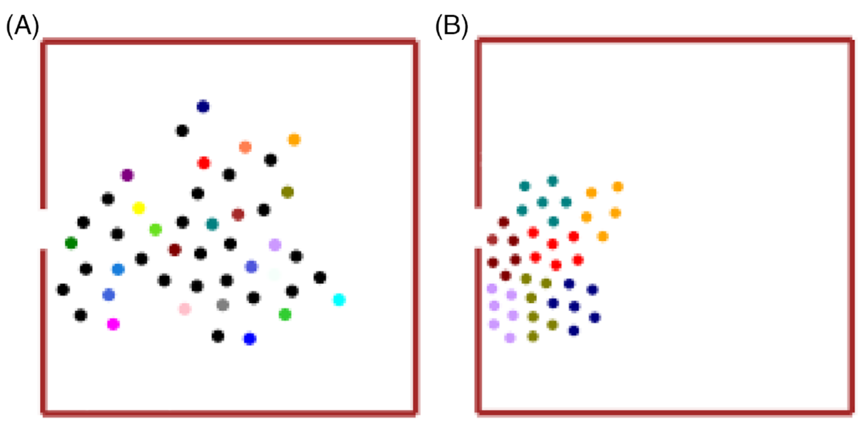

FIGURE 13 Snapshots of the pedestrians at 1.2 and 2.3 seconds, respectively

TABLE 5 The details of two configurations

Configuration	1	2	3	4	5	6
1	1.2 m	Grade 10/11:16 years old	46	Yes	2	Fixed
2	1.2 m	Grade 10/11:16 years old	42	No	6	Loose

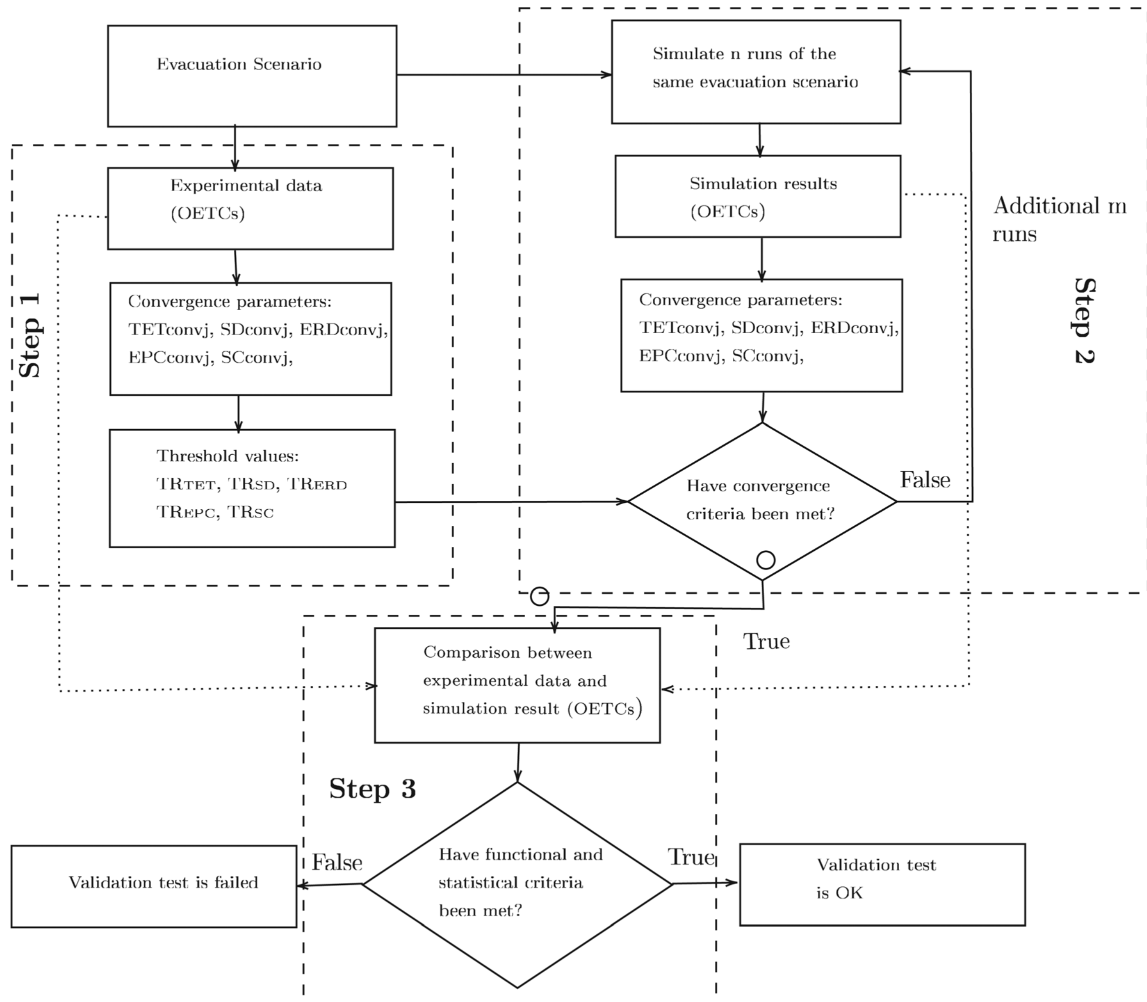

FIGURE 14 Schematic flow chart of the validation procedure (Lovreglio et al[78])

4.2 | Model verification

The presence of emergent phenomena is used to verify the proposed model. Therefore, we conducted several simulations to verify the proposed model and investigated the occurrence of emergent phenomena in emergency situations.

4.2.1 | Arching and clogging

The 100 pedestrians were classified into groups. Of these groups, 22% were composed of only one individual person, 30% of the groups had two people, 21% of the groups had three people, 12% of the groups had four people, and 15% of the groups had five people. The percentage of groups with a given size was determined based on You et al.[42] The simulations were performed in a 2-m corridor connecting two rooms. Its geometry is shown in Figure 9. One hundred pedestrians were positioned in room 1 randomly and moved from room 1 to room 2. The performance measure is the time it takes for the last pedestrian to reach room 2.

Clogging occurs when two or more agents compete to enter the corridor, and it causes a delay in evacuation time (see Figure 10). However, the delay in the evacuation time is not due only to the clogging effect but also to the pedestrians' waiting time before entering

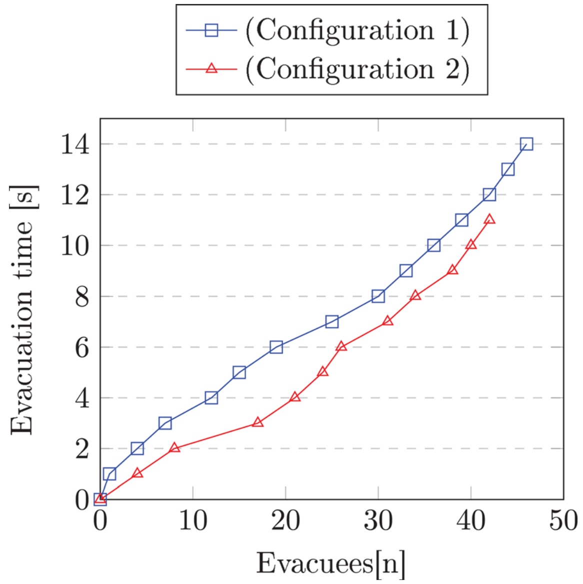

FIGURE 15 Experimental occupant-evacuation time curves

the corridor, that is, if there is no space in the corridor, pedestrians may have to wait. Therefore, we observed the animations and added the plot displaying the number of pedestrians that entered the corridor during the simulation (see Figure 11). Based on our observations, we can conclude that no pedestrian can reach the corridor for longer than 2 seconds when the competition between pedestrians or clogging effect occurs. And this causes the total evacuation time to increase. Due to the high pedestrian density in the corridor, on the other hand, the pedestrians have to wait for less than or equal to 2 seconds to enter the corridor. So we assume clogging when no person entering the corridor for more than 2 seconds. It was observed that during the evacuation process, the "arch and clogging" collective phenomenon around the entrance of the corridor occurred at $t = 7$, 18, and 25 seconds when the pedestrian density is high inside the corridor (see Figure 11).

The means and SD of evacuation time for 100 runs are 40 and 4.83, respectively. This long evacuation time resulted from the clogging effect. This phenomenon, reproduced by our simulation model, turns out to be consistent with empirical observations in a previous study Helbing et al.[11]

4.2.2 | The "faster is slower" effect

We used the geometric plan shown in Figure 9 to test the "faster is slower" effect. However, a 1-m wide corridor was selected with the purpose of allowing only a single individual to enter the corridor at a time, in order to increase the degree of competition around the entrance of the corridor.

The simulation results are shown in Figure 12. The mean value, minimum value, maximum value, and SD of the evacuation time are analyzed and presented in Table 4. The simulation results indicate that for desired velocities above 1.5 m/s, there is an increase in the average evacuation time. However, the minimum evacuation time is obtained for desired velocities between 2.5 m/s and 3.0 m/s. Moreover, high desired velocities cause high fluctuations in the total evacuation time. The main reasons for this are as follows.

- High desired velocities lead to more clogs, and this results in a high evacuation time.
- As a result of the desires of the group members to move closer to each other, pedestrians may either backtrack or wait for the pedestrians who are not able to keep up with the other group members. These conclusions were reached by observing the animations of simulations.

This phenomenon, reproduced by our simulation model, turns out to be consistent with empirical observations in a previous study.[70]

On the other hand, debates on the existence of this phenomenon arise in the literature.[71–73] For example, Haghani et al[72] reviewed the prior work on this subject and performed an empirical experiment to investigate this phenomenon. Of all experiments, all show that faster escape does not increase evacuation time. Unlike it shortens the evacuation time for relatively large crowds, unless competition among people creates physical interactions and anyone shows aggressive drive. Based on their literature review and findings from their experiment, Haghani et al[72] conclude that the degree of physical pressure (like pushing or shoving) between the individuals in the crowd, the crowd density behind the bottleneck points, and the design of evacuation facilities may have a considerable impact on the occurrence of the phenomenon. Clearly, more research is needed to understand this phenomenon and the factors triggering it.

4.3 | Model validation

Remarkably, the reliability of results provided by pedestrian evacuation models depends on the validation undertaken. According to the Dridi,[74] there are two ways to validate these models: (1) comparison with validated models and (2) comparison with real-world experiments. Here, we chose to use the second approach, as it appears to be more reliable in practice.

Moreover, we must use a validation method to test whether our simulation model is accurate enough to describe pedestrian group behavior or not. One can classify the methods used in model validation into qualitative and quantitative.[75] The simplest method is qualitative validation; it aims to detect if the models reproduce certain phenomena without analytical quantification. On the contrary, quantitative validation uses analytical criteria to assess the outcomes of a simulation model. Quantitative methods can be classified as microscopic and macroscopic techniques.[76] Microscopic validation focuses on the individual pedestrian characteristics, such as walking speed and trajectories. On the other hand, macroscopic validation focuses on the aggregate behaviors of crowds. For example, it compares the average

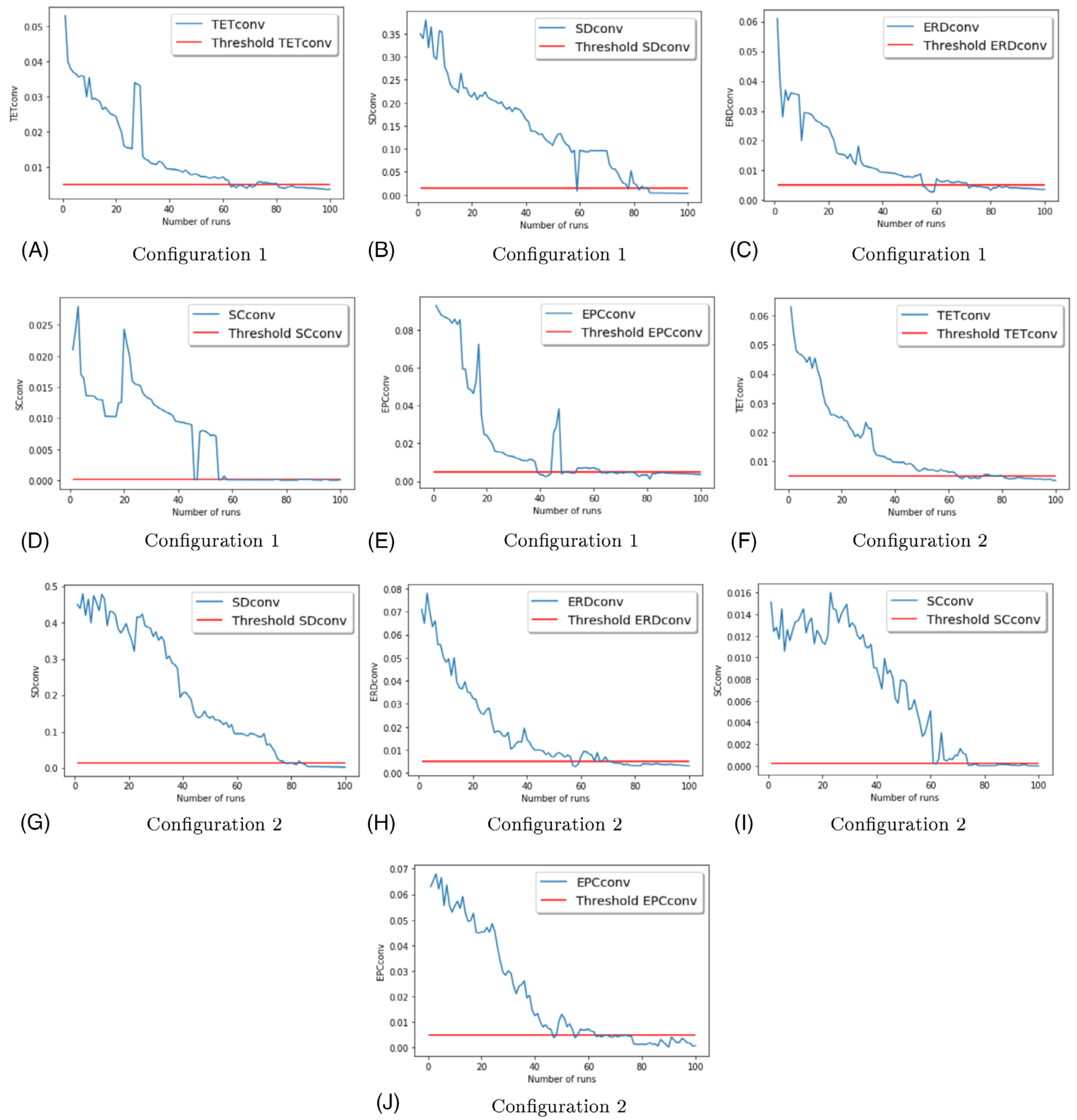

FIGURE 16 Variation of simulated TETconv, SDconv, ERDconv, SCconv, and EPCconv with an increasing number of runs for Configuration 1 and Configuration 2

evacuation time obtained from the simulation model with empirical data.[77] Here, we use a quantitative macroscopic validation procedure.

4.3.1 | Experimental data

Experimental data sets of von Krüchten and Schadschneider[51] were used for the validation of the model. They conducted some evacuation experiments to investigate the effect of social groups on an evacuation. The experiments were conducted using 54 different configurations. The configurations are categorized based on: (1) the exit door width, (2) the age of people, (3) the number of evacuated persons, (4) the presence of the leader, (5) the group size ranging between 1 and 8, and (6) the bond type (fixed or loose) between group members. All experiments were conducted in a room measuring 5×5 m^2. A representative snapshot of the simulation is shown in Figure 13. In this study, we aimed to model leader-centered and group-centered behavior. Therefore, we selected two configurations

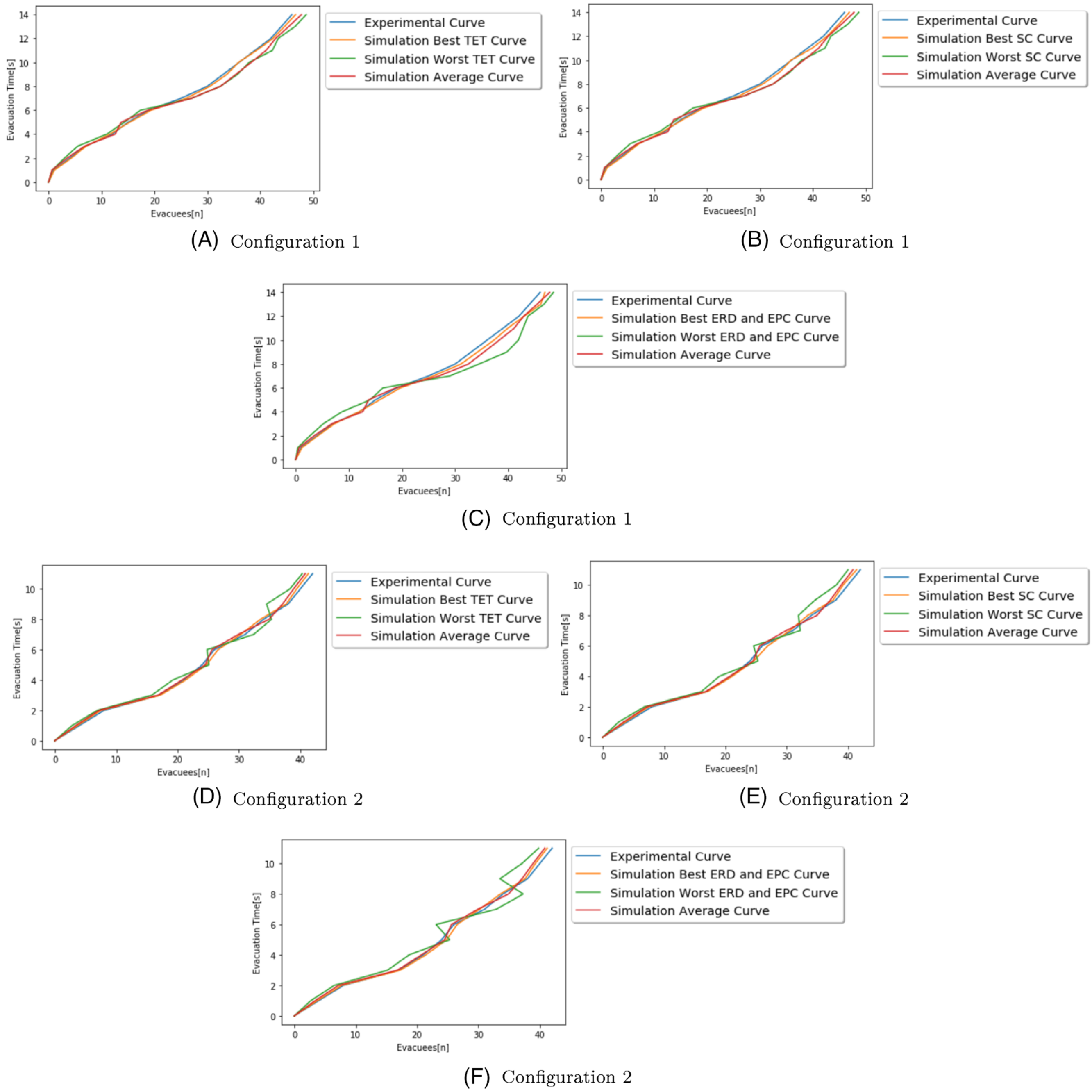

FIGURE 17 Comparison of the simulated average, best and worst (TET, ERD, EPC and SC) curves with the experimental average one for Configuration 1 and Configuration 2

that are compatible with these behaviors. These configurations are described in Table 5, where the columns of Table 5 represent the configuration elements of experiments previously mentioned in this section, respectively.

4.3.2 | Validation

The model was validated by the procedure of Lovreglio et al.[78] Full details of the procedure can be read in the paper. An overview of the procedure is given in Figure 14, where OCETs are the abbreviation for occupant-evacuation time curves; total evacuation time (TET) represents the average maximum evacuation time among several run times; SD represents the standard deviation of maximum evacuation time among several run times; ERD, EPC, and SC are three functional analysis operators, representing the differences between two time curves (time curve: evacuation times of evacuees in ascending order). From these, TETconvj, SDconvj, ERDconvj, EPCconvj, and SCconvj represent the convergence levels of the parameters. TRTET, TRSD, TRERD, TREPC, and TRSC are the corresponding thresholds

TABLE 6 Comparison measures (C1: Configuration 1, C2: Configuration 2)

Comparison criteria	Average	TET_{best}	TET_{worst}	ERD_{best}	ERD_{worst}	EPC_{best}	EPC_{worst}	SC_{best}	SC_{worst}
RD_{TET}^{C1}	0.2	0.02	0.39	0.12	0.31	0.12	0.31	0.14	0.25
ERD^{C1}	0.19	0.06	0.27	0.09	0.41	0.09	0.41	0.11	0.43
EPC^{C1}	0.85	1.1	0.76	1.2	0.68	1.2	0.68	1.3	0.72
SC^{C1}	0.92	1.1	0.82	1.2	0.85	1.2	0.88	1.25	0.74
$RunNumber^{C1}$	-	67	9	59	12	44	28	39	25
RD_{TET}^{C2}	0.25	0.03	0.43	0.16	0.40	0.16	0.40	0.14	0.25
ERD^{C2}	0.20	0.05	0.33	0.11	0.45	0.11	0.45	0.11	0.47
EPC^{C2}	0.75	1.3	0.81	1.35	0.72	1.35	0.72	1.3	0.72
SC^{C2}	0.87	1.3	0.86	1.35	0.91	1.35	0.91	1.28	0.83
$RunNumber^{C2}$	-	75	6	67	15	56	26	47	21

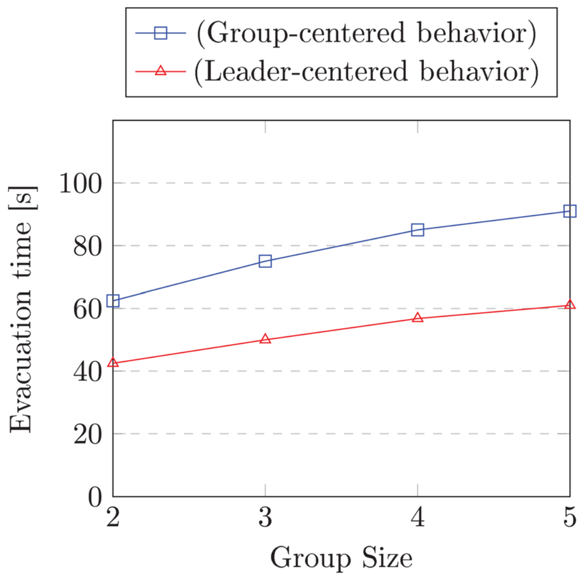

FIGURE 18 Comparison of group-centered behavior and leader-centered behavior

for the convergence levels. Equations (4a) and (4b) represent, respectively, the consecutive average ($\bar{TET}_j$) and standard deviations (S_j) of total evacuation times from different curves. Similarly, convergence measures ERDconvi, EPCconvj, and SCconvj are calculated through Equations (4c) to (4e).

$$TETconvj = \left|\frac{\bar{TET}_j - \bar{TET}_{j-1}}{\bar{TET}_j}\right|, \tag{4a}$$

$$SDconvj = \left|\frac{SD_j - SD_{j-1}}{SD_j}\right|, \tag{4b}$$

$$ERDconvj = |ERD_j - ERD_{j-1}|, \tag{4c}$$

$$EPCconvj = |EPC_j - EPC_{j-1}|, \tag{4d}$$

$$SCconvj = |SC_j - SC_{j-1}|. \tag{4e}$$

The three steps of the validation procedure were performed as follows:

- Step 1: In the first step, the corresponding experimental data were plotted in Figure 15. This plot is used for comparison in Step 3. Because each experiment was repeated once, we cannot present the convergence measure plots.
- Step 2: In the second step, a total of 100 simulations were run until the values of convergence parameters converged to the threshold values. We have used the parameter values suggested by the authors Lovreglio et al.[78] The suggested values of parameters as follows: $TR_{TET} = 0.005$; $TR_{ERD} = 0.005$; $TR_{EPC} = 0.005$; $TR_{SC} = 0.0002$, $s = 2$, $W = 10$. The times of convergence to the threshold for each performance measure are shown in Figure 16. Although the number of simulation runs required for the convergence of each measure are different, all of them were converged after 85th run. Therefore, we can conclude that our model meets the convergence measure criteria, suggesting the stability of the results.
- Step 3: In the last step, we compared the simulation results with experimental results using four comparison measures, that is, TET, EPC, ERD, and SC. The best and worst curves for these measures and simulated average curves are used for making the comparison (see Figure 17). The first three criteria compare the distance of two curves, while the last one (SC) compares the shape of two curves. Figure 17 gives us a preliminary idea about the differences between these curves. However, to more objectively quantify these differences, four comparison criteria, namely RD_{TET}, EPC, ERD, and SC, are used. Table 6 shows the quantified differences between experimental and simulated curves for these criteria. Galea et al[79] provided two types of thresholds-restrictive ($TV_{TET} \le 0.15$, $TV_{ERD} \le 0.25$, $0.8 \le TV_{EPC} \le 1.2$, $TV_{SC} \ge 0.8$) and less restrictive thresholds ($TV_{TET} \le 0.45$, $TV_{ERD} \le 0.45$,

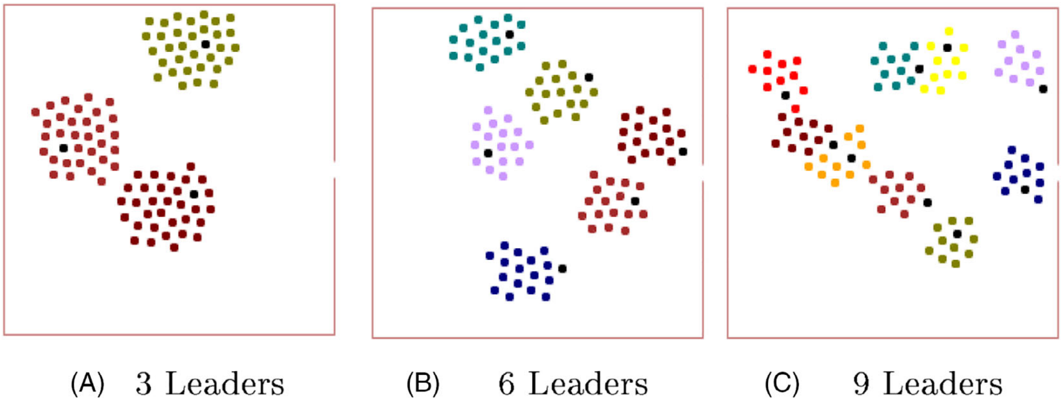

FIGURE 19 Snapshots of the pedestrians at 6.27, 5.70, and 3.90 seconds

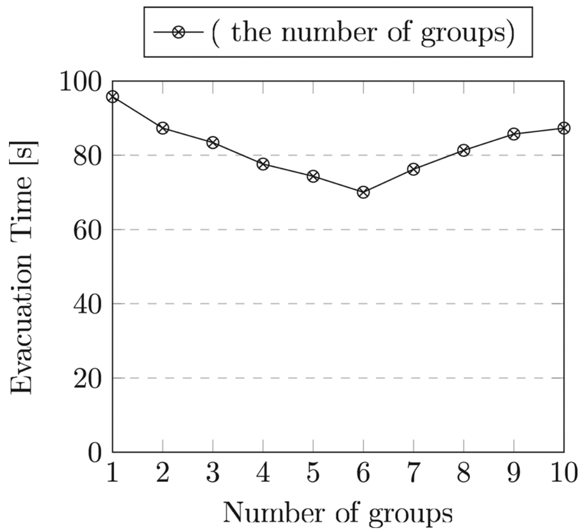

FIGURE 20 Relation between the number of groups (with a leader) and the evacuation time

$0.6 \leq TV_{EPC} \leq 1.4$, $TV_{SC} \geq 0.6$). Both threshold values were used to determine whether the values fall within the acceptable limits. For instance, TET_{best} value 0.02 (see Table 6), which is obtained in 67 simulation runs for Configuration 1, meets the restrictive threshold for the RD_{TET} criteria. The same interpretation can be made for other cells of Table 6. Hence, we conclude that all these values fall within acceptable limits of restrictive or less restrictive thresholds, which indicates the model is reliable in estimating the evacuation time. Here, we have performed a quantitative comparison of simulation and experiments. If we had data on multiple experimental occupant-evacuation times, we could also perform a statistical comparison of them. Moreover, we have used the exit flow rate for the validation of our model. Someone may argue that there could be other factors that have an impact on exit flow rate, such as congestion around the exits. However, congestion is not only a reason, but it is also a consequence of pedestrian conduct during evacuation. There can be several reasons for congestion around the exits, such as exit width, pedestrian density, etc.[80] We consider that group behavior is one more cause of the congestion at the exit, and it might delay the total evacuation. We can evaluate the influence of groups on the performance of crowd evacuation while keeping the other factors (exit width, pedestrian density, etc.) constant. Therefore, we could examine the exit flow rate for various group sizes or group structures (ie, leader-centered behavior and group-centered behavior) and assess how group behavior affects evacuation performance.

4.4 | Simulations

After the validation of our model, we conducted further simulations for exploring some elements that are considered to have significant effects on the evacuation time.

4.4.1 | Test case 1

The first simulation explores the effect of group-centered and leader-centered group behavior on the evacuation time. The simulations were conducted for a square-shaped configuration of a room with size (10×10 m^2). There is only one exit, with a width of 1 m. Small pedestrian groups were employed. The 100 pedestrians were divided into groups of sizes 2, 3, 4, and 5 when possible. Based on the results presented in Figure 18, it is clear that leader-centered groups perform better than group-centered behavior for small groups with respect to evacuation time. We can summarize the main reasons behind this: group-centered behavior causes the group members to move by thinking about the coherence of the group. This leads to a deceleration of the group members, and backtracking at exit points. On the other hand, the members of a leader-centered group just concentrate on the leader, and do not consider the coherence of the group.

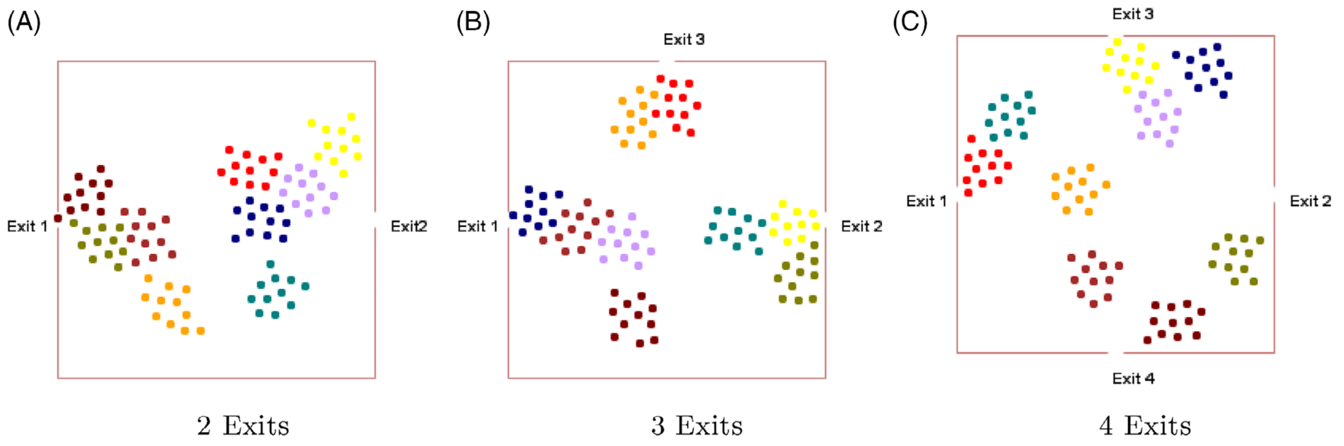

FIGURE 21 Snapshots of the pedestrians at 6.27, 5.70, and 3.90 seconds

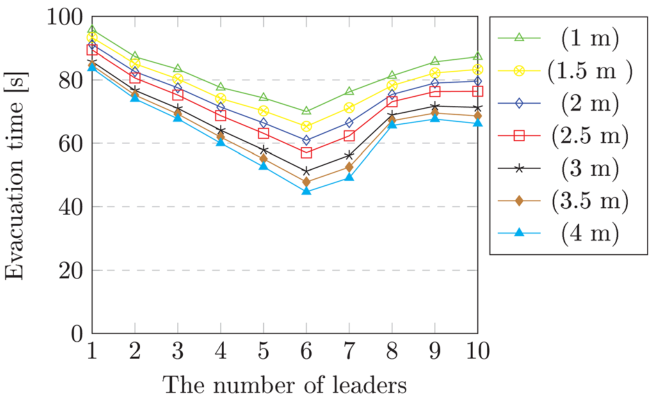

FIGURE 22 Relation between evacuation time and exit width

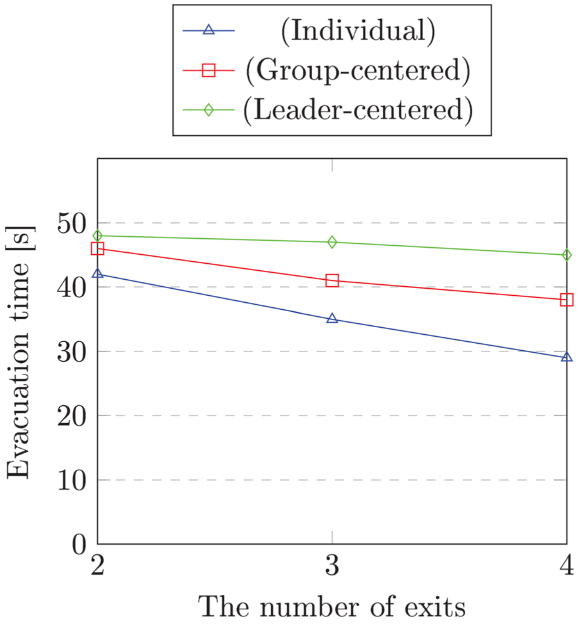

FIGURE 23 Comparison of three types of behavior

4.4.2 | Test case 2

The second simulation explores the relation between the number of leaders and the evacuation time. The setup is illustrated in Figure 19. To simplify the simulations, we assumed that each group has a single leader; hence, the number of leaders is the same as the number of groups. It is assumed that each group member either does not know where the exit is, or needs to keep close to the leader. So each group member follows its group leader. The same room configuration as in Test Case 1 was adopted, which contains 100 pedestrians. The simulation results show that an increase in the number of leaders reduces the evacuation time until the number of leaders reaches six but increases it afterward (see Figure 20). The smaller group force and the position of the leader may negatively affect the impact of the leader on the total evacuation time in the case when the group size is too large to be managed by one leader. On the other hand, the larger group force may increase the competition between groups in the event that two or more groups arrive in front of the exit at the same time. This shows us that the relation between the levels of within-group cooperation and between-group competition has an effect on the total evacuation time. The minimum evacuation time in this case is obtained when there are six leaders (six groups).

4.4.3 | Test case 3

The third simulation explores the effect of the number of leaders on the average evacuation time for different exit widths. The room configuration is the same as that used in the previous test cases. The 100 pedestrians were divided into approximately equal groups if possible, and one of them is selected as a leader. The setup is illustrated in Figure 21. The results are presented in Figure 22. The results show that the width of the door positively influences the evacuation time, but the size of this effect depends on the number of leaders. For instance, if the width of the door is changed from 1 to 4 m, the

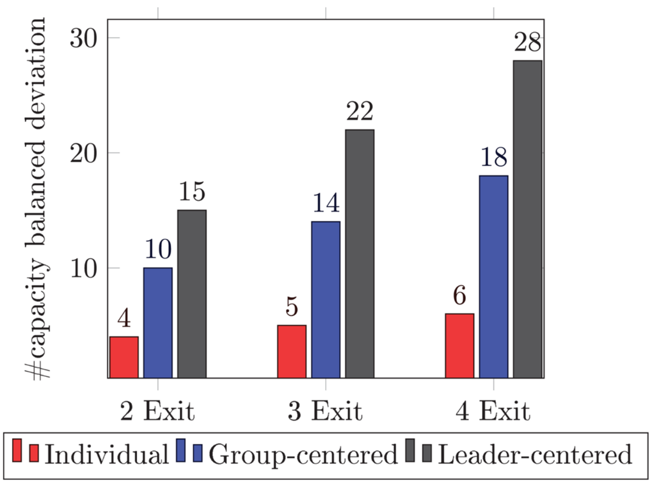

FIGURE 24 Comparison of capacity balanced deviation of three types of behavior

decrease in the evacuation time is greater for six leaders than one leader.

This is because when the number of leaders is small, it takes some time for the pedestrians around the leader to move out of the leader's field of vision and line up behind them to ensure a coordinated exit, and this increases the evacuation time. When the pedestrians reach the vicinity of the exit, the pedestrians tend to exhibit queuing behavior behind the leader. On the other hand, when the number of leaders (which also means the number of groups) is large, competition between the groups increases and this causes clogging around the exits.

4.4.4 | Test case 4

The setup in Figure 19 was designed to demonstrate the effect of individual, group-centered, and leader-centered behavior on the evacuation time and balanced usage of the exits' capacities. If the utilization ratio of each exit is the same, then we can say that it is a perfectly balanced usage of exit capacities. Otherwise, there is an imbalance among the utilizations of the exit capacities, which is called a deviation. To explain how to calculate this deviation, we give a simple example. For instance, if one exit's utilization ratio is 40% and another's is 60%, the deviation from balanced capacity is calculated as follows: $|60–50| + |40–50| = 20$ (in a perfectly balanced situation, the utilization ratio for each exit will be 50%). Unbalanced capacity usage causes idle capacity or overcapacity.

We used the same room configuration as in the previous test cases. Pedestrian exit choice decision for each behavior type is as follows: In individual behavior, each person selects the closest exit to himself in its field of view. In leader-centered behavior, the leader selects the exit, which is closest to himself in its field of view, and all group members follow the leader. On the other hand, in group-centered behavior, each group member moves to the exit, which is the closest to the center of the group and leaves the room using this exit. We conducted the experiments for different group sizes, varying between 4 and 10. The average evacuation times were obtained by averaging the results of the evacuation time of each group size (see Figure 23). Also, the quantities for unbalanced capacity usage were averaged. The balanced capacity deviation is presented in Figure 24. According to the results, while individual behavior is the most effective type of behavior for minimizing the deviations from the balanced usage of the exits' capacities, leader-centered behavior is the least effective type. One leader may not guide each member of the group to the exit that provides them with the quickest escape and may direct the entire group to the exit nearest to them. For this reason, leader-centered behavior causes the non-use of some exits and unbalanced usage of the exits and long evacuation times. Also, group-centered behavior can cause unbalanced usage of the exits when the groups are large. Let us consider a group of 20 in a room with four exits. Suppose, for example, the closest exit to the center of the group is Exit 2, but five members of the group are closer to Exit 4. Despite this, all group members select Exit 2, to maintain the group's coherence. This causes an unbalanced usage of the exits and long evacuation times in a similar way to leader-centered behavior.

5 | CONCLUSIONS

To model group behavior in pedestrian crowds is important. Because the pedestrians tend to move together with other people in open public spaces, such as a hospital, school, shopping center, stadium, or warehouse, the design of these areas clearly affects their evacuation time.

One of the fundamental research questions of this study is how groups of different sizes are formed in simulation models to evaluate group behavior. Most of the previous studies about group behavior primarily concentrate on small groups and do not provide a thorough approach for forming pedestrian groups in the simulation setting. We obtained a procedure to group pedestrians in the simulation environment by blending the research on pedestrian groups from the literature. Our approach facilitates the formation of pedestrian groups of differing sizes in a simulation model. Moreover, the majority of the previous studies focus on pedestrian group behavior in normal situations. But the responses of people when they are aware of the emergency are not the same as how they react in a normal situation. This study utilizes the SFM form that has been developed for emergency cases to address the issue appropriately. Also, this study tackles different kinds of group behavior, namely, single leader-centered, and group-centered. To our best knowledge, this is the first paper to focus on leader-centered behavior and group-centered behavior. We modified that version of the SFM model with the new forces to include these behaviors.

Another research problem of this study is how to modify SFM to obtain a valid pedestrian group behavior model for crowd evacuations. It should be noted that some of the models used in the literature have not been verified and validated. However, the accuracy and reliability of crowd dynamics models depend on the process of their verification and validation. Therefore, first, the proposed model is verified by checking the appearance of emergent phenomena. And then, the proposed model is validated using a systematic validation methodology through a comparison with available experimental data obtained from the literature. We have done a macroscopic quantitative validation with a systematic validation method. However, a microscopic validation of the model has not been carried out due to the lack of adequate experimental data. Therefore, experimental research is needed to prove the accuracy of our model predictions at the microscopic level.

The last research question is on how group-centered behavior differs from leader-centered behavior in terms of crowd evacuations. Therefore, the effect of leader-centered and group-centered behavior on evacuation efficiency is investigated for the different configurations of the environments after verification and validation of the model. The results are useful in understanding the potential disadvantages and advantages of these behaviors regarding the evacuation environment. The results of the experiments are summarized as follows: (1) leader-centered groups perform better than group-centered behavior for small groups in terms of evacuation time; (2) an increase in the number of leaders reduces the evacuation time to some extent; (3) the width of the door positively influences the evacuation time, but the size of this effect depends on the number of leaders. For example, if the width of the door is changed from 1 to 4 m, the decrease in evacuation time for six leaders is larger than that of one leader; (4) group-centered behavior results in less evacuation time than leader-centered behavior in the presence of multiple exits, and leader-centered behavior causes a more unbalanced use of the exits than group-centered behavior.

It must be noted that the results of the experiments may be specific to the characteristics of the experiments, for example, the room configuration, so results may not be generalizable to all evacuation situations. However, the proposed model can be used as a tool to contribute to the division of the pedestrians into groups in terms of minimizing the evacuation time during a coordinated evacuation of these areas, because the results of the experiments demonstrate that the number of groups or leaders affects the evacuation time. For example, in a museum tour for kids, the kids can be split into groups in such a way that the evacuation time is minimized in the event of an emergency. On the other hand, crowd managers can use the findings of the study to establish control over the crowd. For example, in a wedding venue, most of the guests are not familiar with the building and may not be able to leave the building quickly and safely. The findings of the study provide some insight into allocating the tasks to the personnel to guide the crowd to the exit safely.

Although we have reached some important conclusions, there are still some limitations of this study. In this paper, the dynamic pedestrian groups are not considered. Further, the effect that various leadership styles have on the evacuation dynamic still needs more research. Also, more empirical studies into pedestrian group behavior are required to gather further evidence. We believe that these limitations can be overcome with additional research. In future studies, the following unanswered questions could be studied: (1) How do evacuation dynamics change in the presence of more than one leader in a group? (2) What is the effect of different types of a leader on the evacuation dynamics?

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

ORCID

Yakup Turgut https://orcid.org/0000-0001-6485-373X
Cafer Erhan Bozdag https://orcid.org/0000-0003-4522-9071

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APPENDIX: SOCIAL FORCE MODEL

A social force model (SFM) is a forced-based pedestrian motion model. It is based on Newton's second law. According to Newton's second law, objects are accelerated by the forces acting on them. Equation (A1) describes the relation between acceleration and force, where m is the mass of the object, $\vec{F}(t)$ is the net force on the object, and $\vec{a}$ is the acceleration of the object.

$$\vec{F}(t) = m\vec{a}. \tag{A1}$$

There are three different versions of SFM in the literature, proposed by Helbing and Molnar.[11,33,57] Despite their differences in formulation, all versions describe the pedestrian motion as based on three forces: (1) the driving force, (2) the repulsive forces, and (3) the attractive forces. Figure A1 illustrates the driving force, and the repulsive forces applied by the pedestrians in green and by the wall on the pedestrians in red. The driving force reflects the desire of pedestrians to reach a destination point. It enables pedestrians to reach their specific destination points with a certain desired speed. The repulsive forces can be separated into two types: internal repulsive forces and external repulsive forces. The internal repulsive forces, which are not real physical forces, describe the human desire to keep some distance from other pedestrians or borders. On the other hand, the external forces, which are real physical and frictional forces, act on pedestrians when pedestrians have physical contact with other pedestrians or borders. There has been a lot of criticism of SFM, and some extensions of SFM have been proposed to improve its deficiencies.[81–86] In the present study, the formulation, which given in Reference 11, is used because it deals with the behavior of pedestrians in an emergency.

Equation (A2a) describes the driving force $\vec{F}_\alpha^{\text{driving}}$ of pedestrian α, where Equations (A2b), (A2c), and (A2d) detail Equation (A2a). Equation (A2b) indicates that the desired speed of a pedestrian may change, depending on the level of urgency, and the pushy behavior that pedestrians have in an emergency situation. Equation (A2c) implies that the desired speed of the pedestrians changes depending on their waiting time. The desired direction of pedestrian α is described in Equation (A2d), where $\left\|\vec{d} - \vec{x}(t)\right\|$ denotes the distance between the center of mass of pedestrian α and the destination point of pedestrian α. The explanation of the parameters (P) and variables (V) of the driving force formulation is presented in Table A1.

$$\vec{F}_\alpha^{\text{driving}}(t) = m_\alpha \frac{v_\alpha^0(0)\vec{e}_\alpha(t) - \vec{v}_\alpha(t)}{\tau_\alpha}, \tag{A2a}$$

$$v_\alpha^0(t) = [1 - n_\alpha(t)]v_\alpha^0 + n_\alpha(t)v_\alpha^{\max}, \tag{A2b}$$

$$n_\alpha(t) = 1 - \frac{\bar{v}_\alpha(t)}{v_\alpha^0(0)}, \tag{A2c}$$

$$\vec{e}_\alpha(t) = \frac{\vec{d}_\alpha - \vec{x}(t)}{\left\|\vec{d}_\alpha - \vec{x}(t)\right\|}. \tag{A2d}$$

Equation (A3) describes the internal repulsive forces $\vec{F}_{\alpha\beta}^{\text{internal}}(t)$ between pedestrian α and β at time t. Here, $\lambda_i \in [0, 1]$ represents the effect of the anisotropic characteristic of the pedestrians' field vision on the motion. This anisotropy implies that the humans mostly react to the pedestrians who are standing in front of them rather than

TABLE A1 Driving force formulation terminology

P/V	Explanation
$v_\alpha^0(0)$	Desired speed of pedestrian α at time 0
$v_\alpha^0(t)$	Desired speed of pedestrian α at time t
$\bar{v}_\alpha(t)$	Average speed of pedestrian α in the desired direction of motion
$n_\alpha(t)$	Impatience level of pedestrian α at time t
v_α^{max}	Maximum desired velocity of pedestrian α
$v_\alpha(t)$	The velocity of pedestrian α at time t
m_α	The mass of pedestrian α
$\vec{e}_\alpha(t)$	Direction vector of pedestrian α at time t
τ_α	Relaxation time
d_α	Destination point of pedestrian α
$\vec{x}(t)$	The position of pedestrian α at time t

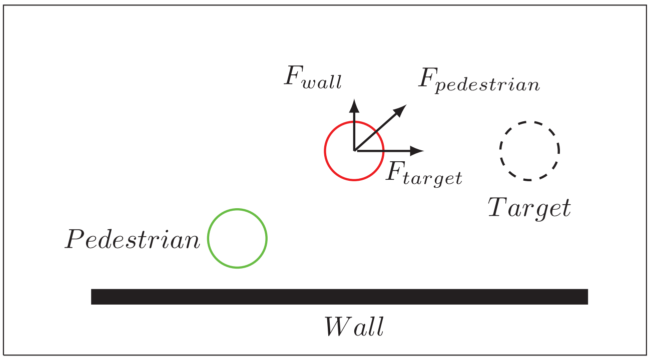

FIGURE A1 Social force model

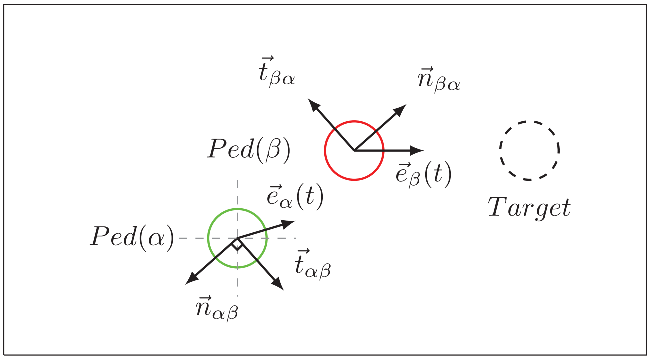

FIGURE A2 Relation between normalized vector and tangent vector

TABLE A2 Repulsive force formulation terminology

P/V	Explanation
A_α	The interaction strength of pedestrian α
B_α	The range of the repulsive interactions
r_α	The radius of pedestrian α
$\vec{n}_{\alpha\beta}$	The normalized vector pointing from pedestrian β to α
$\vec{n}_{\alpha w}$	The normalized vector pointing from border w to pedestrian α
$r_{\alpha\beta}$	The sum of radii of pedestrian α and β
$d_{\alpha\beta}$	The distance between the centers of mass of pedestrian α and β
$d_{\alpha w}$	Distance from pedestrian α to boundary w
λ_α	Anisotropic character of pedestrian α
$\vec{v}_\alpha(t)$	The velocity of pedestrian α at time t
$\vec{v}_\beta(t)$	The velocity of pedestrian β at time t
C_1	Constant
C_2	Constant
$\vec{t}_{\alpha\beta}$	The direction tangential to $\vec{n}_{\alpha\beta}$
$\vec{t}_{\alpha w}$	The direction tangential to $\vec{n}_{\alpha w}$
$\varphi_{\alpha\beta}$	The angle between the directions of motion of pedestrians α and β
$\vec{x}_\alpha$	The position of pedestrian α in two dimensions
$\vec{x}_\beta$	The position of pedestrian β in two dimensions
$\xi(t)$	The noise term

behind them, where $\lambda_i = 0$ means that the humans will be affected by pedestrians who are located in the direction in which they are looking. Equation (A5) describes the internal repulsive forces $\vec{F}_{\alpha w}^{\text{internal}}(t)$ between pedestrian α and the border w. Equation (A6) gives the formulation for $n_{\alpha\beta}(t)$.

$$\vec{F}_{\alpha\beta}^{\text{internal}}(t) = A_\alpha \exp\left[\frac{r_{\alpha\beta}-d_{\alpha\beta}}{B_\alpha}\right]\vec{n}_{\alpha\beta}\left(\lambda_\alpha + (1-\lambda_\alpha)\frac{(1+\cos(\varphi_{\alpha\beta}))}{2}\right), \tag{A3}$$

$$\cos(\varphi_{\alpha\beta}) = -\vec{n}_{\alpha\beta}\vec{e}_\alpha(t), \tag{A4}$$

$$\vec{F}_{\alpha w}^{\text{internal}}(t) = A_\alpha \exp\left[\frac{r_\alpha - d_{\alpha w}}{B_\alpha}\right]\vec{n}_{\alpha w}, \tag{A5}$$

$$\vec{n}_{\alpha\beta} = \left(\vec{x}_\alpha - \vec{x}_\beta\right)/d_{\alpha\beta}. \tag{A6}$$

Equation (A7a) describes the external repulsive forces $\vec{F}_{\alpha\beta}^{\text{external}}$ between pedestrian α and pedestrian β. Equations (A7b) and (A7c) detail Equation (A7a). $\triangle v_{\beta\alpha}^t$ indicates the tangential velocity difference. The explanation of the parameters (P) and variables (V) used in the internal repulsive force and the external repulsive formulation is presented in Table A2. $H(y)$ is a piecewise function defined in Equation (A7b). Figure A2 illustrates the relation between $\vec{t}_{\alpha\beta}$ and $\vec{n}_{\alpha\beta}$. Equation (A8a) describes the external repulsive forces $\vec{F}_{\alpha w}^{\text{external}}$ between pedestrian α and the wall and Equation (A8b) gives the tangential velocity difference for the walls (boundaries). The term $\xi(t)$ in Equation (A9) stands for the randomness or uncertainty in the motions of pedestrians, in other words, it represents the behavior of the pedestrian that cannot be explained by the model.

$$\vec{F}_{\alpha\beta}^{\text{external}} = C_1 H(r_{\alpha\beta} - d_{\alpha\beta})\vec{n}_{\alpha\beta} + C_2 H(r_{\alpha\beta} - d_{\alpha\beta}) \triangle v_{\beta\alpha}^t \vec{t}_{\alpha\beta}, \tag{A7a}$$

$$H(y) = \begin{cases} 0 & y < 0 \\ y & y \geq 0 \end{cases}, \tag{A7b}$$

$$\triangle v_{\beta\alpha}^t = \left(\vec{v}_\beta(t) - \vec{v}_\alpha(t)\right)\vec{t}_{\alpha\beta}, \tag{A7c}$$

$$\vec{F}_{\alpha w}^{\text{external}} = C_1 H(r_\alpha - d_{\alpha w})\vec{n}_{\alpha w} - C_2 H(r_\alpha - d_{\alpha w}) \triangle v_{\alpha w}^t \vec{t}_{\alpha w}, \tag{A8a}$$

$$\triangle v_{\alpha w}^t = \vec{v}_\alpha(t)\vec{t}_{\alpha w}, \tag{A8b}$$

$$\vec{f}_\alpha^{\text{total}}(t) = \vec{F}_\alpha^{\text{driving}} + \sum_\beta \vec{F}_{\alpha\beta}^{\text{repulsive}}(t) + \sum_W \vec{F}_{\alpha W}^{\text{repulsive}}(t) + \sum_\beta \vec{F}_{\alpha\beta}^{\text{attractive}}(t) + \xi(t). \tag{A9}$$