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Entropy-Based Crowd Evacuation Modeling With Seeking Behavior of Social Groups

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ABSTRACT Emergency crowd evacuation, especially in congested indoor scenes, is an important issue in public areas' daily management. Computer simulation is a widely adopted technique to study crowd evacuations and help design reasonable emergence plans due to its flexibility, convenience, and cost-effectiveness. In this paper, we propose ECEM, a novel evacuation model based on agent simulation. In ECEM, we consider a special individual behavior in the evacuation, called seeking behavior, which happens when relatives or friends (i.e., social groups) are in the crowd, and the members within a group may tend to seek each other once separated instead of evacuating alone. Moreover, we incorporate the crowd chaos based on Boltzmann entropy (i.e., crowd entropy) into ECEM to measure the evacuating population's disorder level and present an adaptive velocity smoothing method using crowd entropy for updating individual's velocity. Extensive simulation results demonstrate the effectiveness of ECEM and provide several insights on designing the evacuation strategies.

INDEX TERMS Crowd evacuation, seeking behavior, Boltzmann entropy, social groups.

I. INTRODUCTION

Crowd evacuation caused by emergencies in congested indoor scenes is an important issue that is considered in the design of large buildings and the daily management of public areas. However, due to the limitation of practical exercises and the lack of experience data on the evacuation population, computer simulation is widely adopted for studying emergency crowd evacuations and helping design reasonable emergence plans [1]–[6].

Generally, simulation-based evacuation models can be classified into two categories [7]. One category is the macroscopic evacuation model, including gas-kinetic model, route-choice model, and queuing model, which treats the population as a homogeneous flow [8], [9] and is efficient for large-scale crowd evacuation simulations. However, this kind of method does not consider individual behavior characteristics, thus usually not comply with the actual situations [10], [11]. The other category is the microscopic evacuation model, which enhances the understanding of the evacuating population's dynamic evolution by analyzing individual behaviors, such as age, gender, walking speeds, physical abilities, panic emotions, social relations, environmental perception, decision-making processes, etc. Existing microscopic evacuation models mainly based on three frameworks: cellular automaton (CA) [12]–[14], social force (SF) [15]–[17], and agent-based simulation (ABS) [18]–[23]. Unfortunately, these frameworks have several limitations. First, the CA models assume that a person in a grid (where the evacuation scene is partitioned into a set of grids) can only be influenced by the persons in the adjacent grids, which is not satisfied in the real-world scenarios since a person may be affected by anything in her visual field. Second, the SF-based models treat the relationship between individual perceptions (e.g., noticing a person ahead) and reactions (e.g., avoid collisions) as a static force, overlooking that individual may adaptively make decisions based on personal strategies. Third, the ABS models can provide a flexible simulation based on individual behaviors comparing to the former two frameworks [6], but existing solutions mainly consider the basic behaviors, such as escaping from the exit and avoiding collision, which may be insufficient in some special scenarios, e.g., there are a number of social groups (such as relatives or friends) in the evacuating population.

In this paper, we follow the general agent-based simulation framework and study an essential individual behavior under this framework, called *seeking behavior*, when social groups are in the crowd. Though several existing works [24]–[29]

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consider social groups in the evacuation process, they mainly treat the companions (or members) in a group as a whole (e.g., an agent with a larger radius) and assume the companions always stay together during evacuation. However, this kind of assumption may not be reasonable in practice. Instead, the companions may want to keep a close distance from each other and seek each other once separated. For example, a mother would be more likely to seek her child when the child is far away from her or invisible in her visual field. The seeking behavior brings new challenges for designing an evacuation model, such as importing more randomness and making the evacuation more chaotic. To address these issues, we propose an Entropy-based Crowd Evacuation Model, called ECEM, to evaluate the influence of the seeking behavior within social groups in the crowd evacuation. Our approach has two main novelties. First, based on the agent-based simulation, we define the movement rules for individuals to search their companions according to the characteristics of evacuation behaviors. Second, we incorporate the Boltzmann entropy to measure the chaos degree of the crowd and use the entropy as an update factor to illustrate the effect of chaos on individuals' velocities. Specifically, we make the following contributions:

- We propose an evacuation model that incorporates the seeking behavior and three basic behaviors (including exit behavior, avoidance behavior, and cohesion behavior). An individual's movement is determined by the aggregation of these behaviors, which is more consistent with realistic scenarios.
- We integrate the crowd chaos based on Boltzmann entropy into the proposed model to measure the evacuating population's disorder level and present an adaptive velocity smoothing method for updating individual's velocity. This method enables us to better simulate the behaviors in the emergence of evacuation.
- We implement ECEM and conduct extensive evaluations on the proposed model. The simulation results demonstrate our model's effectiveness and provide several insights on how to design appropriate evacuation strategies.

The rest of this paper is organized as follows. Section II introduces the related work. Section III presents the proposed ECEM algorithm. Section IV demonstrates the effectiveness of the proposed evacuation model by simulation experiments. The conclusions is described in Section V.

II. RELATED WORK

A. EVACUATION WITH SOCIAL GROUPS

The evacuation models with social groups can be categorized into two methods: real-life experiments [30]–[34] and model simulation [24]–[29]. The real-life experiments [30]–[34] focus on discovering intrinsic laws from actual phenomena, and these findings are important references for evacuation modeling. However, this method is cost-expensive, and usually it is difficult to collect sufficient data of the evacuating population. On the contrary, the simulation-based method is convenient and flexible, thus is widely adopted. [24] analyzes the influence of social groups with various sizes and shapes on the evacuation efficiency based on the CA technique. [25] proposes an extended floor field CA model and finds that the total evacuation time increases significantly with the existence of social groups in the crowd. Similarly, [26] proposed a CA model to simulate the behavior of relatives in crowd evacuation. Moreover, [27], [28] describe social groups' behavior through a group attractiveness force based on the SF technique. [29] designs an agent-based evacuation model to simulate the influence of social relations on the behavior and decision-making of evacuees during a fire evacuation scenario.

Though existing evacuation models consider the social groups, they treat a social group as a particle with a larger radius than the standard individual and assume that group companions always stay together during evacuation. This assumption is relatively strong because it is often challenging to guarantee that they are not separated in the real-world emergence of evacuations. In particular, if the companions are relatives or friends, they tend to seek each other first once separated. Our evacuation model focuses on this seeking behavior within social groups in the evacuation process; thus, it is more consistent with realistic scenarios. Besides, we further explore the effect of the seeking behavior on the crowd's chaos degree as well as the evacuation efficiency.

B. BOIDS MODEL

The BOIDS model was first proposed in [35], which describes the birds' flocking phenomenon through three basic rules: cohesion, collision avoidance, and alignment. Due to the ability of BOIDS to express grouping behaviors [36]–[38], several following works [39], [40] explore its usage in the simulations of crowd evacuation. [39] proposes a variant of BOIDS model using an improved collision avoidance rule to solve the problem that agents in the evacuation may overlap with others. [40] focuses on the study of crowd grouping behaviors based on the BOIDS model and the social force technique. However, in these models, the rules of individuals are the same, and the existence of social groups is not considered. Thus, they are not applicable to our problem. Inspired by the BOIDS model, our evacuation model uses its cohesion and avoidance rules and invents a rule for the seeking behavior in the considered evacuation scenarios.

C. CROWD ENTROPY

Crowd chaos is one of the critical causes of crowd accidents in the evacuation. Nevertheless, existing works related to crowd state mainly focus on the anomaly recognition and detection in videos surveillance [40], [41]. Entropy, a classic concept for measuring the state of a system in thermodynamics and informatics, is usually applied to quantitatively interpret the crowd state. For example, [42], [43] establish crowd entropy models to analyze the degree of crowd aggregation. They show that the larger the entropy is, the more obvious the crowd gathering. Meanwhile, [44] proposes an agent-based entropy model to interpret the heterogeneity of the crowd, and [45] describes the instability of crowd movement by calculating the information entropy of the velocity direction.

Given the similarity between crowd movement and particle thermal movement, [46] introduces Boltzmann entropy to detect abnormal crowd behavior. Also, [47] discusses the limitation of information entropy; that is, it only considers the distribution probability but ignores the number of people participating in the crowd movement. In this paper, we utilize the Boltzmann entropy to describe the crowd chaos (i.e., crowd entropy) during evacuation and propose an adaptive velocity smoothing method for individuals based on the calculated crowd entropy.

III. ECEM MODEL

To better understand how the seeking behavior of social groups affect the evacuation process, we propose ECEM, an entropy-based crowd evacuation model. In particular, we adopt the rule-based multi-agent simulation method, similar to [48], where each agent (i.e., individual) is assumed to be a circular particle with a specific diameter and is given various attributes (e.g., velocity, visual field, etc.) for the simulation. In each iteration of the evacuation process, each agent moves according to a velocity until leaving the exit.

Figure 1 gives an overview of ECEM. After initialization, we iteratively compute the following steps for each agent that does not leave the exit. First, we calculate several velocity components of the agent in the current iteration. The required velocity components for agents are different according to whether an agent is going to seek its companions. The velocity components and velocity calculation will be proposed in Section III-A and III-B, respectively. Second, we execute an adaptive velocity smoothing step to incorporate crowd chaos (i.e., the evacuating agents' disorder level) into evacuation, making the evacuation model more consistent with realistic scenarios. This step will be presented in Section III-C. Third, we compute an additional velocity correction step, as will be described in Section III-D, to prevent the agents from overlapping with each other or colliding with obstacles. Finally, we update the agents' positions and check if the evacuation is finished. The process ends when all the agents leave the exit. Algorithm 1 presents the ECEM simulation algorithm, and the detailed constructions will be introduced in the following subsequent subsections.

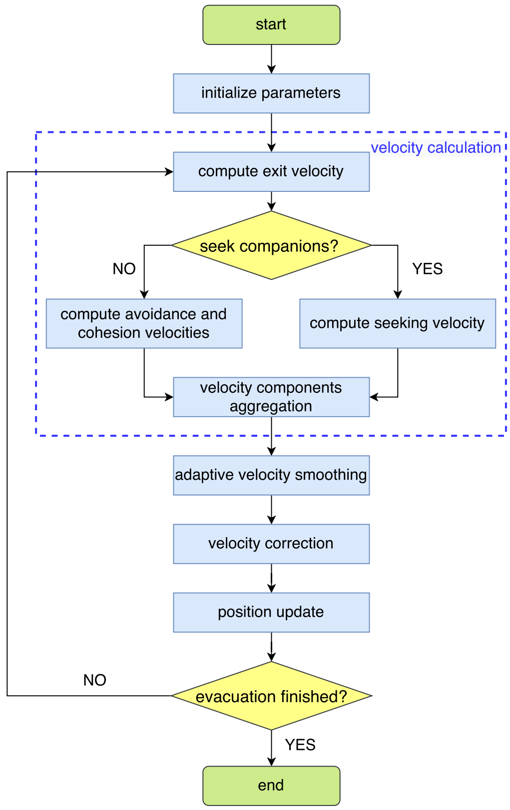


FIGURE 1. The workflow of ECEM algorithm.

A. VELOCITY COMPONENTS

In ECEM, we consider two types of agents in our model. One is the individual agent who evacuates alone. The other is the agent in a social group who may seek its companion(s) under specific circumstances, which we will discuss shortly. There are four velocity components for an agent, including exit velocity, avoidance velocity, cohesion velocity, and seeking velocity. Now we describe the meaning of each velocity.

1) EXIT VELOCITY

This velocity refers to an agent's behavior moving toward the exit or the direction closest to the exit within its visual field. In the evacuation process, especially in indoor scenes with no obstacles or few obstacles, the agents usually have a relatively reliable short-term memory of the exit direction. Once the evacuation begins, agents can move in the direction of the exit according to memory. Inspired by the static field of the cellular automata evacuation model [49], in ECEM, we discretize the evacuation scene into a set of unit grids and define the *escape field value* of a grid as the distance from the center of that grid to the center of the exit. As a result, based on whether the exit is visible, an agent's exit velocity is either toward the exit or the grid with the smallest escape field value in its visual field.

2) AVOIDANCE VELOCITY

This velocity represents the behavior of avoiding obstacles (e.g., walls) and preventing them from colliding with other agents (especially when the population density is high). Therefore, when there are obstacles (or other agents) in an agent's visual field and the distance to the obstacles (or other agents) is less than a comfortable distance, the agent will tend to stay away from them to avoid colliding or overlapping.

Algorithm 1: ECEM Simulation Algorithm

```
initialize simulation parameters;
while not all agents leave the exit do
    compute exit velocity Eqn (1);
    if no seeking behavior then
        compute avoidance velocity Eqn (2);
        compute cohesion velocity Eqn (3);
    else
        compute seeking velocity Eqn (4);
    end
    compute velocity increment Eqn (5);
    compute entropy in each agent's vision field Eqn (6);
    compute smoothed velocity Eqn (7);
    velocity correction to avoid overlapping;
    update each agent's position based on velocity;
end while
```

3) COHESION VELOCITY

As described in [50], agents tend to gather and follow the crowd during evacuation. Thus, we use this velocity to reflect self-organizing cohesion behavior. In particular, we assume that the agents are inclined to move to the crowd's average position in their visual fields.

4) SEEKING VELOCITY

Since we consider social groups' seeking behavior in our model, we define a seeking velocity when an agent is looking for its companion(s). In this paper, we assume that an agent has at most one companion for simplicity. However, the situation that an agent has multiple companions can be easily generalized. Specifically, when the distance between an agent and its companion in a social group exceeds a certain threshold, the agent would seek its companion instead of directly escaping toward the exit. In ECEM, each agent keeps observing and recording the position of its companion while evacuating. We define three rules of an agent's seeking behavior, including:

- if the distance from its companion is no larger than a comfortable distance, the agent will not search for the companion, and the velocity calculation is the same as that of an individual agent;
- if the distance is greater than the comfortable distance but does not exceed the agent's visual field, the agent will tend to move towards its companion;
- if its companion is not visible, the agent will search for its companion according to the last position of the companion it records, and if the agent has already arrived that position but still cannot find its companion, it will search randomly.

Before moving to a new position, an agent needs to determine its desired moving velocity (i.e., speed and direction) through the above behaviors. As illustrated in Figure 1, if an agent does not seek its companion, we compute the exit velocity, avoidance velocity, and cohesion velocity for the agent; otherwise, we compute the exit velocity and seeking velocity. In the following subsections, we present how to calculate these velocity components of an agent in ECEM.

B. VELOCITY CALCULATION

Let $\{\boldsymbol{v}_i, \boldsymbol{p}_i, e_i, C_i, P_i^C\}$ be the attributes of an agent A_i in the evacuation, where $\boldsymbol{v}_i$ denotes its velocity vector, $\boldsymbol{p}_i$ is its current position, e_i is the crowd entropy within its visual field (will be discussed in Section III-C), C_i is the set of its companions ($C_i = \varnothing$ if it has no companion), and P_i^C is the historical positions of its companions. Besides, we denote the vision radius of every agent as r_{vision}, and the corresponding visual field is a fan-shaped area (e.g., with 200 degrees). Figure 2 illustrates the visual field of an agent, where the black squares are obstacles. Therefore, the gray areas are invisible to the agent.

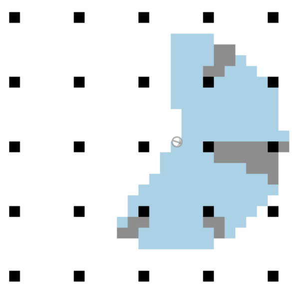


FIGURE 2. The illustration of an agent's visual field.

Note that we assume that an agent has at most one companion (see Section III-A), thus, we let A_j be the companion of A_i if $C_i \neq \varnothing$, $\boldsymbol{p}_j$ be the current position, and $\boldsymbol{p}_j^h$ be the historical position of A_j, respectively. In addition, let r_{ease} be the comfortable distance of agents. There are two cases according to whether the seeking behavior is activated.

First, if A_i has no companion or the distance between A_i and its companion A_j is less than r_{ease}, then velocity increment $\Delta\boldsymbol{v}_i$ is calculated according to the exit velocity, avoidance velocity, and cohesion velocity. Specifically,

1) For exit velocity, if the exit is invisible, A_i's moving target is the grid with the smallest escape field value in its visual field; otherwise, the target is the nearest exit grid from its current position $\boldsymbol{p}_i$. Let the moving target's position be $\boldsymbol{p}_{\text{goal}}$, then A_i's exit velocity is:

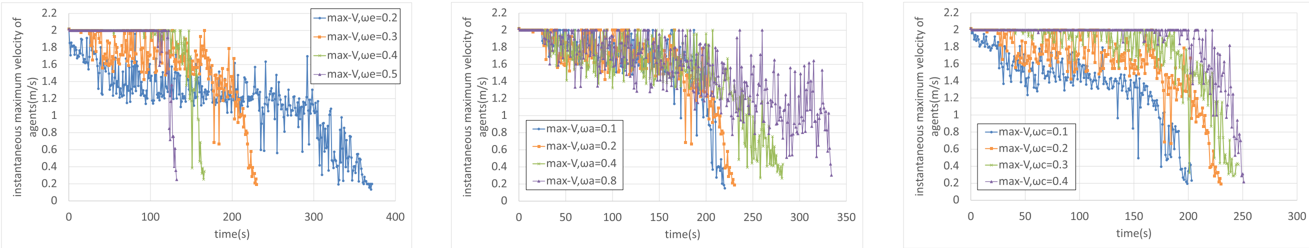
$$\boldsymbol{v}_i^e = \boldsymbol{p}_{\text{goal}} - \boldsymbol{p}_i \tag{1}$$

2) For avoidance velocity, let $\boldsymbol{p}_a$ and $\boldsymbol{p}_o$ be the nearest agent and the nearest obstacle within A_i's comfortable distance r_{ease}, then we have:

$$\boldsymbol{v}_i^a = (\boldsymbol{p}_i - \boldsymbol{p}_a) + (\boldsymbol{p}_i - \boldsymbol{p}_o) \tag{2}$$

3) For cohesion velocity, let $\boldsymbol{p}_{\text{crowd}}$ be the average position of the crowds within A_i's visual field, then we have:

$$\boldsymbol{v}_i^c = \boldsymbol{p}_{\text{crowd}} - \boldsymbol{p}_i \tag{3}$$



(a) Instantaneous maximum speed of the evacuation crowd with different w_e when $w_a = 0.2$ and $w_c = 0.2$

(b) Instantaneous maximum speed of the evacuation crowd with different w_a when $w_e = 0.3$ and $w_c = 0.2$

(c) Instantaneous maximum speed of the evacuation crowd with different w_c when $w_e = 0.3$ and $w_a = 0.2$

FIGURE 3. **Relationship between various weights and the instantaneous maximum speed of evacuation crowd.**

As a result, the velocity update $\Delta \boldsymbol{v}_i$ of A_i can be computed by the weighted aggregation of these three velocities.

Second, if A_i has a companion and the distance between A_i and its companion A_j is no less than r_{ease}, then the seeking behavior is activated. Specifically, the exit velocity is the same as that in the first case, i.e., Eqn (1), and the seeking velocity is computed according to the rules described in Section III-A, which is:

$$\boldsymbol{v}_i^s = \begin{cases} \boldsymbol{p}_j - \boldsymbol{p}_i, A_j \text{ is visible} \\ \boldsymbol{p}_j^h - \boldsymbol{p}_i, A_j \text{ is invisible } \wedge \boldsymbol{p}_i \neq \boldsymbol{p}_j^h \\ \boldsymbol{p}_{\text{random}} - \boldsymbol{p}_i, A_j \text{ is invisible } \wedge \boldsymbol{p}_i = \boldsymbol{p}_j^h \end{cases} \tag{4}$$

where $\boldsymbol{p}_{\text{random}}$ denotes a random position in A_i's visual field.

To summarize, A_i's velocity increment $\Delta \boldsymbol{v}_i$ is computed as follows according to the above two cases:

$$\Delta \boldsymbol{v}_i = \begin{cases} w_e \boldsymbol{v}_i^e + w_a \boldsymbol{v}_i^a + w_c \boldsymbol{v}_i^c, A_j = \varnothing \vee A_j \text{ within } r_{\text{ease}} \\ (1 - w_s)\boldsymbol{v}_i^s + w_s \boldsymbol{v}_i^s, \text{ otherwise} \end{cases} \tag{5}$$

where w_e, w_a, w_c, w_s are the corresponding weights of the exit velocity, avoidance velocity, cohesion velocity, and seeking velocity, respectively. We will discuss how to choose these weight values in the simulation in Section IV-B.

C. ADAPTIVE VELOCITY SMOOTHING

To make an agent's velocity transition as smooth as the realistic movement, we use the exponential smoothing method [48], [51] to update the agent's velocity. However, directly applying a fixed smoothing factor through the whole evacuation process may be problematic. The reason is that the evacuated agents may show irrational behavior due to the excessive chaos in the emergence of evacuation.

In ECEM, we consider the influence of the chaos degree to smooth an agent's velocity. Specifically, we use the crowd entropy in the perspective of an agent as the smoothing factor to adaptively update the agent's velocity. The crowd entropy is used to quantify the chaos degree in the crowd. We compute the crowd entropy based on the Boltzmann entropy [52], because it can better reflect the population density [47], which is more suitable in crowd evacuation. Assume that there are N people within the visual field of A_i. We first divide both the

TABLE 1. **Simulation parameters.**

Notation	Description	Default value
N_{total}	total number of agents in evacuation	200
r_{agent}	agent radius	0.3m
r_{vision}	vision radius	5m
r_{ease}	comfortable distance	2m
v_{limit}	speed limit of any agent	2m/s
w_e	weight of exit velocity	0.3
w_a	weight of avoidance velocity	0.2
w_c	weight of cohesion velocity	0.2
w_s	weight of seeking velocity	0.9

velocity direction i.e., [0, 360), and the velocity magnitude, i.e., $[0, v_{\text{limit}}]$, into four equal parts, where v_{limit} is the speed limit of any agent (in scalar). Then we have 4*4 velocity distribution cells. Let n_j be the number of agents in the j-th cell, such that $\sum_{j=1}^{16} n_j = N$. As a result, we can compute the crowd entropy of A_i in the current iteration by:

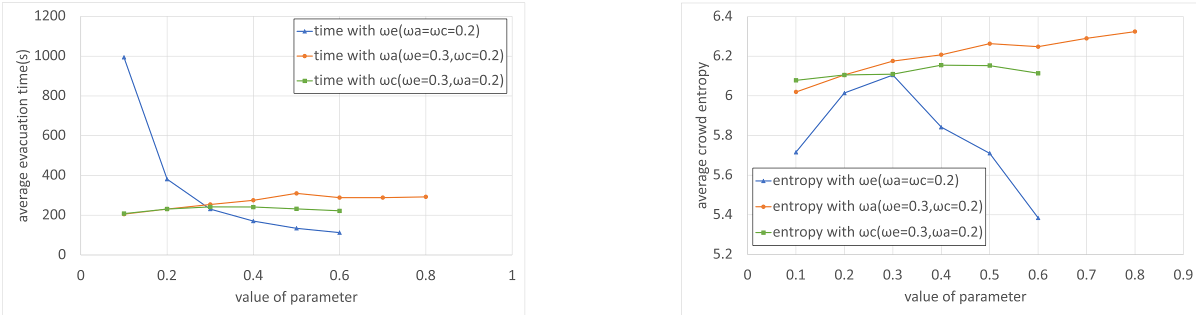
$$e_i = k \cdot \ln \left(\Pi_{j=1}^{16} C_{N - \sum_{t=1}^{j-1} n_t}^{n_j} \right) \tag{6}$$

where k is a constant. Recall that in the thermodynamic Boltzmann entropy formula $S = k_B \cdot \ln \Omega$ [52], k_B is the Boltzmann constant, and the Boltzmann entropy depends entirely on the number of possible microscopic states of the system Ω. The larger Ω is, the more chaotic and disorder the system is. Since k_B is extremely small, and its value does not affect the transition trend of entropy, we use $k = 0.0138$ for the crowd entropy calculation.

After obtaining the crowd entropy, we can compute the smoothed velocity of the current iteration as follows.

$$\boldsymbol{v}_i = \alpha \cdot \boldsymbol{v}_i^{\text{prev}} + (1 - \alpha)\Delta \boldsymbol{v}_i \tag{7}$$

where $\alpha = e_i/2$ and $\boldsymbol{v}_i^{\text{prev}}$ is the velocity in the previous iteration. By applying the adaptive entropy-based velocity smoothing, the evacuation model is more consistent with the realistic scenario: when the surrounding people are more chaotic, the individual behavior will be more likely to continue the previous inertial movement; on the contrary, when the surrounding people are more orderly, the individual can make more rational and appropriate decisions based on the current situation.



(a) Average evacuation time *w.r.t.* different velocity weights

(b) Average crowd entropy *w.r.t.* different velocity weights

FIGURE 4. **Average evacuation time and average crowd entropy *w.r.t.* various velocity weights. The default weights are: $w_e = 0.3$, $w_a = 0.2$, and $w_c = 0.2$. For each line in the figures, we fix two weights with their default values and change the remaining weight within the range $[0.1, 0.8]$ in the simulations.**

D. VELOCITY CORRECTION

Another consideration is to correct the velocity before moving to a new position. The rationale is that an agent may overlap with other agents or the obstacles if it directly moves to the designated position. Therefore, we apply several heuristics for velocity correction. Specifically, we let the agent do the following step by step after obtaining the velocity increment $\Delta \boldsymbol{v}_i$:

1) if there is no overlap, then update the position; otherwise, decrease its velocity (for example, in half) and go to step 2;
2) if there is no overlap, then update the position; otherwise, turn to the direction where the crowd density is the smallest or there is no obstacle and go to step 3;
3) if there is no overlap, then update the position; otherwise, set the velocity to 0 and wait for position updating in the next iteration.

By doing so, we can ensure that the agents will not overlap in the evacuation process. Consequently, each agent moves to the desired position. An agent will continue the next iteration until it finishes the evacuation (i.e., leave the exit).

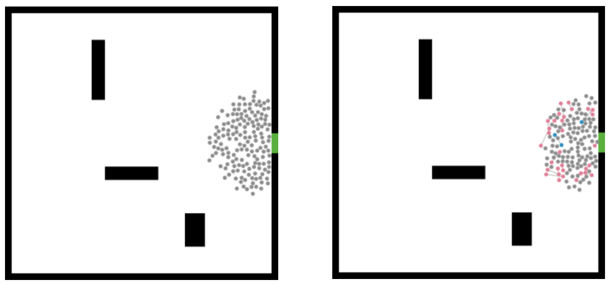
IV. SIMULATION AND ANALYSIS

In this section, we evaluate the proposed evacuation model through simulation. The simulation setup is given in Section IV-A. We explore the appropriate settings of various velocity weights and verify the effectiveness of ECEM in Section IV-B, and analyze the impacts of the seeking behaviors and crowd chaos on the evacuation process in Section IV-C.

A. SIMULATION SETUP

We implement and simulate ECEM using NetLogo,[1] a multi-agent programmable modeling environment. Our program[2] can be found on GitHub. We conduct experiments on a machine equipped with Intel (R) Core (TM) i5-8265U CPU @ 1.60GHz and 8.00GB of RAM, running Windows 10. Table 1 describes the default settings of the simulation parameters. The evacuation scene is a $40 \times 40\text{m}^2$ room with a single exit whose width is 3m. The total number of agents in the simulation N_{total} is 200, and the radius of each agent r_{agent} is 0.3m. Besides, the agent's speed limit v_{limit}, vision radius r_{vision}, and comfortable distance r_{ease} are set to 2m/s, 5m, and 2m, respectively.

[1]https://ccl.northwestern.edu/netlogo/
[2]https://github.com/clxvivi/ECEM



(a) Evacuation without social groups when $t = 46$s

(b) Evacuation with 20% social groups when $t = 66$s

FIGURE 5. **The illustration of arch-like collective blocking around the exit.**

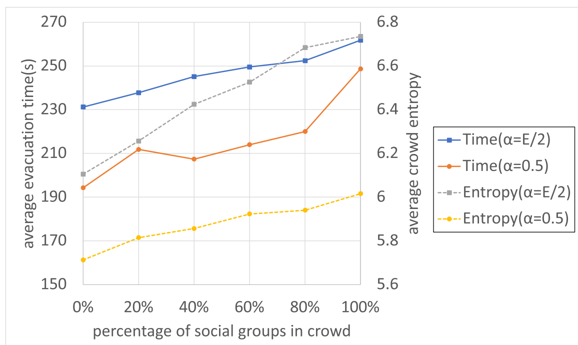
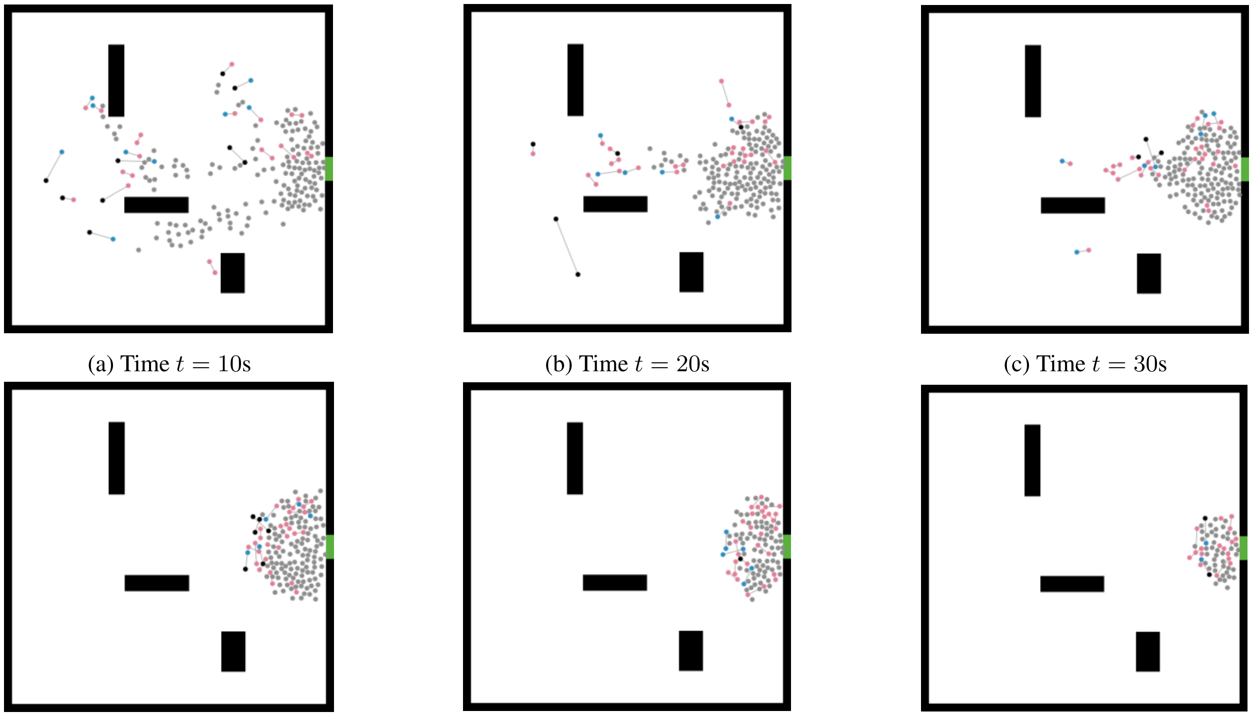


FIGURE 6. **Effect of the smoothing factor on the average evacuation time and average crowd entropy.**



(a) Time $t = 10$s (b) Time $t = 20$s (c) Time $t = 30$s (d) Time $t = 50$s (e) Time $t = 100$s (f) Time $t = 150$s

FIGURE 7. **The evacuation process *w.r.t.* evolved time (the percentage of social groups is 20%).**

B. EVACUATION MODEL VERIFICATION

In order to ensure the effectiveness of the simulation model, we first conducted a series of comparative simulation experiments with different parameters to determine the value ranges of the velocity weights. Specifically, we study the effects of weights for the exit velocity, avoidance velocity, and cohesion velocity, i.e., w_e, w_a, and w_c. We fix two of them with default values and evaluate the effect of the remaining weight. Specifically, the default weights are set to $w_e = 0.3$, $w_a = 0.2$, and $w_c = 0.2$, respectively. Besides, we assume that the distribution of each agent's initial velocity follows the Gaussian distribution $\mathcal{N}(1.5, 0.15)$.

1) EFFECTS ON INSTANTANEOUS MAXIMUM SPEED

Figure 3 shows the relationship between various velocity weights and the instantaneous maximum speed of the evacuation crowd, where the latter refers to the maximum speed (in scalar) of any agent in the crowd in an iteration. In this set of experiments, we adopt the same random seed, which means the pseudo-random number generator in NetLogo will generate a fixed random sequence for each simulation, ensuring that the simulations are reproducible.

From Figure 3a, we can observe that w_e influences the instantaneous maximum speed throughout the whole evacuation process. When $w_e \leq 0.2$, the instantaneous maximum speed is always less than the agent's speed limit v_{limit}, and it gradually decreases in the middle and late stages of evacuation. As w_e increases, the individual's instantaneous maximum speed increases quickly in the early stage of evacuation, and the time of its gradual decrease is shortened in the later stage, leading to a significantly reduced evacuation time. Intuitively, in the early stage of evacuation in realistic scenarios, the agents are able to approach the speed limit in areas where the crowd density is small; however, when the crowd gather around the exit and form an arch-like collective blocking (as will be shown in Figure 5), the agents cannot stay at the speed limit anymore. As a result, we set the default weight of exit velocity $w_e = 0.3$ for two reasons. On the one hand, if w_e is too small, the individual waiting time around the exit will be long since the avoidance and cohesion behaviors also affect the velocity increment. On the other hand, if $w_e \geq 0.4$, then during about 80% of the evacuation period, the individual's instantaneous maximum speed is always the agent's speed limit v_{limit}, which is not reasonable in realistic scenarios. Also, a large w_e would make the proportions of other velocity components too low, thus those behaviors cannot be well interpreted.

According to Figure 3b, w_a mainly affects the instantaneous maximum speed of the individual and its oscillation amplitude in the late stage of evacuation. The larger the w_a is, the higher the instantaneous maximum speed, the greater the amplitude, and the longer the evacuation time. This result shows that if given a large w_a, the agents tend to be mutually repelled by avoidance, leading to hovering near the exit. Therefore, the evacuation efficiency is undesirable.

Moreover, from Figure 3c, we can see that as w_c increases, the instantaneous maximum speed of the individual increases, the oscillation amplitude increases in the late stage of evacuation, and the evacuation time extends. In particular, when $w_c = 0.4$, the same phenomenon occurs as when $w_e \geq 0.4$, that is, the instantaneous maximum speed continues to be too large, which is unrealistic.

2) EFFECTS ON THE EVACUATION PROCESS

Figure 4 presents the effect of velocity weights on the evacuation process. In this set of experiments, the random seed is randomly generated. For each experiment, we conduct 50 independent trials and report the average result. From the experimental results, w_e has the most significant impact on the average evacuation time and average crowd entropy. As w_e increases, the average evacuation time decreases significantly and becomes stable, and the average crowd entropy first increases and then decreases. The reason is that when w_e is large, the time for the crowd to move to the exit can be reduced, improving the evacuation efficiency. However, when $w_e \geq 0.4$, the increased agents that reach the speed limit tend to stabilize such that the further reduced time is not apparent. For crowd entropy, when w_e is increased to 0.3, the agents would be congested around the exit in most evacuation time. This situation would increase crowd entropy because the uncertainty of velocity is also influenced by the avoidance and cohesion velocities. But when $w_e \geq 0.4$, the exit velocity is dominant, such that the agents' velocity direction is similar (i.e., towards the exit), and thus the movement is more order.

For w_a, its influence on the average evacuation time and average crowd entropy is not obvious, comparing to the other two weights. In terms of w_c, we can see that as w_c increases, the average evacuation time first increases and then slightly decreases. When w_c is small, it is less likely for individuals to gather; the herding phenomenon becomes more pronounced when w_c increases; and when w_c is large, individuals tend to gather into several large groups, improving the evacuation efficiency. This is consistent with what is observed in [34] that the evacuation time will be reduced when the group size is large.

3) VERIFICATION OF EVACUATION MODEL EFFECTIVENESS

Finally, we verify the effectiveness of ECEM given the default weights described above. Figure 5 shows the simulation results. We can observe that, regardless of whether the crowd contains social groups, the proposed evacuation model can correctly reproduce the arch-like collective blocking phenomenon around the exit. As investigated in previous work [25], [53], the arch-like collective blocking phenomenon demonstrates the effectiveness of the evacuation model. Therefore, our evacuation model performs consistently with crowd evacuation in realistic scenarios.

C. EVACUATION ANALYSIS

Now we analyze the effects of crowd chaos and seeking behaviors on the evacuation process, which is to give a better interpretation of our evacuation model and provide some insights on how to design effective evacuation strategies under this circumstance.

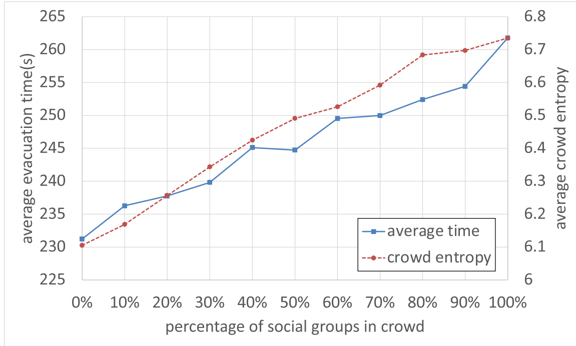
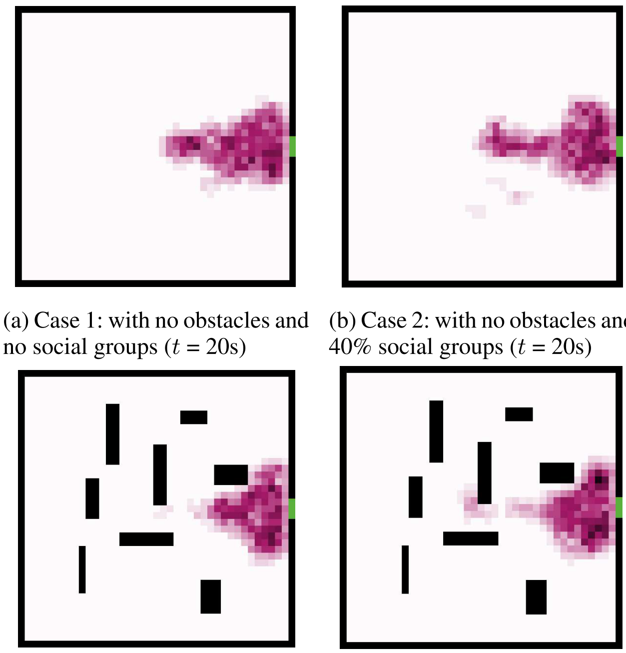


FIGURE 8. **Effect of the percentage of social groups on the average evacuation time and average crowd entropy.**

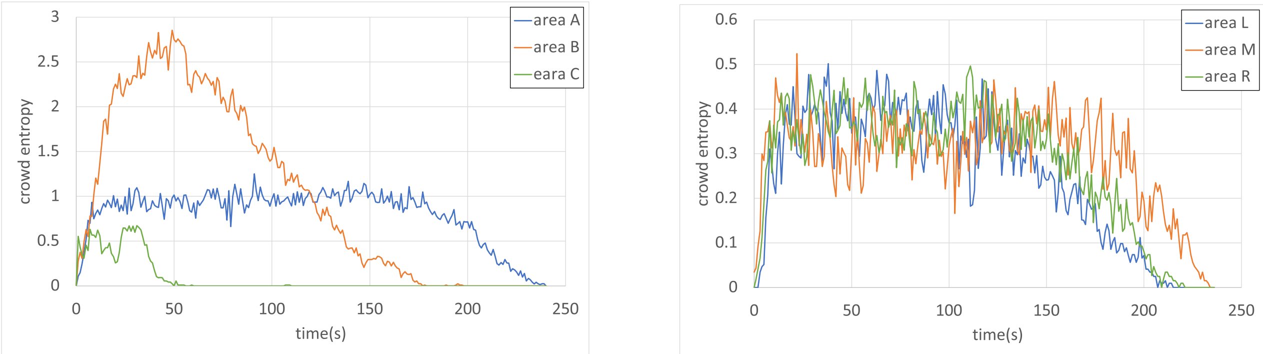


(a) Case 1: with no obstacles and no social groups (t = 20s) (b) Case 2: with no obstacles and 40% social groups (t = 20s) (c) Case 3: with dense obstacles and no social groups (t = 40s) (d) Case 4: with dense obstacles and 40% social groups (t = 40s)

FIGURE 9. **Illustration of evacuation *w.r.t.* obstacles.**

1) EFFECT OF ADAPTIVELY VELOCITY SMOOTHING

In our evacuation model, we incorporate the sense of crowd chaos into the velocity smoothing formula (i.e., Eqn (7)) for the agents, by setting the smoothing factor to half of the crowd entropy in each agent's visual field, i.e., $\alpha = e_i/2$. To illustrate the effect of this method, we compare it with a baseline using a fixed smoothing factor $\alpha = 0.5$. Figure 6 presents the evacuation process with respect to the two smoothing factors and different percentages of social groups. The comparison results show that no matter whether social groups exist (non-zero percentages) or not (zero percentage), the entropy-based



(a) Crowd entropy in partitioned areas A, B, and C

(b) Crowd entropy in partitioned areas L, M, and R

FIGURE 10. **The evolution of crowd entropy within partitioned areas.**

velocity smoothing method incurs a longer average evacuation time and a higher average crowd entropy comparing to that with the fixed smoothing factor. This demonstrates that the crowd chaos has a negative impact on evacuation, which is in accordance with the realistic situation.

2) EFFECT OF SEEKING BEHAVIOR ON EVACUATION

Figure 7 presents the evacuation process *w.r.t.* evolved time, where the percentage of social groups is set to 20%. In the figure, gray particles represent individuals, pink particles represent social groups whose companions are within the comfortable distance, blue particles represent social groups whose companions are beyond the comfortable distance but still visible, and black indicate social groups whose companions are invisible. We can observe from the simulation results that, in the early stage of evacuation, the seeking behaviors mainly occur during the movement of social groups; and in the middle and late stages of evacuation, the seeking behaviors occur around the periphery of the arch-like collective cohesion.

Next, we evaluate the effect of the percentage of social groups on the average evacuation time and average crowd entropy, as illustrated in Figure 8. Generally, the average evacuation time and average crowd entropy increase linearly as the percentage of social groups goes large. The reason is that, when the percentage is larger, more agents will seek their companions, leading to a more chaotic evacuation and a longer evacuation time. Besides, we can observe from Figure 8 that, when the percentage of social groups is 0%, the simulation result is the evacuation without seeking behaviors in the crowd. In this situation, the simulation is ideal as the negative impact caused by seeking behaviors is ignored, which may not be in line with the realistic scenario.

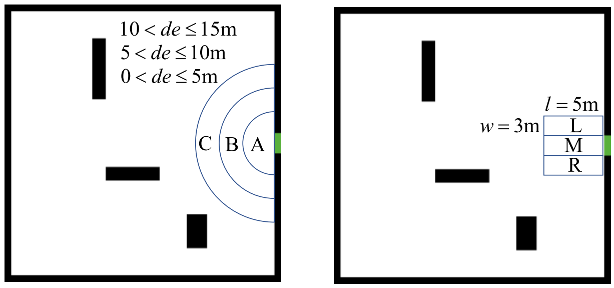
3) EFFECT OF OBSTACLES ON EVACUATION

We further compare the evacuation with and without obstacles. Specifically, we consider the following four cases:

1) Case 1: with no obstacles and no social groups;
2) Case 2: with no obstacles and 40% social groups;
3) Case 3: with dense obstacles and no social groups;
4) Case 4: with dense obstacles and 40% social groups.

TABLE 2. **Comparison of evacuation *w.r.t.* obstacles.**

	Case 1	Case 2	Case 3	Case 4
Evacuation time	214.48s	222.1s	216.76s	225.42s
Crowd entropy	6.0592	6.1791	6.1418	6.3914
#Seeking (visible)	0	1076.98	0	1130.84
#Seeking (invisible)	0	785.42	0	800.04



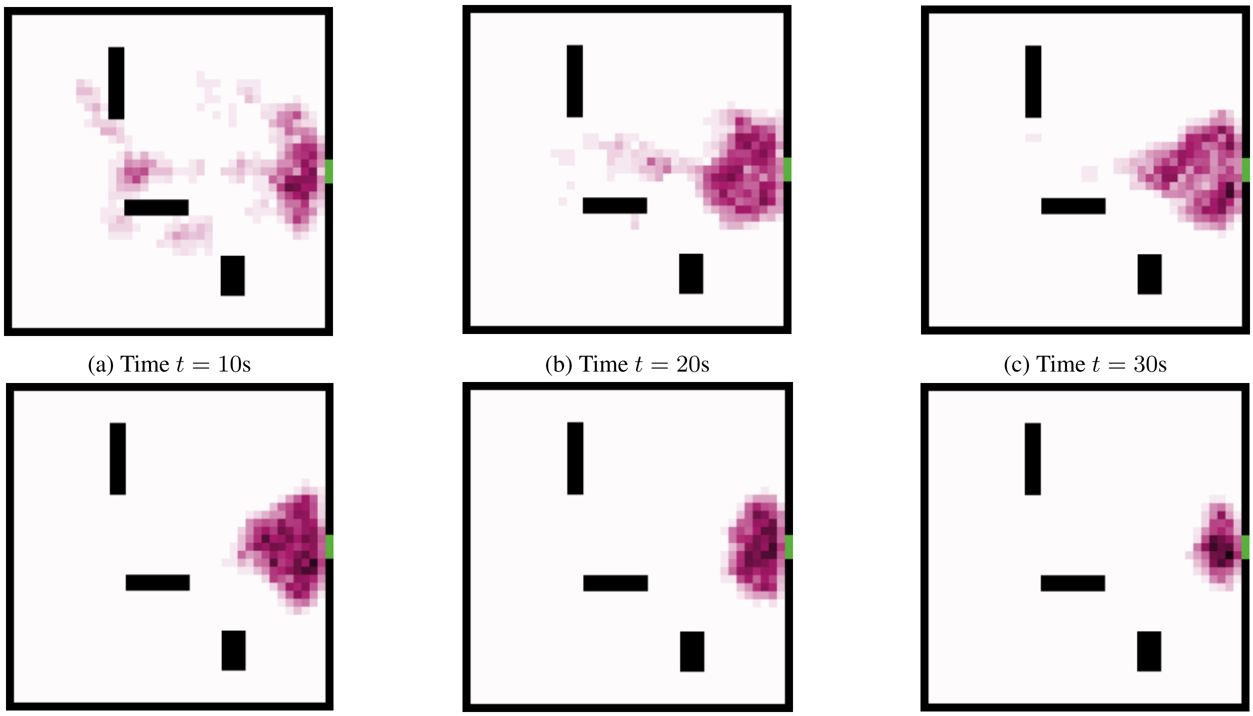
(a) Based on distance to exit

(b) Based on location of exit

FIGURE 11. **Illustration of partitioned areas.**

For a better illustration of the chaos degree in the crowd during the evacuation, we utilize Eqn (6) to calculate the Boltzmann crowd entropy for each grid and visualize in Figure 9 at a specific timestamp (the darker the color is, the higher crowd entropy in the grid). In addition, we summarize the number of seeking behaviors during the whole evacuation in Table 2, where *visible* represents the companion is within an agent's visual field, and *invisible* represents the opposite. We report the average result of 50 independent trials.

We have three observations. First, the results show that the proposed ECEM algorithm is suitable for evacuation scenarios with different obstacle distributions. Second, as shown in Figure 9, the existence of social groups slows down the progress of individuals gathering to the exit, and there are more dark grids near the exit (indicating that the crowd is more chaotic). Together with the evacuation time in Table 2,



(a) Time $t = 10$s (b) Time $t = 20$s (c) Time $t = 30$s

(d) Time $t = 50$s (e) Time $t = 100$s (f) Time $t = 150$s

FIGURE 12. The distribution of crowd entropy *w.r.t.* evolved time (the percentage of social groups is 20%).

we observe that the seeking behaviors lead to a prolonged evacuation process, which is consistent with the findings mentioned above. Third, by comparing Case 2 and Case 4 in Table 2, we can see that, when the percentage of social groups is the same, given obstacles, the number of seeking behaviors (including both visible and invisible seeking) increases notably. This dues to that the obstacles restrict the individual's visual field and increase the uncertainty of the evacuation path. Therefore, the obstacles negatively impact evacuation efficiency and the crowd's chaos degree.

4) ANALYSIS OF CROWD CHAOS AROUND THE EXIT

Because the crowd is usually congested around the exit for a long time during the evacuation process, we are interested in the crowd chaos within this area. For a better analysis, we partition the area around the exit by two strategies, as shown in Figure 11. One strategy is based on the distance to the exit, with A, B, and C areas (Figure 11a). The other strategy is based on the exit location, with L, M, and R areas (Figure 11b).

Figure 10a describes the evolution of crowd entropy for the first partition strategy. We can observe that, in area B (i.e., between 5m and 10m from the exit), the degree of crowd chaos is the most serious, and the magnitude of change is the most drastic; in area A (i.e., less than 5m from the exit), the state of crowd chaos lasts the longest, but the degree of chaos is relatively stable; and in area C (i.e., between 10m and 15m from the exit), the duration of crowd chaos is the shortest and its degree is the lowest.

Similarly, Figure 10b presents the evolution of crowd entropy for the second partition strategy. During time $t = 25$s to $t = 100$s, the crowd entropy in area M is lower than that in areas L and R, which means that the crowd in the middle of the exit is more orderly than the left and right sides. This is because the population density is higher during this period, and the competition between the crowds on both sides of the exit is more intense. Meanwhile, the avoidance velocity, cohesion velocity, and velocity correction make the uncertainty of individual velocity much higher in areas L and R. While in area M, the velocity direction is more consistent and therefore more orderly. When $t > 100$s, the degree of chaos in areas L and R gradually weakened and is less than that of area M. The reason is that, in the late stage of evacuation, the scale of the arch-like collective blocking becomes smaller, and individuals are more likely to escape through area M. As a consequence, the crowd density in area M is larger, and the competition is more intense than on both sides of the exit.

Finally, by calculating the crowd entropy in each grid (using Eqn (6) for each grid), we show the crowd entropy distribution during the whole evacuation process to identify the most chaotic areas, as illustrated in Figure 12. The simulation results are consistent with the above analysis: the most chaotic area is B when $t = 10$s and 20s (i.e., early stage), is R when $t = 30$s and 50s (i.e., middle stage), and is M when $t = 100$s and 150s (i.e., late stage), respectively.

The simulation results could help design emergency evacuation plans and optimize the management of evacuating crowds. For example, the observations inspire us to focus on those areas with higher disorder levels during the simulation and take further measures, e.g., adding markers or guidance, to prevent the evacuating crowd from being too chaotic and causing casualties.

V. CONCLUSION

We have proposed ECEM, an entropy-based crowd evacuation model, that considers the seeking behavior in evacuation where social groups are in the population. Moreover, we incorporate the crowd chaos based on Boltzmann entropy into the model, ensuring that an individual adaptively computes its velocity according to the disorder level in its perspective. Finally, we demonstrate the effectiveness of ECEM through extensive simulations and further provide insights on designing evacuation strategies in realistic scenarios based on the experimental analysis.

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