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Research Article

Exploring the Effects of Different Walking Strategies on Bi-Directional Pedestrian Flow

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Three types of different walking behaviors (right preference, conformity, and space priority) are taken into account to model bi-directional pedestrian flow in the channel with cellular-automata formulation. The fundamental diagrams of *R*-pedestrian flow, *C*-pedestrian flow, and *S*-pedestrian flow are obtained from the simulation result to analyze the effect of these behaviors on bi-direction flow. The *C*-pedestrian flow has the minimum critical density and *R*-pedestrian flow has the highest, while the *S*-pedestrian flow has higher average-speed than other two types of pedestrian flow under the same density. Further, through the study of pedestrian distribution in the channel and the proportion of pedestrians not able to move to the front cell, reasons leading to different characteristics of these three types of pedestrian flow are analyzed. Moreover, the simulation experiment based on BehaviorSearch is designed to explore the optimal percentages of *R*-pedestrian, *C*-pedestrian, and *S*-pedestrian in pedestrian flow. The result of the experiment shows that the condition that makes the highest average speed of pedestrian flow is not that pedestrian flow consists of purely one type of pedestrians, but pedestrian flow mixed with *S*-pedestrians as majority and *C*-pedestrians and *R*-pedestrians as minority.

1. Introduction

In recent years, pedestrian flow research has found great interest in many research fields [1–3]. The complex behaviors of pedestrian can emerge a variety of interesting self-organization phenomena, such as the oscillations at bottlenecks [4], the lane formation in pedestrian bi-directional flow, or the turbulent movement in dense crowds [5]. It is known to us that understanding the behavior of pedestrian is fundamental to developing a predictable model for the design of urban infrastructures, traffic management, or crowd safety during mass events or evacuation processes. However, pedestrians' behavior movement is flexible and changeable according to walking conventions, psychology, environment, and so forth. Thus, it is a great challenge to model pedestrian behavior accurately.

Recently, many models of pedestrian behavior have been developed to simulate pedestrian flow including social-force model [6–8], lattice gas model [9], cellular-automata (CA) model [10–13], and agent-based models [14]. Particularly, cellular automation has been widely used to simulate pedestrian movement, in which an approximate actual pedestrian behavior can be described by setting simple local rules to each individual, and the collective behavior of pedestrians emerges as an outgrowth of microsimulation rule set. The collective phenomena of pedestrian flow like the best known spontaneous formation of lanes in bi-directional pedestrian flow and oscillatory changes of the walking direction at narrow passages have been successfully simulated by CA approach due to the computational efficiency. To achieve more realistic simulations, various CA models begin to consider pedestrians' sociological and psychological characteristic. Researchers are paying more attention to pedestrians' behavior to enhance the model and to study the effects of different behavior on pedestrian flow operation.

Among the existing bi-directional pedestrian CA models, the following sidling and walking back behavior were considered and their effects on pedestrian dynamic were discussed such that the back-step strategy can reduce the jamming condition significantly [15–17]. On the other hand, some researchers focused on the individual movement behavior influenced by the interaction or relationships between other individuals. Ma et al. (2010) built the KNN CA model based on the k-nearest-neighbor interaction pattern that pedestrian's direction of choosing behavior was effected by the distribution of fixed neighbors, which presented self-organization phenomena and validated that the k-nearest neighbors play a fundamental role in the emergency of pedestrian collective behavior [18]. Wang et al. (2012) proposed a CA model to simulate team moving behavior and conducted the simulation experiment to discuss the effect of this type of behavior. It was found that the capacity of channel would decrease if the teeming number increased [19].

However, the models mentioned above mainly concentrated on certain type of pedestrian behavior and ignored the complexity and randomness of pedestrian behavior. Thus, in this paper we present a bi-directional pedestrian model where each individual may take different walking strategies while walking. This modified model can be used to analyze the effect of different moving strategies on pedestrian flow through the simulation method, which will be helpful to understand the operating mechanism of pedestrian flow and to put forward measures to improve its operating efficiency.

What is more, for simulation experiment, a challenging task is to vary the parameters of the model continuously and discover the impact of different parameter setting on simulation results. For example, if we want to check whether the critical density is independent of the system size as many pedestrian simulations have done, we need to run the model with all combinations of parameters setting exhaustively. It is generally time consuming and not feasible. So in this paper, the new soft tool BehaviorSearch is introduced and applied to explore the parameter space of model, and thus a new method and idea of performing this work for pedestrian flow simulation is provided [20].

The major objective of this paper is to study the effects of different walking strategies on bi-directional pedestrian flow. The remainder of this paper is organized as follows. The next section presents the process of modeling pedestrians with three different walking strategies using CA approach; Section 3 provides the simulation results to analyze the effect of these walking strategies on bi-directional pedestrian flow. At the same time, the simulation experiment based on BehaviorSearch for the purpose of exploring parameter space is described, which will help us gain insight into the relationship between pedestrian behavior and pedestrian flow operation. Finally, the major findings and conclusions are summarized and the direction for future work is provided in the last section.

2. Model Development

2.1. Initialization. In this model, pedestrian moving space is portioned into $W \times L$ grids in the plane. Every grid is a cell with the size of 0.4 m × 0.4 m [18], which is the typical space occupied by a pedestrian in a dense crowd. Each cell must be occupied by one pedestrian or must be empty. There are two types of pedestrian in the system. One is moving to the right, and the other is moving to the left, as is shown in Figure 1.

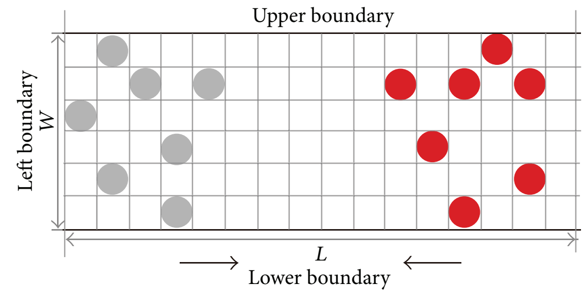


Figure 1: Schematic illustration of the system of pedestrian counterflow.

Every pedestrian can move to an empty grid or stay still at each time step. At the initial time step, all pedestrians are randomly distributed on the $W \times L$ grids with a given density.

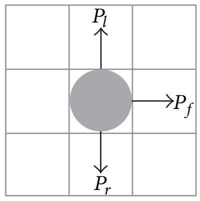
The upper and lower boundaries of the system are closed, while the left and right ones are periodical, meaning that when the right-moving pedestrians reach the right boundary, they will move back from the left boundary, and when the left-moving pedestrians arrive the left boundary, they will return back from the right boundary. Thus, the total number of each type of individuals is constant and the density of pedestrian flow during each simulation experiment is fixed.

2.2. Basic Rules. As the walking back behavior is not considered in the model, the pedestrians can move in three different directions: those are forward, right, left (see Figure 2). The probability of moving to the neighboring grids is always not the same, depending on pedestrian walking strategy or walking habit, and so forth. For example, the probability of walking in the destination direction is the largest, which has been observed or surveyed in research work [21]. However, the probability of walking to the left or right neighboring grid is biased.

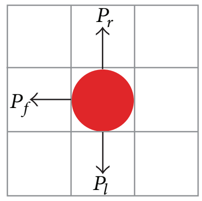
In this model, we consider that pedestrian makes decision of movement direction randomly during the walking process. Three behavior walking strategies are taken by each individual mainly according to his or her own subconscious behaviors, the distribution of other pedestrian around, and other pedestrians' walking behavior. More specifically, pedestrians are accustomed to walking along the right-hand side of the road considering the traffic rule and customs; pedestrians tend to follow other pedestrians walking behavior under the conformity psychology; pedestrians prefer to walk on the side with fewer other pedestrians there to meet his or her own personal space requirement. For convenience sake, the three walking strategies mentioned above are called R-strategy, C-strategy, and S-strategy, respectively, in the following.

At first, we set the transition probability of moving forward 0.70 based on the survey result in reference [21]. Then the probabilities of moving to the right and left grid are the same, while none of the walking strategies is adopted by pedestrians. When different walking strategies are taken into account, the probabilities of right and left movement are not equal and set as follows.

2.2.1. For R-Strategy. As to pedestrians with R-strategy, they would be used to walking on the right side. And the



(a) The transition probability for a right walker



(b) The transition probability for a left walker

FIGURE 2: Schematic diagram of pedestrians' transition probability.

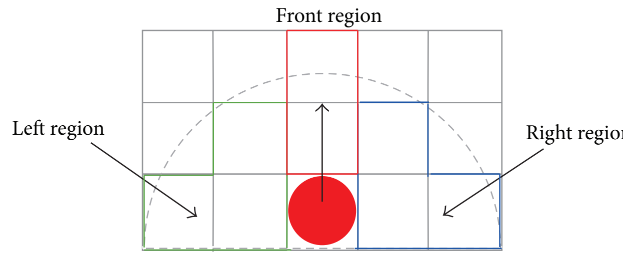


FIGURE 3: Schematic diagram of pedestrians' visual field, in the figure $r = 2$.

probability of moving to the right grid is higher. So the right-hand walking preference coefficient is introduced to justify the transition probability. Thus

$$p_r = \frac{K}{1+K}\left(1-p_f\right), \qquad p_l = \frac{1}{1+K}\left(1-p_f\right), \tag{1}$$

where K represents the strength of right preference and p_f is the transition probability of moving forward. If one of the right and left cells is occupied by other pedestrian, the pedestrian would choose to walk to the left or right side at the probability of $1 - p_f$. When the front cell is occupied, the pedestrian would walk from the left side or right side separately at the probability of

$$p_r = \frac{K}{1+K}, \qquad p_l = \frac{1}{1+K}. \tag{2}$$

When the left (right) cell is also occupied, the pedestrian have to move to the right (left) side. And when all the three cells are occupied, the pedestrians keep still.

2.2.2. For C-Strategy. Those who choose C-strategy have a sense of conformity. When making the moving decision, they would take others' choice into consideration and finally follow the majority. Hence to determine the moving probability of these people, we should first collect other pedestrians' moving direction in their sight. If the majority are sure to or have the decision to walk to the left (right) side, these pedestrians will also choose to walk to the same side. Therefore, in the model, we set that pedestrians have the sight with the radius of r, and divide the sight into tripartition, the forward visual field, the left visual field and the right visual field, as shown in Figure 3. Their moving probability can be determined as follows:

$$\begin{aligned} p_r &= \frac{M_r}{M_r+M_l}\left(1-p_f\right), \\ p_l &= \frac{M_l}{M_r+M_l}\left(1-p_f\right), \end{aligned} \tag{3}$$

where M_r, M_l represent the number of other pedestrians in right and left visual field who chose to walk to the right or left side. And when one of the right and left cells is occupied by other pedestrians, the pedestrians would choose to walk to the left or right side at the probability of $1 - p_f$.

Similarly, when the cell at front is occupied, these pedestrians would walk from the left side or right side at the probability of

$$p_r = \frac{M_r}{M_r+M_l}, \qquad p_l = \frac{M_l}{M_r+M_l}. \tag{4}$$

When the left or right cell is occupied, then the pedestrian would move to the opposite side. And when all the three cells are occupied, the passenger cannot move at all.

2.2.3. For S-Strategy. Pedestrians sometimes choose to walk on the left or right side depending on where there are less other pedestrians. Pedestrian would compare the number of other pedestrians on each visual field before they make the moving decision. Correspondingly, the probabilities of moving to right and left are

$$\begin{aligned} p_r &= \frac{N_l}{N_r+N_l}\left(1-p_f\right), \\ p_l &= \frac{N_r}{N_r+N_l}\left(1-p_f\right), \end{aligned} \tag{5}$$

where N_r, N_l represent the number of other pedestrians in right and left visual field. And when one of the right and left cells is occupied by other pedestrian, the pedestrian would choose to walk to the left or right side at the probability of $1 - p_f$.

Similarly if the front cell is not empty, the pedestrian would walk to the left or right cell separately at the probability of

$$\begin{aligned} p_r &= \frac{N_l}{N_r+N_l}, \\ p_l &= \frac{N_r}{N_r+N_l}. \end{aligned} \tag{6}$$

When the left or right cell is occupied, then the pedestrian would move to the opposite side. And when all the three cells are occupied, the pedestrian cannot move at all.

According to the basic rules described above, each pedestrian can move to one of the unoccupied neighbor grids or stay at present cell at each discrete time step with certain transition probability. The update rules are applied to all pedestrians at the same time, namely, parallel update.

2.3. Conflict Elimination. Due to the use of parallel rule, it is possible that two or more pedestrians will choose the same target grid. Such situation is called conflicts as is shown in Figure 4. The conflicts between pedestrians are resolved by the following way [22].

(1) Whenever two or more pedestrians try to attempt to move to the same target grid, the movement of all involved pedestrians is denied with the probability of u; that is, all pedestrians remain at their original position.

(2) With $1-u$ probability, one of the involved pedestrians is chosen randomly to move to the target gird, while others stay still.

2.4. Repulsion Processing. Repulsion occurs when pedestrians with different walking directions encounter. In such situation, each pedestrian will chose one side to evade. According to the experimental result, when pedestrians choose the side on which they evade, they always show a right-hand preference [23]. So the repulsion is dealt with that each pedestrian chooses to move to his or her right side, shown in Figure 5.

3. Simulation Result

3.1. Parameter Definition. D is the total density of pedestrian flow. The total number of pedestrians N is defined as the value of $D \times W \times L$. The average speed of pedestrians moving in one time step is defined as the value of the number of pedestrians moving forward divided by the total number of pedestrians N. The flow of pedestrians Q is defined as the value of $D \times V$. For each simulation, 10000 time steps were run and the first 1000 steps were discarded with the purpose of reducing error. Each simulation experiment is carried out for 10 times.

3.2. Simulation Experiment 1: Model Validation. Before exploring the effects of different walking strategies on bi-directional pedestrian flow, it is necessary to validate that the basic rule of model is reasonable. The simulation experiment 1 is designed for this. In this simulation experiment, walkers randomly choose one of the three strategies with the same probability during the walking process. The size of simulation system is set as follows: $W = 30$; $L = 100$. The friction probability μ is 0.05.

We change the density from smaller values to bigger values, and the phase transition course can be observed. As is shown in Figure 6, the red circles represent the left walker and the grey circles stand for the right walker. When the density is below critical density, the typical collective pattern of lane formation emerged for bi-directional pedestrian flow (see Figure 6(a)). While the density exceeds the critical value, the jam occurred in the system (see Figure 6(b)). These phenomena are in good agreement with empirical observations, which support the idea that the model's basic rule is reasonable.

3.3. Simulation Experiment 2: Exploring the Effects on Critical Density. The simulation experiment 2 is designed to study the effect of different walking strategies on the critical density of bi-directional pedestrian flow. The width and length of system set 30 and 100, which is consistent with the simulation experiment 1. The coefficient of the right-hand walking preference K is 8 and that of sight radius r is 10. The friction probability is still 0.05.

In this simulation experiment, parts of the pedestrians in the system have certain probability to take one certain kind of walking strategies during the walking process. Then using the R-strategy, C-strategy, and S-strategy to repeat this experiment, the phenomena of critical density point drift occur. The quantitative relationship of critical density with percentage of pedestrians taking certain strategy can be occupied (see Figure 7).

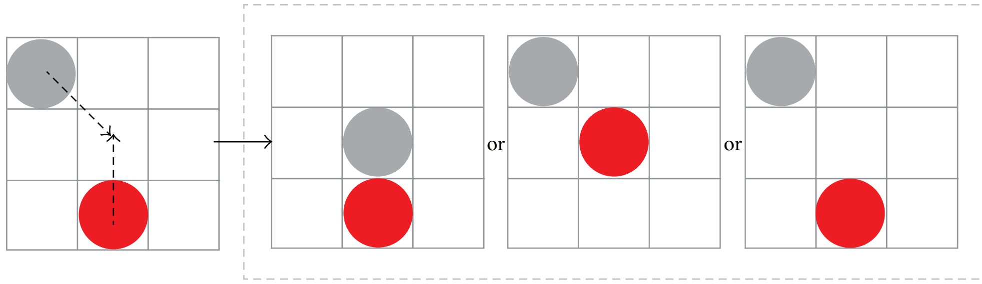
It can obviously be seen that the C-curve is below the S-curve and the R-curve is at topside. What is more, the C-curve and S-curve are in declined trend with the increasing of probability, while the R-curve shows the opposite trend (see Figure 8). This means that the R-strategy has positive effect on corridor capacity, while the moment pedestrians take the C-strategy or S-strategy, the capacity reduces significantly, and jam will easily happen.

3.4. Simulation Experiment 3: Exploring the Effects on Fundamental Diagram and Collective Phase. Pedestrians in the corridor are set to take a same walking behavior, namely, in the three simulation, the R-strategy, C-strategy and S-strategy are made 100% in turn to study the features of different types of pedestrian flow. Although the assumed condition that all the pedestrians in the system take the same walking strategy is not existed in reality, it helps us to observe and compare the effects of different walking strategies on bi-directional pedestrian flow clearly. This is called simulation experiment 3.

The density-speed curves and density-volume curves under the condition that pedestrians fully take the R-strategy, S-strategy, or C-strategy, respectively, are drawn. It is indicated that, the pedestrian flow, no matter composed by which walking strategy, obeys the same varying tendency. There are critical density points in the curves. Below the critical density point, the speed varies gently and the volume increases with the density. When density exceeds the critical point, both the speed and volume experience a sharp decline to 0. However, it should be pointed out that there are great differences between the fundamental diagrams of the three types of pedestrian flow composed of pedestrians with different walking strategies.

By comparison, it is shown that when the pedestrian flow is not in the jamming phase, the average speed and volume of S-pedestrian flow are higher than the other two pedestrian flow under the same density. While those of R-pedestrian flow and C-pedestrian flow are basically the same when the density is no more than 0.20, yet their critical densities are different. Meanwhile, C-pedestrian flow starts to jam under the density of 0.25, while R-pedestrian and S-pedestrian flow jam under about 0.40 and 0.45, respectively.

Therefore, when pedestrians take S walking strategy, the operating efficiency of the pedestrian flow will be relatively increased, mainly indicated in the improvement of average speed, volume, and critical density. When they take C walking



(a) one stays and one moves (b) one stays and one moves (c) both stay still

Figure 4: Occurrence of conflict and processing method.

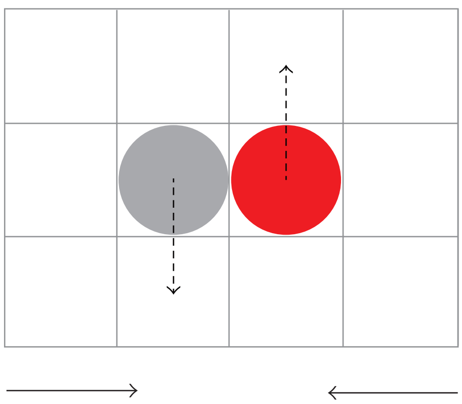
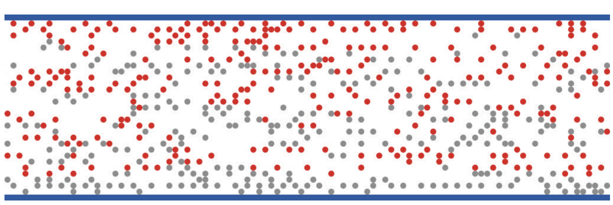
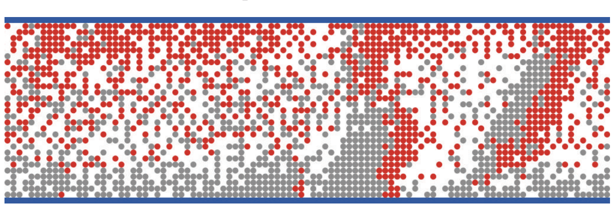


Figure 5: Repulsion processing.



(a) Collective phenomenon: lane formation



(b) Collective phenomenon: jam phase

Figure 6: Collective phenomena.

strategy, the pedestrian flow starts to jam under a smaller density. It may be explained that the herding behavior in walking leads to the gathering of pedestrians on one side or in a small area, causing congestion within one part of space. Moreover, congestion in a small or partial area is inclined to expand to the whole pedestrian flow system so as to make the system out of balance and enter the jamming phase. Therefore, it is essential to guide pedestrians with necessary information to avoid blind walking strategies taken after other pedestrians [24].

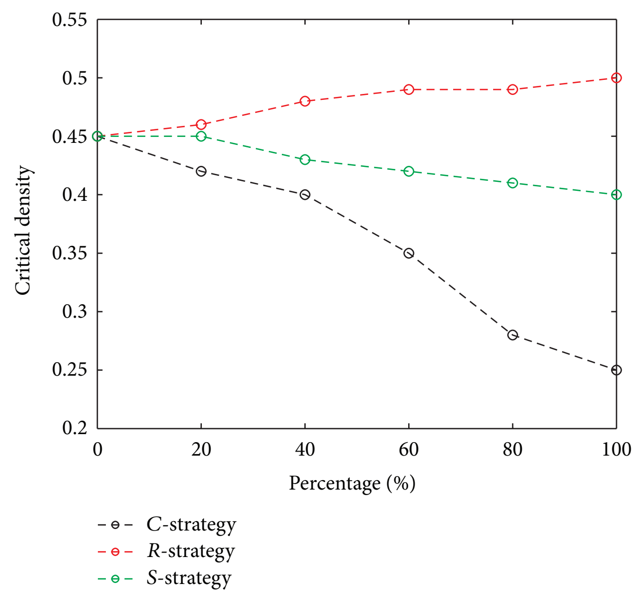
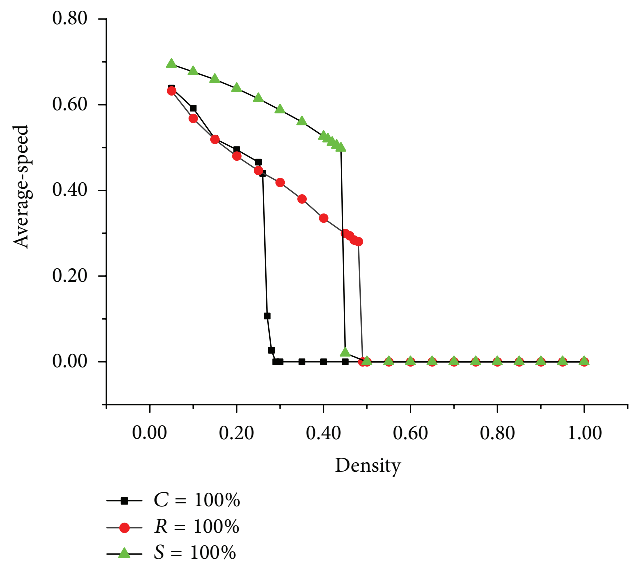


Figure 7: The effect of different walking strategies on critical density.

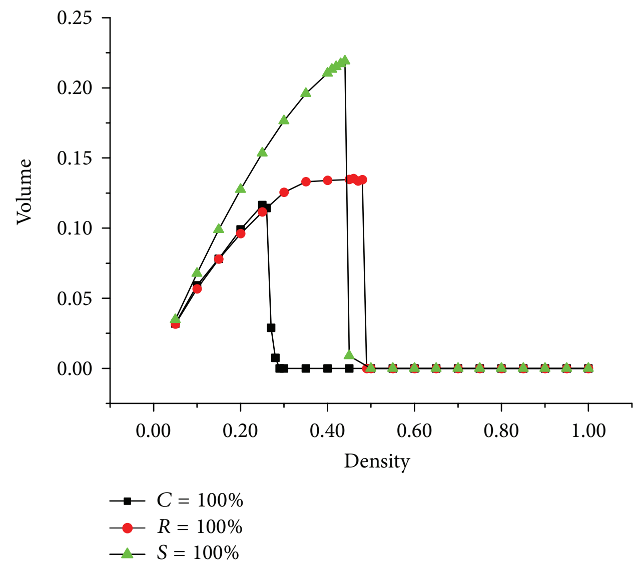
It also indicates that in the simulation, as shown in Figure 9, pedestrians with conformity psychology mainly gather in the middle of the channel while walking. While R-pedestrians are scattered to the two sides of the channel, S-pedestrians are well-distributed in the channel. When pedestrians' distribution is among a certain range, although the pedestrian density in the whole channel is low, it is very high in the pedestrian assembling area. That is why C-pedestrian flow appears to be jammed under the density of 0.25.

The definition of average speed indicates that only those who choose to move forward contribute to the average speed of the whole pedestrian flow. Though in the model, the probability of the three type pedestrians' choice of moving forward is all set to be 0.70, and the average speed differs sharply. This is mainly related to the proportion of pedestrians whose front cell is occupied by pedestrians from the opposite or same direction, and they cannot choose to go forward.

This index, therefore, is worked out, as is shown in the Figure 10. When the pedestrian density is under the critical density, the proportion of pedestrians not able to go forward increases with the density, which is also the direct cause of speed decline as pedestrian density increases. And when the density reaches the critical point, a leap occurs in

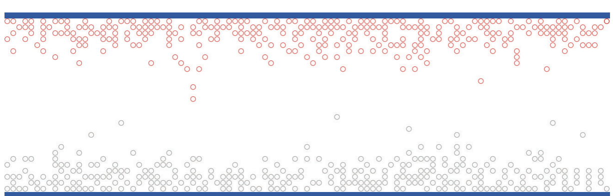


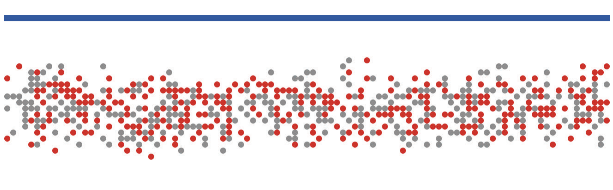
(a)



(b)

FIGURE 8: Diagram of the average speed and the volume against the density.


(a) Pedestrian flow with R-strategy


(b) Pedestrian flow with C-strategy

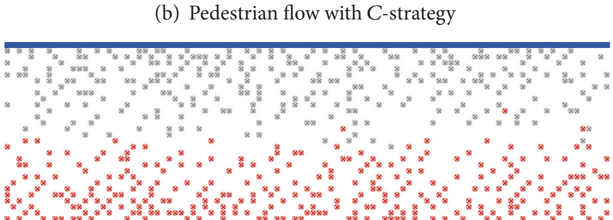

(c) Pedestrian flow with S-strategy

FIGURE 9: The collective phase of different pedestrian flow.

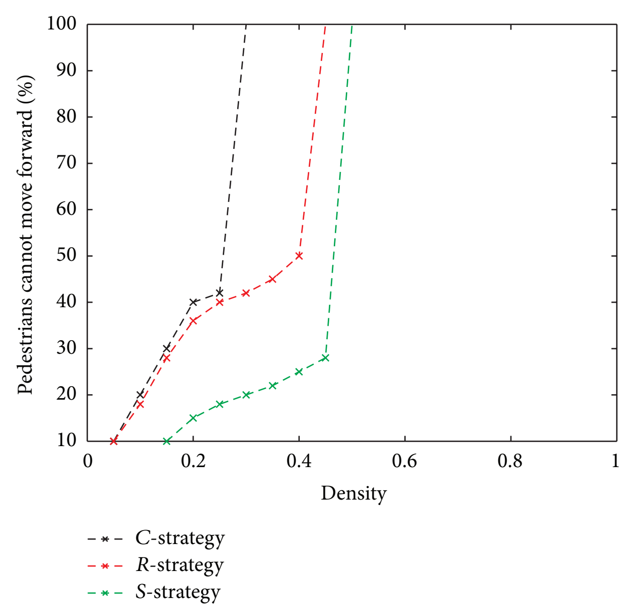


FIGURE 10: The percentage of pedestrians cannot move forward with different pedestrian flow against density.

the proportion. For instance, under the density of 0.25 in C-pedestrian flow, the proportion increases suddenly from 40% to 90%. An overall comparison of the three types of pedestrian flow shows that, under the same density, the proportion not able to choose going forward is the least in S-pedestrian flow, while that in C-pedestrian flow is similar to R-pedestrian flow before it is in a jamming phase. This is because there is much space available in the channel when the density is low. Even if pedestrians begin to gather in the center or on the two sides, many pedestrians' front cells in the assembling area are still empty for them to choose. However, when the density increases, instead of moving forward, most pedestrians have to stop or change steps to the left or right.

3.5. Experiment 4: Behavior Search. We analyze the impact of walking strategies on the pedestrian flow through research on the characters of the pedestrian flow which is purely formed pedestrians with only one walking strategy. And it is found out that the distribution of pedestrians in the channel has great impact on the movement of pedestrian flow. However, the pedestrian would not have only one type of moving strategy because of the random combination of pedestrian crowd in reality. The real pedestrian flow is formed of pedestrians with various random moving strategies. Hence, one may expect the problem that which probabilities of R-strategy, C-strategy, and S-strategy are taken by pedestrians, respectively, when pedestrian flows have relatively high operating efficiency. If we want to explore the answer to this question, it needs to set the value of parameter R, C, and S to simulate the pedestrian flow under every combination. Thus, according to the condition that $C + R + S = 100\%$, $C \in [0, 100]$, and $R \in [0, 100]$, $S \in [0, 100]$, there will be 6161 parameter combinations as the C, R, and S are integer, which form a parameter space. Simulating every parameter combination will be a difficult and time-consuming task. To perform the search, we design the simulation experiment based on BehaviorSearch. BehaviorSearch is a software tool implemented in java and interfacing with NetLogo modeling environment which can help with automating exploration the parameter space of any models written in the Netlogo language. The desired parameters and ranges to explore, the search objective function, and the search method to be used are set as follows (see Figure 11). We run the BehaviorSearch to discover the best result when the density is 0.10, 0.20, and 0.30. The data is collected from all of the simulations running along the way, and the result is shows in Table 1.

The result of the experiment shows that the condition that makes the highest average speed of pedestrian flow is not that pedestrian flow consists of purely one type of pedestrians but mixed with S-pedestrians as majority and C-pedestrians and R-pedestrians as minority. However, when the density increases, the percentage of C-pedestrians in optimal combination will be smaller and smaller, while the percentage of S-pedestrians will be larger and larger.

Now we analyze the contour map of the average speed of pedestrian flow in the parameter space with a density of 0.20 in detail. According to Figure 12, the average speed of pedestrian flow ranges from 0.48 to 0.64, and the average speed of pedestrian flow with optimal combination is 33.3% higher than that of pedestrian flow with worst combination. This also demonstrates the fact that different walking strategy has some influence on pedestrian flow from another aspect. Meanwhile, in the contour map, speed stratification is primarily based on the percentage of taking C-strategy: when the probability of C-strategy ranges from 0% to 15%, the average speed is between 0.60 and 0.65 and when the percentage ranges from 15% to 40%, the average speed is between 0.60 and 0.56.

These results indicate that the features of pedestrian flow are related to the probability of pedestrians with different walking strategy. When the probability of taking C-strategy in the pedestrian flow is comparatively large, it will be a disadvantage to the average speed of pedestrian flow. However, if probability of taking C-strategy is controlled in a certain range (such as 15% in the simulation experiment), there will be no big influence. Another essential conclusion is that the pedestrian flow consisting of pedestrians with different walking strategies can make space resource of roads fully used to some extent, resulting in a higher average speed compared with the pedestrian flow made up of only one strategy taken by pedestrians with the same density.

Table 1: The results of simulation experiment based on behavior search.

Density	R	C	S	Max average speed
0.10	16%	11%	73%	0.695
0.20	12%	6%	82%	0.639
0.30	9%	0%	91%	0.590

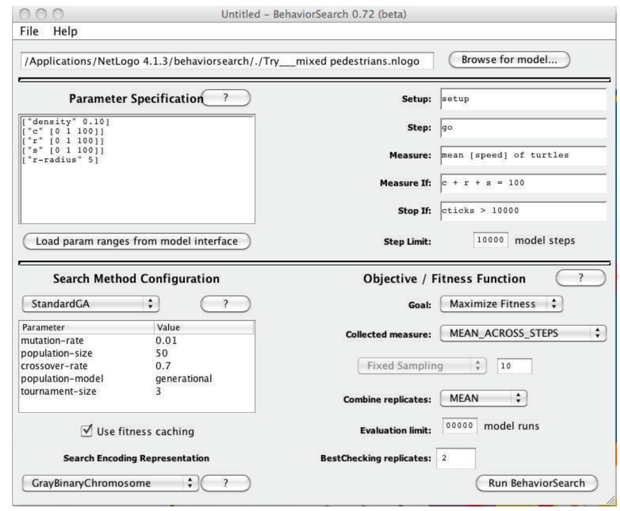


Figure 11: Screenshot of the BehaviorSearch GUI with the setting of parameters.

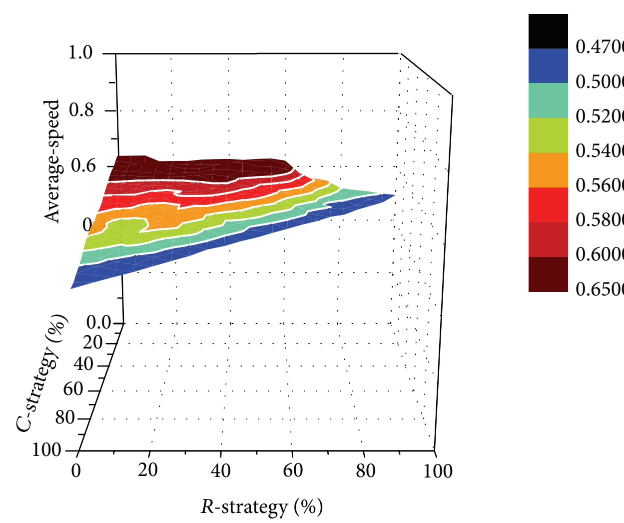


Figure 12: The contour map of average speed under all kinds of parameter combination.

4. Conclusion

Based on the research of walking habits and psychological characteristics of pedestrians, this paper summarizes three types of pedestrians' walking behavior when they are walking, namely, R-strategy, S-strategy, and C-strategy, as well as establishing the bi-directional pedestrian flow model under mixed walking strategies. In order to explore the effects on pedestrian flow of the three different walking strategies, we compared the critical density, fundamental diagrams, and collective phenomena of pedestrian flow caused by each walking strategy. The R-strategy has positive effect on corridor capacity, while the C-strategy and S-strategy have negative one. What is more, the S-strategy contributes to improving the operation efficiency of the bi-directional pedestrian flow. Observed from the simulation, the distribution in the channel of pedestrians with different walking behavior is different. Pedestrians with C-strategy mainly gather in the middle of the channel. Pedestrians with S-strategy are uniformly distributed in the channel, while pedestrians with R-strategy gather at the two sides of the corridor. This difference of spatial distribution directly leads to the difference of the three basic diagrams of pedestrian flow. With further analysis, the reason causing speed change of pedestrian flow is the proportion change of pedestrians who cannot choose walking forward. In addition, in order to explore the problem that which is the optimal proportion of these three types of pedestrians in pedestrian flow, we designed a simulation experiment based on BehaviorSearch. According to the search of the parameter space under the condition that $C + R + S = 100\%$, $C \in [0, 100]$, $R \in [0, 100]$, and $S \in [0, 100]$, the optimal combination proportion when density is 0.1, 0.2, and 0.3 is obtained, respectively, and specifically analyzed the contour map of C-R-F against average speed when density is 0.20. For the mixed pedestrian flow with mainly S-pedestrians and a small percentage of C-pedestrians, the pedestrian flow is basically not affected. However, if the percentage of C-pedestrians in the crowd gradually increases, the average speed of pedestrian flow will decrease. These researches can help us understand the psychology and walking characteristics of pedestrians as well as the macrofeatures of pedestrian flow. They are also beneficial for traffic engineers, planners, and policy makers to develop reasonable engineering measures to guide rational distribution of pedestrians in walking space, which can be helpful to improve the operating efficiency of pedestrian flow, and avoid congestion. In our future work, the presented model will be extended to investigate pedestrian walking strategies in evacuation or crowded situation.

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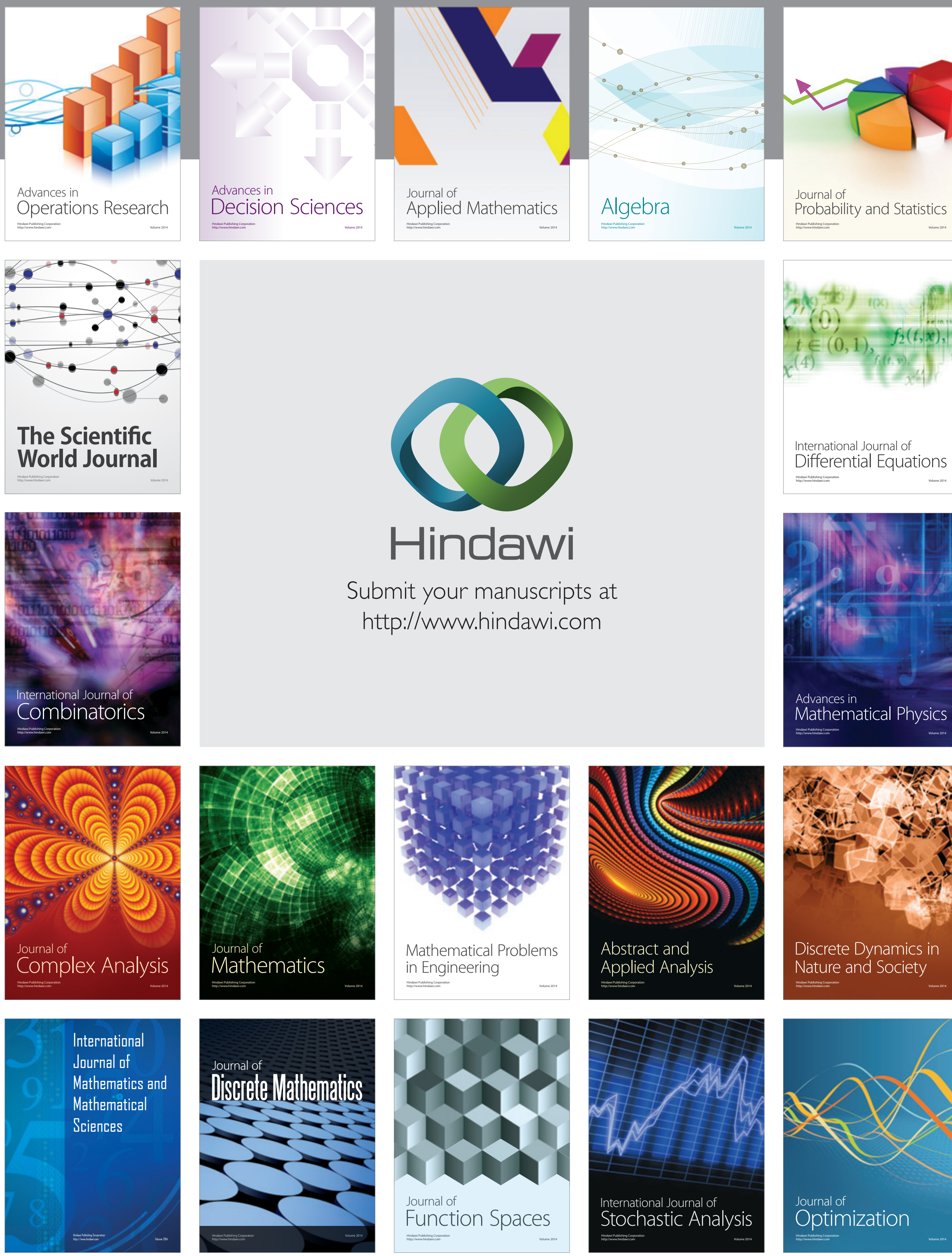
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