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Studies on the Evacuation Model for Limited Visibility and Evacuation Optimization in an Emergency

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Abstract: In emergencies such as fire, pedestrian evacuation for limited visibility is significantly different from normal visibility. On the basis of the previous studies for limited visibility, the novel evacuation model is proposed. And the herd effect is achieved. More, using the programming language, pedestrian evacuation is simulated. The simulation shows that the proposed evacuation model can well reflect the process of pedestrian evacuation and the evacuation signs of reasonable design can optimize the process when the evacuation is not a jam; under the condition of the equal total width, the design with double exits improves the evacuation efficiency compared with the single exit. In most cases, the universal herd can short the evacuation time; but the contrary results are also found. In order to solve the problem and make full use of positive factors of the herd, rational herd and blind herd are introduced. The simulation results show that the rational herd has a positive effect on the evacuation in any cases.

Key words: Computer simulation, cellular automata, evacuation model, limited visibility

INTRODUCTION

Pedestrian evacuation has characteristics, such as gathering themselves in the exits together, competing to the exit space and escaping the evacuation space; especially in emergencies such as fire, the research on evacuation has been the key problem (Helbing *et al.*, 2000; Shields *et al.*, 2009; Erica and Dennis, 2009). In simulation on the pedestrian evacuation, Cellular Automata (CA) simulation technology has been widely used; the development of CA can be traced back to 1940s when Neumann and Burks studied biological reproduction and crystal growth. CA is a discrete model which consists of a regular grid of cells, each cell in one of a finite number of states. At present, in the study of pedestrian evacuation simulation, many evacuation models based on CA has established, such as floors model (Huang and Guo, 2008), lattice gas model (Helbing *et al.*, 2003), dynamic parameters model (Yue *et al.*, 2009), etc. However, this is often not the case during fire emergencies, as smoke or a failure of the electrical power supply reduces the orientation significantly. Because of the toxic effects of smoke, fast evacuation is particularly important, but little is known about the behavior of people under conditions of bad visibility. Due to the less study on pedestrian evacuation for limited visibility, the further work should be showed in the study.

In this study, we will therefore focus on the investigation of the evacuation process from a room with limited visibility. For the effective evacuation, the pedestrians need to know environment around the pedestrian and evacuation information. The pedestrian evacuation for limited visibility is a complex and dynamic process (Yue *et al.*, 2009; Isobe *et al.*, 2003). Our study is focused on two aspects that are theoretical analysis of evacuation model and evacuation simulation. In the model, the evacuation strategies, pedestrian moving rules and the herd effect are described and proposed in section 2. The pedestrian evacuation is simulated and studied using the evacuation model for limited visibility in section 3. The simulation results are as follows: In section 3.1, the effect of evacuation signs is showed; in section 3.2, the evacuation processes and time on single and double exit are compared; in section 3.3, the universal herd of all pedestrians is simulated and the positive and negative influences on evacuation are

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showed; in section 3.4, the rational herding is proposed which is different from the blind herd. This topic research will further improve the evacuation model and theory, make up for the lack of research on pedestrian evacuation for limited visibility and provide the useful guidance on the evacuation optimization and emergency management of evacuation.

EVACUATION THEORY AND MODEL

Basic rules of pedestrian movement: The simulation area is a 24×24 m rectangular room. The size of a cell corresponds to 0.4×0.4 m, then the simulation area is divided into 60×60 square cells. Moore neighborhood is used in the study in Fig. 2. In the model, each cell is occupied by one pedestrian or is empty. Each pedestrian can move to one of its unoccupied adjoining cells at each discrete time step according to transition probabilities or keep the primary cell. These probabilities are decided by the danger field of the selected exit. The pedestrian will not enter the system after leaving the evacuation system.

The danger field is introduced in the evacuated room and each cell corresponds to a value of danger grade in the danger field. The pedestrians decide the goals at next time step according to the danger grade. Assuming that the values of the danger grade for the cells at exit are zero, the values of the other cells are determined by the distance from the cells to exit. The farther the distance from exit is, the greater the danger value is. The danger values are given (Yuan and Tan, 2007):

$$P_D = \begin{cases} kS_{xy}^{k_s}, & \text{the cell is empty} \\ M, & \text{the cell is occupied} \end{cases} \quad (1)$$

$$S_{xy} = \min_n(\min_m \sqrt{(x - x_n^m)^2 + (y - y_n^m)^2}) \quad (2)$$

where, PD is the danger value; k is the ratio coefficient; k_s is the exponent to adjust the sensitive degree between distance and danger value; S_{xy} is the shortest distance between the cell (x, y) and the exit cells; n is the serial number of the exit; (x, y) is the coordinates of the cell in

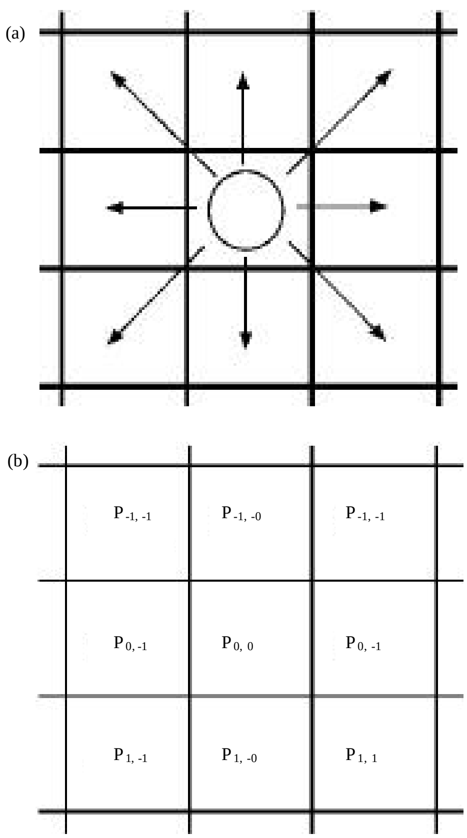

Fig. 1(a-b): (a) Moore neighborhood and (b) pedestrian movement direction

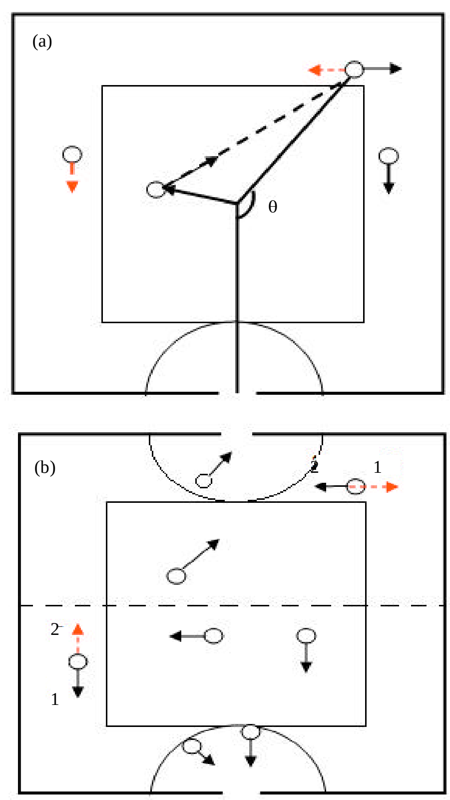

Fig. 2(a-b): Analysis figures on evacuation time (a-b) Are the figures of single exit and double exits, respectively evacuation system; (x_n^m, y_n^m) is the coordinates of the m^th^ cell in exit n; M is a very large positive number which indicates that the wall or the occupied cells are not selected as the movement goal. Using the same method, the danger value of the room with one exit can be calculated.

It should be noted that the way pedestrians update their position is a very complex process and the parallel update is adopted in the evacuation model. The basic update rules include:

- In the visible area of exit, the pedestrians select the adjoining cell based on the safety benefits. The cell with the maximum safety benefits will win
- In the visible area of wall, the pedestrians adopt the moving directions that are parallel to the wall. If the front cell is occupied, the right-front cell is selected. Then the left-front cell is selected when the front and right-front cells are occupied. If the three cells are occupied, the pedestrian will keep its waiting
- In the blind area of pedestrian movement, the pedestrians will select one of the eight adjoining cells randomly to walk. If the process is blocked, the pedestrian will wait till succession.

If there are evacuation signs in the room, the following running rules are used (a) The pedestrians in the blind area walk along the selected direction, (b) When they find evacuation signs, the pedestrians move to the visible area of wall; then move along the direction of signs and (c) The pedestrians in the visible area of wall select the provided direction after seeing the evacuation sign. If more evacuation signs are found by the pedestrians, the sign near to the exit will be selected.

Evacuation strategies: The pedestrian movement for limited visibility is decided by the evacuation information in the range of perception that is the area within the vision distance. The right or wrong information on voice is not distinguished by pedestrians, so the perceived information does not include voice. Firstly, the evacuation strategy for single exit is analyzed. The evacuation area is divided into three components: the visible area of exit, the visible area of wall, the blind area of pedestrian movement. The visible area of exit is the range that the distance to exits is less than or equal to the visible distance; the visible area of wall is the range that is less than or equal to the visible distance; the blind area of pedestrian movement is the rest area except the visible area of exit and the visible area of wall. At the beginning of evacuation, all pedestrians are randomly located in the room. Due to different information in different areas, the pedestrians will select different evacuation strategies that are suitable for their areas. The strategy is as follows:

- Pedestrians in the visible area of exit move directly to the exit, then evacuated to the external security space
- Pedestrians in the visible area of wall select clockwise or counterclockwise direction to move, until they enter the visible area of exit
- Due to the less information in the blind area of pedestrian movement, the pedestrians move along one of eight directions randomly, until they enter to the visible area of exit or the visible area of wall

Using evacuation strategies, all pedestrians can leave the room and arrive at the security space.

Evacuation time analysis: Evacuation time for limited visibility in the case of no jam is mainly decided by the path of pedestrian movement. The evacuation signs have an obvious effect on the path choice. The average evacuation time with or without evacuation signs are analyzed and deduced. In the process of deducing the formulas, we assume that the visible distance is much smaller than the size of room. Supposing the distance from initial position to the visible area of wall is defined by r_i; v is the moving velocity. d (θ) is distance to exit following the wall. the evacuation time for single exit and double exits are analyzed (Fig. 2).

The total evacuation time is decided by the longest walking path of pedestrians which includes all paths in the three areas. The longest walking path in the blind area is nearly equal to the diagonal length of the blind area which is $r' = 2^{0.5}d/(0.5\pi)$. The walking length for single exit in the visible area of the wall is half of a circumference of the room; the length for double exits is a quarter of the circumference. So, the design with double exits can shorten the evacuation time and increase the evacuation efficiency. So, the ratio of evacuation time for single exit and double exits is approximately given by the following equation:

$$\frac{T_2}{T_1} = \frac{t'_{max}}{t_{max}} = \frac{\sqrt{2}+1}{\sqrt{2}+2} \approx 0.71 \quad (3)$$

The value 0.71 is an estimated value, not an exact value.

More studies show that under the same total width, more exits mean the short walking path and high efficiency which shows that the exit design should consider the convenience of pedestrian evacuation.

Introduction of the herd effect: Herd is a kind of typical psychological phenomenon, especially in emergencies such as fire. If the pedestrians are not familiar with the surrounding environment, they are in a blind state and show the obvious herd effect. In bad visibility the pedestrians know less information on evacuation which means not to determine the best evacuation route. So, the pedestrians will select their directions according to the mainstream direction in visible distance. In the study, the herd effect is determined by two parameters. One is the ratio of pedestrian number for certain direction in the visible distance that is expressed by η; the other is the pedestrian number of certain direction in the visible distance that is expressed by n_c. The rules of herd effect are the following (1) The number ratio of the selected direction is maximum and more than certain value and (2) The pedestrian number is more than certain value. The two rules must be satisfied meantime.

SIMULATIONS RESULITS AND ANALYSIS

In simulation, the pedestrians are distributed in the room randomly before evacuation. The same initial distribution and the same initial direction of pedestrians are used in multiple simulations under different situation. The exit is designed in the middle of each wall; there are eight signs that are designed in a third point in all walls. Each signs only occupy one cell. The evacuation time is given using average value of five times' independent calculation.

Evacuation analysis for single exit: First, the pedestrian evacuation in the room with single exit is simulated using the evacuation model for limited visibility. In simulation, the visible distance is 4 cells and the visible range of exit and evacuation signs is 6 cells. The evacuation processes of 200 pedestrians with 8 signs are simulated.

Figure 3 shows the evolution figures with 200 pedestrians for initial distribution, the 20, 40 and 60th time step. From the figures, the pedestrians in the blind area select certain direction and walk along the direction until enter the visible area of wall or the visible area of the exit. The pedestrians in the visible area of wall select the clockwise or counterclockwise direction randomly to move before seeing the evacuation sign; when seeing the sign the pedestrians adjust the right direction and select the optimal path to escape. From the figures, we also find that under the effect of the signs, in the left area of the room the direction of the pedestrians is mainly counterclockwise (blue marks) and in the right area of the

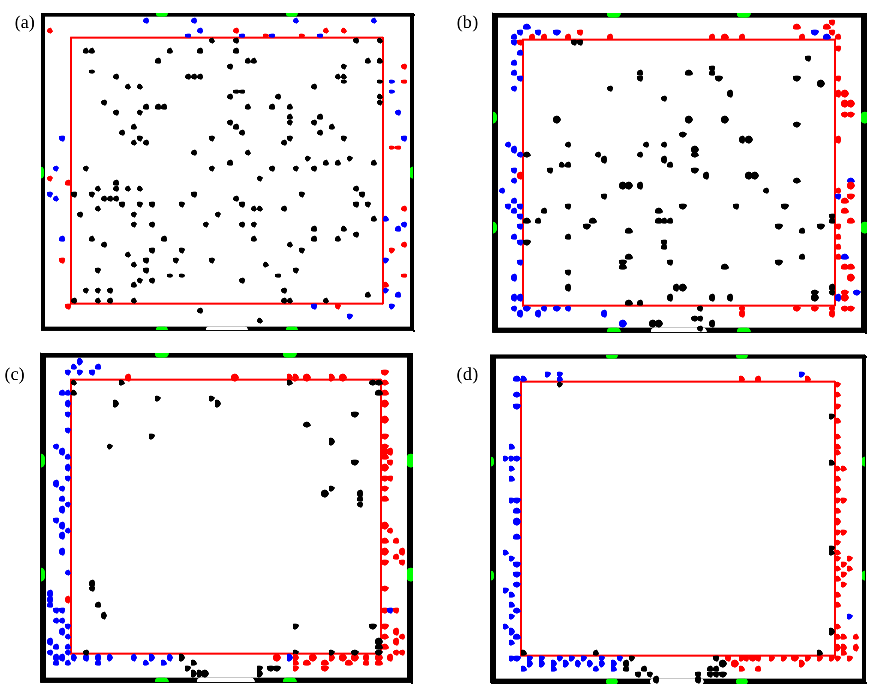

Fig. 3(a-d): Evolution figures with 200 pedestrians (a) time step: 0 red: Clockwise; blue: Counter clockwise, (b) Time step: 20 red: Clockwise; blue: Counter clockwise, (c) Time step: 40 red: Clockwise; blue: Counter clockwise and (d) Time step: 60 red: Clockwise; blue: Counter clockwise room the direction of the pedestrians is mainly clockwise (red marks). In the visible area of the exit, the pedestrians move to the exit using idea of the danger field. Simulation shows that the evolution process accords to the evacuation model and the dynamical characters of pedestrian evacuation. The calculation result of the evacuation time is 156 time steps. The calculation also shows if no evacuation signs, the evacuation time for 200 pedestrians is 279 time steps which is low efficiency.

Here, the simulation results show that evacuation model for limited visibility is reasonable and effective. The evacuation signs can provide the effective and correct evacuation information that can optimize path and improve the evacuation efficiency.

Comparative analysis of single exit and double exits: In this section, the pedestrian evacuation for the single exit and double exits is studied under the condition of the same total exit width; then the exit design is advised. For double exits, the width of two exits is equal and they are distributed in the middle of the opposite walls. In the simulation, the number of initial pedestrians is 200. The visible distance, visible ranges of the exit and evacuation signs are the same as the parameters in section 3.1.

Figure 4 provides the relations of the evacuation time and the ratio of evacuation time with the total width of room exits for single exit and double exits. From the datum of simulation and calculation, we can see that when there are two exits, the evacuation time becomes short; then the evacuation efficiency is enhanced obviously. Therefore, when the total width of single exit and double exits is equal, the design with double exits is superior to the design with single exit obviously. Moreover, the evacuation time of single exit and double exits decreases with increase of the total width of exits. When the total width is less than 4 cell lengths, the decreasing trend of evacuation time is obvious with increase of the total width of exits; when the total width is more than 4 cell lengths, the decreasing trend is weak. This reason is that when the total width is less than 4 cell lengths, the evacuation at the exit is jammed; then the evacuation time depends on the exit width. When the total width is more than 4 cell lengths, the evacuation at the exit is unobstructed; then the time depends on the longest path of pedestrian movement. Meanwhile, the calculation shows the ratio of evacuation time with single exit and double exits is near 0.71 when the total width is more than 4 cell lengths. The ratio can accord with the Eq. 10 in section 2.3. On the contrary, when the exits are jammed, the ratio is more than 0.71 which is result of jam.

Meanwhile, in Fig. 5 the evacuation time and ratio of evacuation time corresponding to different initial number of pedestrians are compared. The total width is 8 cell lengths. From the figure, it can found that for any initial pedestrian number the evacuation efficiency for double exits is more efficient than single exit which shows the design with two exits is optimal than single exit. Further, the ratio of evacuation time is showed in Fig. 5 and we can find that when the number of pedestrians is less than 300, the ratio is near 0.71; otherwise, when the number is more than 300, due to the jam the ratio is smaller than 0.71. So, the above results under the condition of different initial number of pedestrians prove the correctness and rationality of the pedestrian evacuation theory and design with double exits.

The simulation results show that for the more effective evacuation the exits should select optimal design; by contrast, without severe jam, the evacuation with double exits is more effective than the evacuation with single exit.

Effect of universal herd on evacuation: In emergency such as fire, due to limited visibility pedestrians in the room

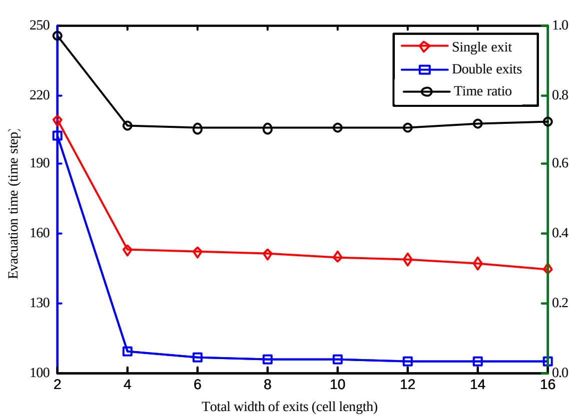

Fig. 4: Evacuation time and time ratio with the total width

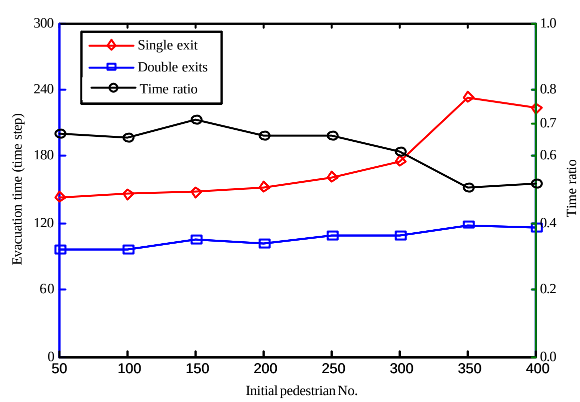

Fig. 5: Evacuation time and time ratio with No. of pedestrians

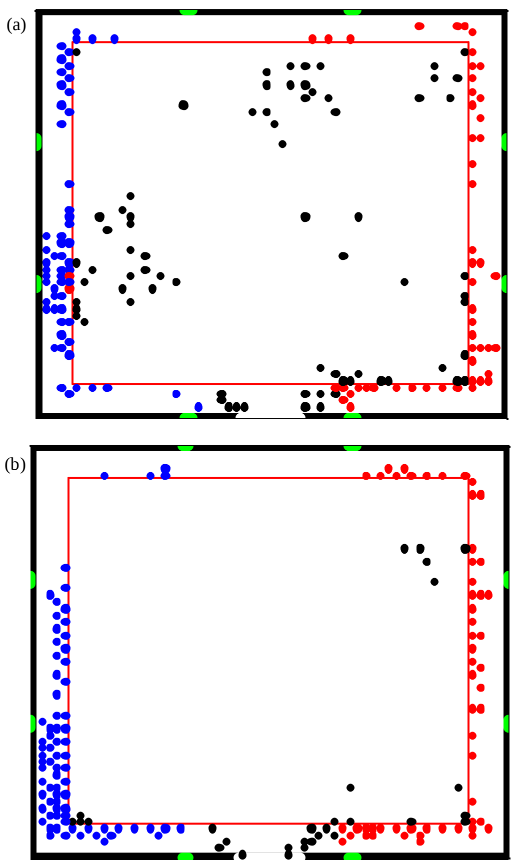

Fig. 6(a-b): Evolution figures with 200 pedestrians and universal herd for the 20 and 40th time step (a) Time step: 20 red: Clockwise; blue: Counter clockwise and (b) Time step: 40 red: Clockwise; blue: Counter clockwise

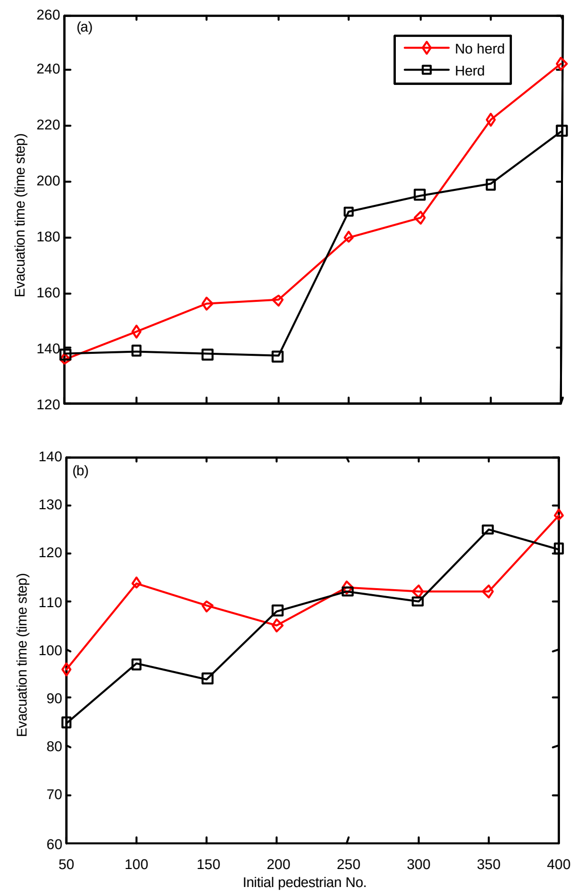

Fig. 7(a-b): Evacuation time with and without universal herd effect against pedestrian number for single exit and double exits

know little information on evacuation. In this case, the herd phenomenon becomes obvious. In this section, we will focus on the effect and influence of herd effect on pedestrian evacuation. Then according to the simulation and analysis on herd, suggest evacuation strategy that can raise efficiency of pedestrian evacuation. First, all pedestrians in any positions and areas adopt the herd strategy which is called 'universal herd'.

Figure 6 provide the evolution figures for the 20 and 40th, time step with 200 pedestrians and 8 evacuation signs. The results show that no herd effect the evacuation time is 157 time steps; after considering the herd effect, the evacuation time is 137 time steps which shortens 20 time steps which shows the herd is beneficial to improving evacuation efficiency. By comparing Fig. 3 and 6, the reason is as follows: If no herd effect, the pedestrians in the blind area walk to the visible areas of wall and exits gradually and the movement is not affected by the pedestrians around the current position, the interaction among the pedestrians is limited. After considering the herd effect, crowd phenomenon of the pedestrians appears (see the figure for the 20th time step in Fig. 6). And the herd effect can make the pedestrians who enter the visible area of wall to adjust the walking direction before seeing the evacuation signs which avoids the phenomenon of detour and decreases the time.

More studies on herd are showed. The evacuation time for single exit and double exits under no herd effect and considering herd effect is calculated (Fig.7). Figure 7a is the time of single exit; Fig. 7b is the time of double exits. After all pedestrians adopt the herd effect, the evacuation time is reduced in most cases, but there are some cases of increasing time, such as the evacuation time of 300 pedestrians in room with single exit is 187 and 195 time steps before and after considering

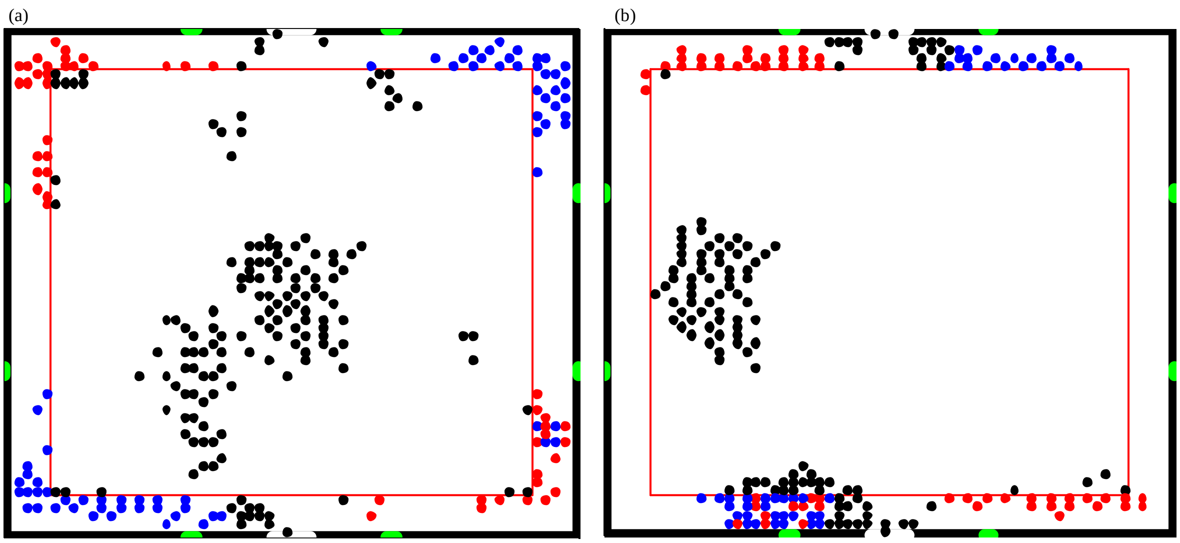

Fig. 8(a-b): Evolution figures with universal herd and 350 pedestrians for the 20 and 40th time step (a) Time step: 20 red: clockwise; blue: Counter clockwise and (b) Time step: 40 red: Clockwise; blue: Counter clockwise

the herd effect, respectively; the evacuation time of 350 pedestrians with double exits is 119 and 125 time steps before and after considering the herd effect, respectively.

By analyzing the evolution figures on pedestrian evacuation, the reason of time delay after considering herd effect is showed. Fig. 8 provides the evacuation figures of double exits for the 20 and 40th time step. From the figures it is found that the herd effect forms the crowed phenomenon of the pedestrians in the blind area; then the crowed pedestrians move to the visible area of wall and result in the asymmetric distribution in the process of evacuation; the asymmetric distribution delay the evacuation time.

Universal herd, as a kind of familiar psychological behavior in an emergency will cause certain influence to the pedestrian evacuation. The results have showed that the universal herd is beneficial to evacuation in most cases but the positive effect is not suitable for any cases. In order to make full use of the psychology of herd effect, more studies need to be done. In the blind area, due to the less information on exit, the selection on movement direction is blind; it is not sure whether the herd effect is positive or negative; so the herd effect should not be used in the blind area. In the visible area of wall, due to the effect of the evacuation signs the right information can be achieved which can provide the right information on exits to the pedestrians who just enter the visible area of wall from the blind area by using the herd effect. When the herd effect is adopted, the blind detour can be avoided which can shorten the evacuation time. So for the positive effect of the herd, the pedestrians in visible area of wall should adopt the herd effect, but the pedestrians in blind area don’t adopt the herd effect which is called ‘rational herd’.

Optimization of rational herd on evacuation effect: Rational herd has positive effect on the pedestrian evacuation with limited visibility. However, the effect of blind herd is unknown. For the positive effect of herd, only the rational herd is used which can avoid the negative influence of blind herd in the blind area. Based on the rules of herd in section 2.4, the evacuation time with single exit and double exits is calculated before and after considering the herd effect in the visible area of wall, respectively (Fig. 9). Figure 9a-b show the evacuation time in single exit and double exits, respectively. From Fig. 9, it is found that using the rational herd, in any cases the time is shortened, but the difference is random which is decided by the initial distribution of pedestrians and initial movement direction. The results of the herd effect show that the rational herd is different from the universal herd and realize the goal of high evacuation efficiency.

More studies show that the room size and the number of exits do not affect the positive effect of rational herd; the rational herd has is applicable to the pedestrian evacuation with limited visibility. So, the rational herd should be used for the pedestrian evacuation.

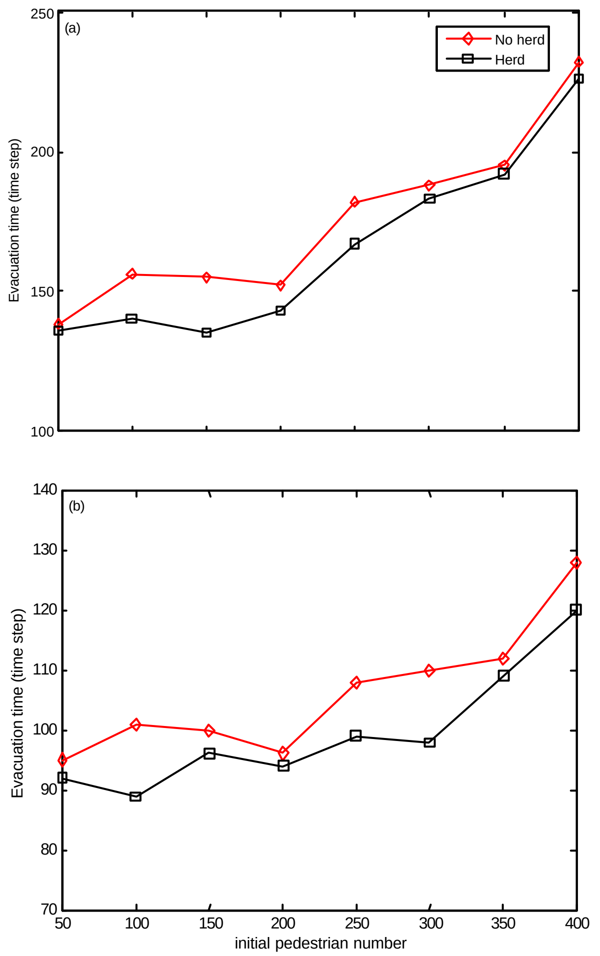

Fig. 9(a-b): Evacuation time with no herd and rational herd for (a) Single exit and (b) Double exits

CONCLUSION

The evacuation strategies and update rules are suggested based on the evacuation situations for limited visibility. And the herd effect in evacuation is introduced. The simulation results are as follows:

- The proposed evacuation model can well reflect the process of pedestrian evacuation and the evacuation sign has the positive effect on pedestrian evacuation
- Supposing the total exit width to be fixed, it is found that the evacuation time for double exits is shorter than the time for single exit. The design of double exits improves evacuation efficiency. For no jam, the time between single exit and double exits is near 0.71
- In most cases universal herd will improve the evacuation efficiency, but there are some cases of decreasing time for asymmetric crowed phenomenon. So the rational herd is proposed which only considers the herd effect in the visible area of wall
- The simulation shows that the rational herd is benefit for the evacuation for single exit and double exits which proves the analysis on rational herd and blind herd

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