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Study on pedestrian flow evacuation with individual-guidance mechanism

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Abstract

Purpose – The purpose of this paper is to provide the possible and better selection for pedestrian flow evacuation.
Design/methodology/approach – Simulation.
Findings – First, according to the model with self-decision agents, the paper figures out that the effect of evacuation guided by the random-walk mechanism exceeds that guided by the inertial mechanism, and specifically, the effect of evacuation could significantly improve if random-walk agents restraint the probability of random walk under 0.4. Besides, on neighborhood reference mechanism, individuals who take neighbors' average direction as reference tend to achieve better effect of evacuation than that of following majority rule. Furthermore, this paper proposes that an optimal ratio of the proportion of clever individuals and system density exists for evacuation effect improvement. Finally, the evacuating effect with barrier locating in different space is also studied in our research.
Originality/value – The effect of evacuation could significantly improve if random-walk agents restraint the probability of random walk under 0.4. On neighborhood reference mechanism, individuals who take neighbors' average direction as reference tend to achieve better effect of evacuation than that of following majority rule.

Keywords Behaviour, Artificial intelligence, Intelligent agents, Learning, Social networks, Simulation
Paper type Research paper

1. Introduction

Collective activities of human beings have exploded dramatically as society developed. However, a great number of casualties caused by catastrophes and emergencies such as earthquakes, fires and stampedes, are rooted in the local spatial congestion without timely guidance. In this field, theory of pedestrian flow is one of the basic regularities for the design of pedestrian facilities and collective activities places, and also for pedestrian flow management, control and guidance.

On the research of pedestrian evacuation, simulation techniques based on pedestrian micro-behavior characteristics have become a direction for the macro-feature exploration, under different pedestrian evacuating situations. And these studies also have practical significance in public security and fire safety engineering.

Macroscopic models of pedestrian flow were primarily proposed by Henderson (Henderson, 1971, 1974; Henderson and Lyons, 1972), on which Henderson concluded that: pedestrians could move freely as gas molecules in motion features with relatively low system density; however, pedestrians move with a certain constraints as fluid molecules in motion features with relatively high system density. Further, pedestrians

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in condition of relatively high system density followed Maxwell-Boltzmann statistical theory if in equilibrium, which is capable of finding macro-statistics of the system with statistical average methods.

A mesoscopic model of lattice gas model (Muramatsu *et al.*, 1999; Muramatsu and Nagatani, 2000a, b) was utilized to characterize self-organization behaviors and critical phase transitions in pedestrian flow. The representative one was biased random walk lattice gas model (Muramatsu *et al.*, 1999), which was put forward on the basis of multi-agent DLA simulation. With relative improvement to macroscopic models, lattice gas model yet could hardly capture the interactions among pedestrians. Tajima and Nagatani (2001) researched on the characteristics of pedestrian evacuation dynamics in a specific architectural structure.

Microscopic models such as social force model, cellular automation model and agent-based model can capture specific behaviors of pedestrian flow, and thus drawn attention from scholars of different fields. Dirk Helbing (Helbing and Molnar, 1995; Helbing *et al.*, 2000), as the first mathematician and sociologist to combine the social force with physical force, proposed a concept of "social force" to dominate pedestrian flow on the basis of molecular dynamics, analyzed some affected factors of pedestrian flow, and also explained some self-organization behaviors and collective effects. In the late 1990s, Cremer and Ludwig (1986) primarily introduced cellular automation models into vehicles motion with verification of real transportation data. Soon some scholars (Blue and Adler, 1998, 2001; Fukui and Ishibashi, 1999) adapted cellular automation model into pedestrian flow simulation and burgeoned cellular automation-based pedestrian flow models. In addition, in order to characterize complex, non-linear and inconsecutive motion behaviors, agent-based pedestrian models (Chen *et al.*, 2010) were carried out for specific individual simulation of decision making (Bonabeau, 2002). Agent-based models perform excellently in simulating panic and congestion in evacuation, and also provided explanations for evolutionary mechanism.

Besides the classical models above, there are many other models in pedestrian flow including magnetic model (Okazaki, 1979), queuing network model (Løvås, 1994; Thompson and Marchant, 1995), centrifugal force model (Yu *et al.*, 2005), mean-field model (Nagatani, 2001; Yanagisawa and Nishinari, 2007), dynamic game model (Zhang *et al.*, 2004; Li *et al.*, 2007; Ji *et al.*, 2008), etc. Furthermore, some scholars tried to combine different methods to construct models, such as the simulation model based on fragmental magnetic field and dynamic game (Ji *et al.*, 2009), cellular automation model on the basis of lattice gas (Yamamoto *et al.*, 2007), which all provided grounds for the further study of pedestrian dynamics.

Owing to capability for simulation of physical system and natural phenomenon, cellular automation models are widely employed in the simulation of pedestrian flow and evacuation analysis.

Dai *et al.* (2013) simulated gradient force, repulsive force, resistance force and random force by agent-based model to verify pedestrian behaviors in Guangzhou Metro. Ha and Lykotrafitis (2012) utilized the agent-based model to simulate the evacuating effect of exits of different sizes and various evacuating speeds of social force model in a complex-structure building. Both works of Yang *et al.* (2011) and Yamamoto (2013) took advantage of agent-based model to simulate the evacuation in a fire of a building. Ben *et al.* (2013) researched on the evacuating effect under indoor barriers and order based on CA circumstance. Ren *et al.* (2009) simulated the evacuating situation in an explosion disaster based on agent-based model. Sharma and Lohgaonkar (2010) combined agent-based model and fuzzy logic to simulate population behaviors including goal finding behavior, collision detection and avoidance behavior.

Laughery (1998), Lee *et al.* (2010) and Norling (2004) all utilized the BDI framework to study the decision-making process of individuals in group evacuation.

The references above concentrated on the impacts of individual's own decision and environmental conditions on the system evacuation. However, this paper incorporates individual-guidance mechanism into agent-based models, and discusses the condition of existence for the mixed strategy with agent-based models under various settings.

2. Pedestrian flow model with individual-guidance mechanism

In real system, a minority of individuals with complete information about location of exits, existence and direction of barrier, distinct movement directions, etc., can be named by clever agents. In reverse, most of individuals possess little information and make decision with neighboring reference and history references are called ordinary agents.

This paper proposes an agent-based pedestrian flow model, and discusses the guidance effect of clever agents as well as the decision-making way of ordinary agents.

The agent-based simulation pedestrian flow model can be realized by setting a certain simple individual decision-making mechanisms, interaction mechanisms among agents and between agents and the environment, according to specific complex emerging. Some assumptions of basic model are as below:

(1) The features of the agents and the density of the space: a certain proportion of "clever agents" exist in the system, and they distinctively know exact exits locations for evacuation. Therefore, decision-making behavior and strategy of clever agents can be defined as complete rational behaviors. The clever agents tend to evacuate the system as soon as possible. Under the condition of neighboring reference, a part of ordinary agents could also be guided by clever agents for quick evacuation. Thus, we figure out that the effect of evacuation has to do with the proportion of clever agents, density of agents, etc.

(2) The strategies for the individual to choose: ordinary agents have two optional strategies: referring to neighbors or finding route by oneself. For referring to neighbors, they may choose from two kinds of rules: majority rule and average direction rule. Majority rule means that individuals follow the direction which is chosen by most neighbors, and the average direction rules is that individuals take the neighbor average direction as reference to choose the direction. For the strategy of finding route by oneself, there are also two mechanisms, maintaining the inertia and random walk.

(3) Exits setting: exits are asymmetrically placed on both sides of the system.

The agents' characteristic and their environment could be explained by the flow diagram in Figure 1.

3. The effect of evacuation analysis with maintaining inertia and random walk

3.1 Autonomy with maintaining inertia

Characteristics of decision-making process for agents are summarized as follow:

$$\begin{cases} T_i(t) = P' \cdot \Omega(T_i(t-1)) + \left(1-P'\right) \cdot \Psi(T_i(t-1)); \\ \Omega(T_i(t)) = \Phi\left(T_{x-1,y}, T_{x-1,y+1}, T_{x-1,y-1}, T_{x,y-1}, T_{x,y+1}, T_{x+1,y}, T_{x+1,y-1}, T_{x+1,y+1}\right); \\ \Psi(T_i(t)) = \Gamma(T_i(t-1)); \end{cases} \quad (1)$$

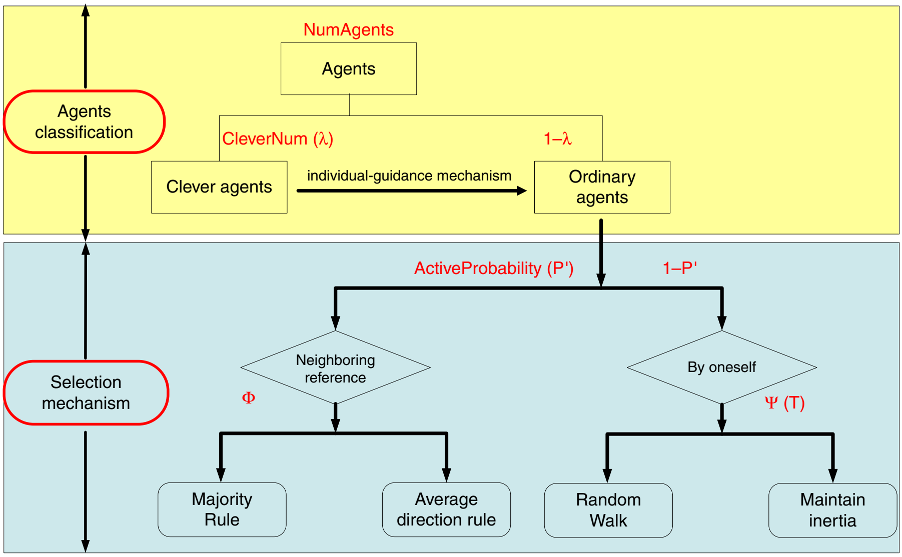


Figure 1.
The flow diagram of the agents' characteristic and environments

where (x, y) is the coordinate of $T_i(t)$; and φ_i follows random walk process. $\Omega(T)$ is the strategy choosing function of neighbors reference for agents; and $\Phi(T_{x-1,y}, T_{x-1,y+1}, T_{x-1,y-1}, T_{x,y-1}, T_{x,y+1}, T_{x+1,y}, T_{x+1,y-1}, T_{x+1,y+1})$ the majority rules. $\Psi(T)$ is the autonomy choosing function. In the basic model:

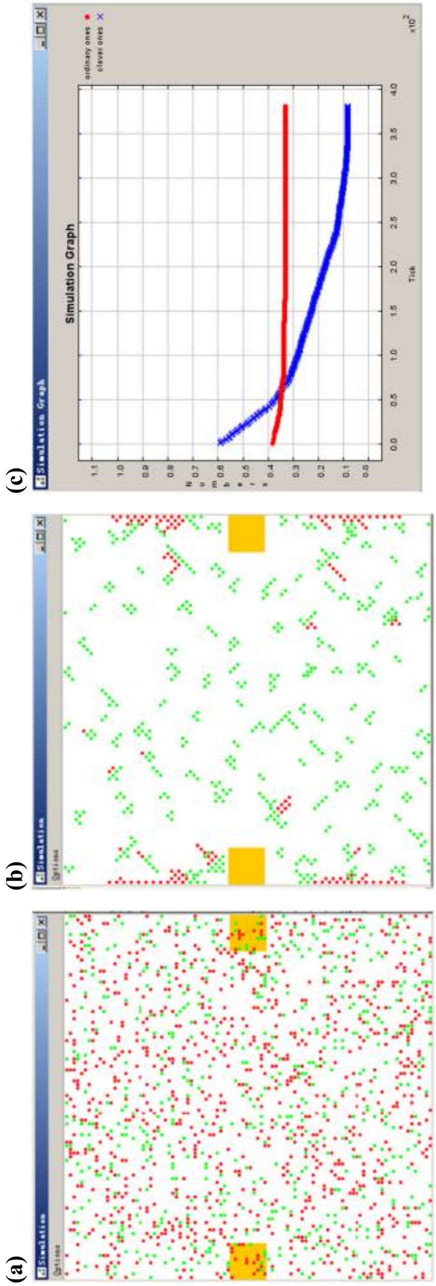
$$\Gamma(T_i(t)) = \Theta \cdot T_i(t) \tag{2}$$

where Θ denotes indicator function. When the value of Θ is 1, agent keeps the direction same with that of last moment; and when the value is 0, it means that the agent are in quiescent state.

Figure 2 presents the simulation results of finding route by oneself by maintaining inertia. Figure 2(a) displays the situation of agents in a relatively high-density. As Figure 2(b) shown, simulation results are remarkably consistent with some related sociology research conducted by Dirk Helbing.

Dirk Helbing has systematically illustrated the effect between social force and physical force in high-density situation: when the density of system is too high for agents' movement, social force loses its importance while physical force becomes the main thrust causing the congestion. In addition, a serious stampede occurring near Mecca, Saudi Arabia on January 12, 2006 is a cogent example for this conclusion. The video record of the local fixed camera displayed that when such emergency occurred, big groups would be dispersed into several small groups, interacted with adjacent ones. The pressure relief was unpredictable and uncontrollable.

Besides, referring to database of September 11 attacks from Building Disaster Assessment Group in UK, the record also support our simulation partially. The record of North Tower revealed that about 90 percent (62/69) of individuals form groups before evacuating, and only 10 percent of persons chose to escape by themselves. In South Tower, 88 percent (69/88) of individuals grouped and 12 percent of them escaped on their own. Further, in South Tower, the formed groups were not large: 90 percent (19/21) were as small as less than five members, and 62 percent of them only



Notes: In Figure 2(c), the horizontal axis (*Tick*) represents the time step for the agents to evacuate out of the system, and the vertical axis (*Numbers*) represents the number of agents left without evacuation in time. $P' = 0.6$, $\lambda = 0.6$ and NumAgents=1,500

Figure 2.
The simulation results of finding route by oneself by maintaining inertia

included two persons. In North Tower, the scales of formed groups tended to be average, among which small ones(less than five persons), medium ones (six-ten persons) and large ones (more than ten persons) were relatively evenly distributed.

As shown in Figure 2, simulation results reveal four significant characteristics for the congestion of system: first, the congestion mainly appears in local-scale instead of global-scale. Next, the congestion effect follows a characteristic of self-similarity, and the shape of local congestion is typically similar to each other. Further, the closer agents approach exists, the more serious congestion seems to be. Finally, it can be conclude that the clever agents also suffer from congestions in the process.

In real situation, the conditions of Figure 2(b) probably seldom appear, the phenomenon is due to the combined effect of the social force and physical force. Real situations may go beyond Figure 2(b) if physical force makes influences with relatively wide-horizon and rational agents. However, when it turns to social force as main influences instead of physical force, the local congestion showed in Figure 2(b) would probably occur.

3.2 Autonomy with random walk

Far from maintain inertia, if agents find route by oneself with $\Psi(T(t))$ following random walk process, the stable state of the system is shown in Figure 3:

$$\Psi(T) = R_r \tag{3}$$

Panic Index is defined as the probability for agents to tradeoff between referring of neighbors and finding route by oneself. Practically, the evacuation opportunity is the optimization process of Panic Index. According to Len Fisher, Panic Index would better be manipulated on about 0.4, i.e. agent spent 40 percent of time following the crowd, and used 60 percent to think and dominate by themselves.

As Figure 4 shown, under the condition of find route by oneself, evacuating effect of random walk for agents exceeds that of maintaining inertia.

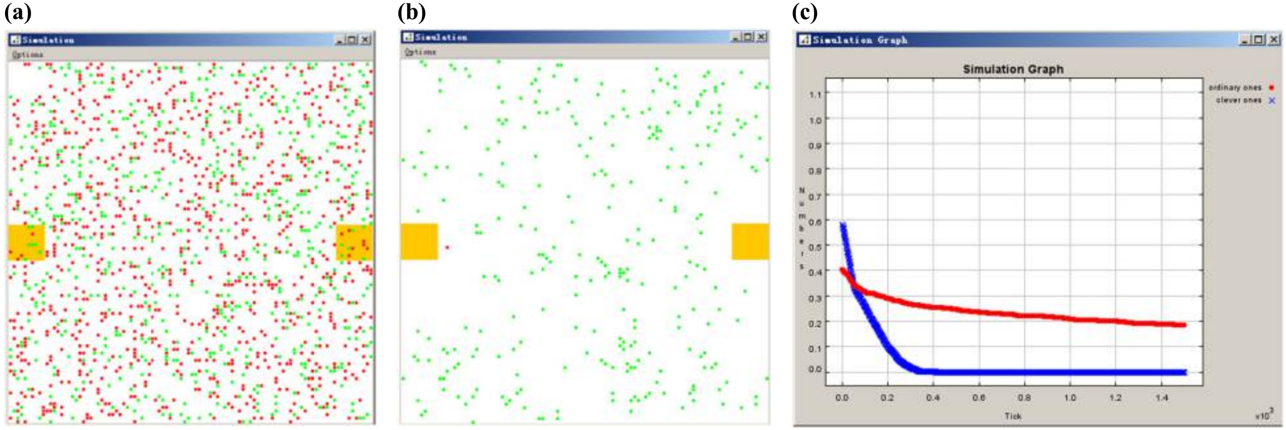
In the simulation system, owing to guidance of clever agents, the probability kept by ordinary agents to find route by oneself (i.e. numeric equivalent of Panic Index) has to do with system density, probability of random walk, etc.

Therefore, we compare the evacuating effect of system under reference degrees (i.e. different probabilities of random walk). As shown in Figure 5, although appropriate randomness of agents may benefit the effect of evacuation, yet over-high randomness tend to cause a worse evacuation effect. As $1-P' \leqslant 0.4$, the evacuating effect improves significantly. The simulation results are consistent with research results of Panic Index by Len Fisher.

4. Average direction rule for referring to neighbors

As models discussed above, when considering decision-making mechanism on finding route by oneself, agents tend to follow the majority rule as reference of neighbors. When the reference mechanism alters, the evacuation effects of the system may be different. This seemingly easy poll question did not be verified until Page (Hong and Page, 2001, 2004) verified the average value could be the basic reference to ensure the reliability of the collective decision in the late 1990s. Page introduced the diversity prediction theorem which reveals the relationship among the error of the collective prediction and the average errors of individual prediction.

Figure 3.
The simulation results of finding route by oneself by following random walk process



Initial distribution state

Asymptotic stable state

The evacuation effect of the system when reaching asymptotic stable state

Notes: Figure 3(b) show the simulation results of the agents when the system is in an asymptotic stable state. The comparison of Figure 3(b) and Figure 2(b) reveals that the evacuation effect of the system following the random walk process is superior to that of agents maintaining inertia. $P'=0.6$, $\lambda=0.6$ and NumAgents=1,500

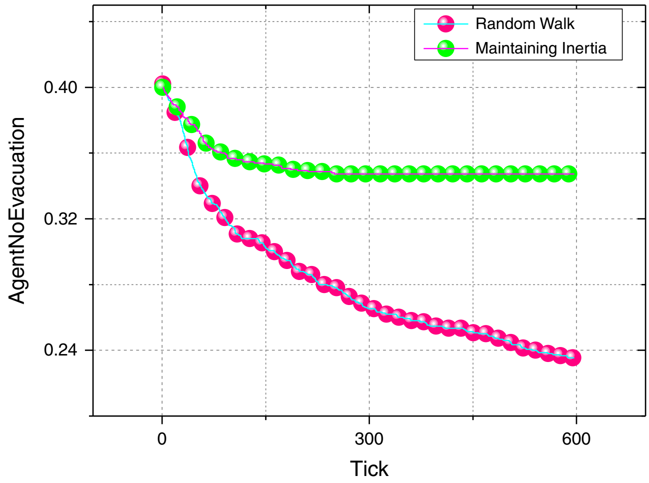
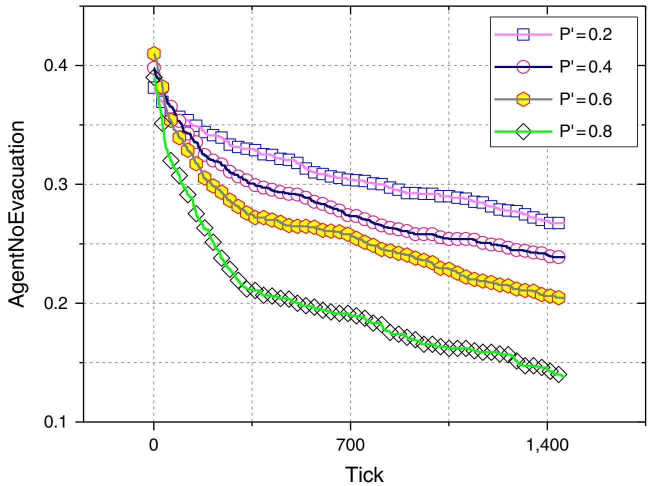


Figure 4.
The comparison of evacuating effect between random walk and maintaining inertia ($P' = 0.6$, $\lambda = 0.6$ and NumAgents = 1,500)



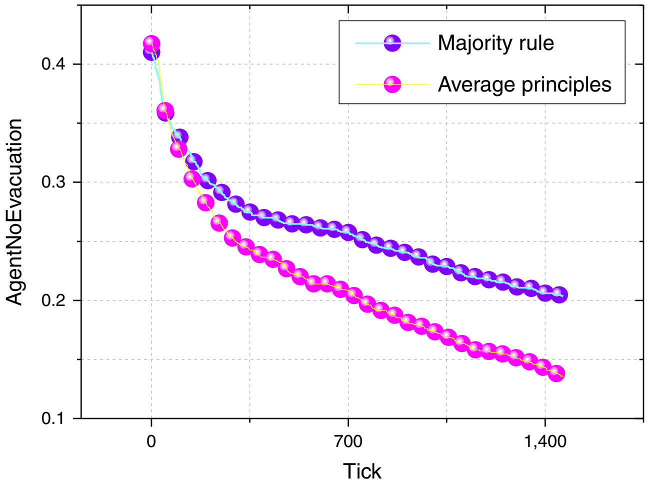
Note: As the results shown, evacuating effect is better as randomness of agents decline, like $1-P' = 0.2$

Figure 5.
The evacuating effect under different reference probabilities ($\lambda = 0.6$ and NumAgents = 1,500) $1-P'$ represents the probability for agents to find route by oneself

For further study of different mechanisms of the reference of neighbors, we operate a new simulation, namely, changing $\Phi(T_{x-1,y}, T_{x-1,y+1}, T_{x-1,y-1}, T_{x,y-1}, T_{x,y+1}, T_{x+1,y}, T_{x+1,y-1}, T_{x+1,y+1})$ into average direction rule of the referring to neighbor.

From simulation results shown in Figure 6, we could draw a comparison of evacuating effect between the average direction rule and majority rule. In Figure 6, $P' = 0.6$ and the amount of agents is 1,500. And we could figure out that under condition of the reference of neighbors, average direction rule is superior to majority rule. The results also verified the diversity prediction theorem by Scott E. Page from the perspective of agent-based simulation.

When emergency occurs in reality, the strategy for evacuation that individuals chose to randomly follow their neighbors is not the best one. If individuals had



Notes: $P'=0.6$, $\lambda=0.6$ and the amount of agents is 1,500. It could be figured out that under condition of the reference of neighbors, average direction rule is superior to majority rule

Figure 6. The comparison of evacuating effect of referring to neighbors' base on average direction rule and majority rule

expected that their neighbors probably evacuated without direction, they could attain better choice by roughly filter or calculation than following mechanically.

No matter what kind of decision, evacuating decisions is probably not a simple follow, but a route-choosing process with some simple calculation rules. The "average direction rule" refers to a route-choosing process by valuing choice of all neighbors with equal weight, instead of precise calculation of average directions. In such situations of evacuation, the choice which seems ridiculous or reasonable is of equal value for reference.

5. Factors of the proportion of clever agents and density of the system

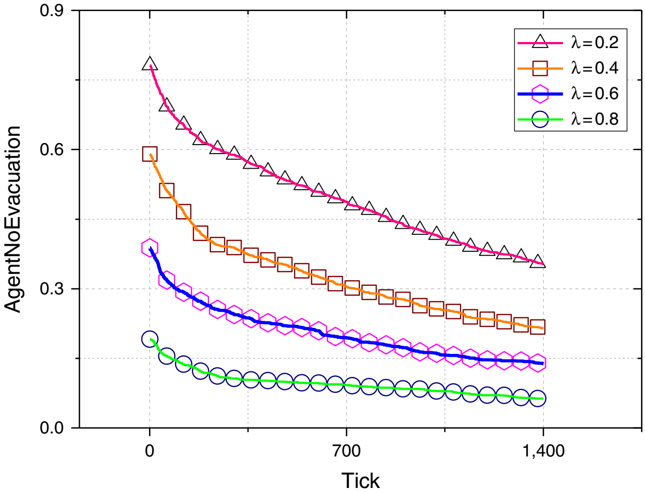
Theoretically, a higher proportion of clever agents reflect a higher efficiency of evacuating effect. Though in practice, the proportion of clever agents tends to depend on a tradeoff between increasing cost and increasing efficiency. For instance, adding to more ushers and mobile advisory stations may cause a cost of management and transportation, even a reduced efficiency in whole system. Therefore, a discussion on optimized proportion of clever agents is necessary.

As shown in Figure 7, the results indicate that with the higher proportion of clever agents, the better evacuating effect it will be. In addition, this paper finds as λ increase from 0.2 to 0.4, the corresponding evacuating effect improves with greatest range.

Considering the comprehensive effect combined with system density and the proportion of clever agents, this paper analyzes whether the interval of the ratio between system density and the proportion of clever agents exists, and further study how the evacuating effect varies under a given proportion of clever agents as the system density alters.

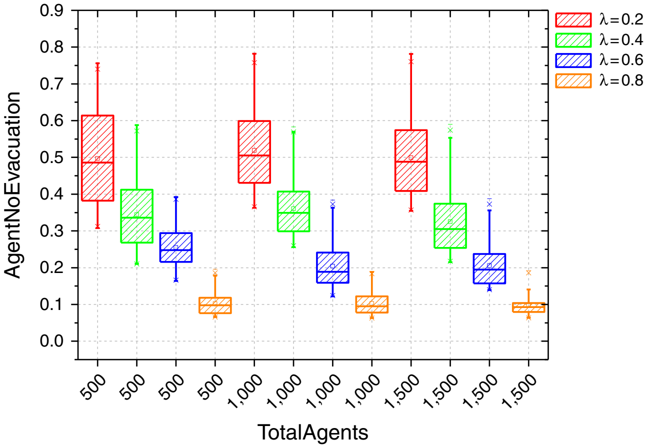
The simulation results show that there would be a specific ratio between system density and the proportion of clever agents exists for optimizing the effect of evacuation (Figure 8).

With relatively low proportion of clever agents $\lambda = 0.2$ and system density of agents 500, the simulation experiment obtains a relatively good evacuating effect. And with a



Notes: The horizontal axis represents the length of time in simulation and vertical axis represents the proportion of agents without evacuation. The total amount of agents is 1,500, $P'=0.6$, while λ represent the proportion of clever agents

Figure 7. Simulation results under different proportions of clever agents



Notes: The horizontal axis *TotalAgents* represents the system density (i.e. total amount of agents) and vertical axis *AgentNoEvacuation* represents the proportion of agents without evacuation when the system approaches static state. Red candlestick charts represent simulation results with the proportion of clever agents 0.2; green candlestick charts represent simulation results with the proportion of clever agents 0.4; blue candlestick charts represent simulation results with the proportion of clever agents 0.6; orange candlestick charts represent simulation results with the proportion of clever agents 0.8

Figure 8. The comparison of evacuating effect with different proportions of clever agents and system density ($P'=0.6$)

proportion of clever agents $\lambda = 0.4$, to some extent, simulation experiments with system density 500 and 1,500 make nearly no difference, however, the simulation experiment with system density 1,500 obtain a more stable evacuating effect of system and lower average percentage of agents without evacuation than those of system density 500.

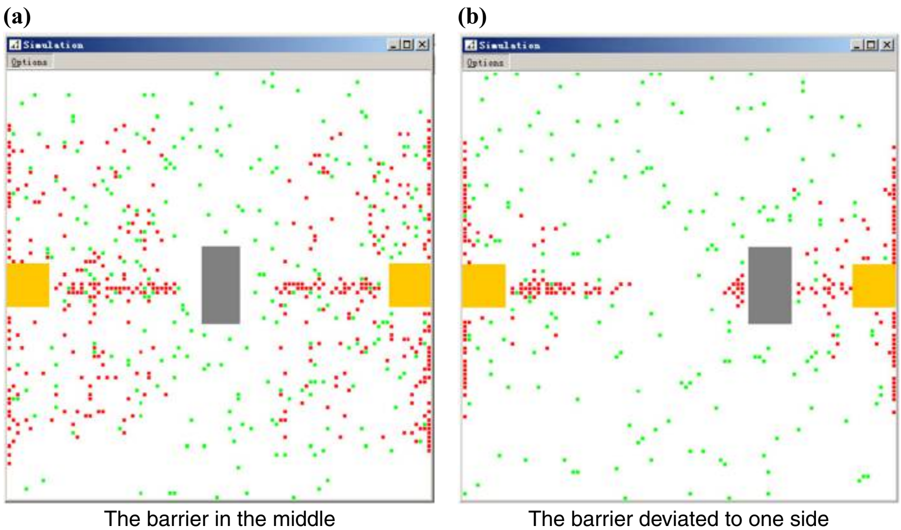
It is noteworthy that with the proportion of clever agents $\lambda = 0.6$, the simulation experiment with a medium value of system density 1,000 does obtain a significantly better evacuating effect than experiments with system density 500 or 1,500. Furthermore, with higher proportion of clever agents $\lambda = 0.8$, simulation results with different system density make nearly no difference.

6. The evacuating effect analysis with barrier

The setting of barrier in the system could usually be an adverse factor for congestions; however, it could turn to be a beneficial one of evacuation by constructing evacuating routes. We found that when the system tends to be stable, the barrier does not put significant impact of individual evacuation and there is no congestion around the barrier.

Figure 9(a) is the pedestrian flow formed in the process of stabilization. Comparing to the results from Figure 9(a), it is clear that barrier in the medium location would not cause significant congestion in evacuation; however, changing the barrier in the medium location into the sign conducing could probably accelerate and improve evacuation in the system by exerting force on agents who approach the sign conducing.

When the barrier was placed on one side of the system, a few clever agents were blocked in the barrier area when the system approaches stable state. Repeating the



Notes: The gray rectangle represents the barrier. The agents consist of clever agents and ordinary agents; and agents follow average direction rule for reference of neighbors. When the barrier is deviated to one side, the formation of route has guidance on the individuals. Though some clever individuals may be blocked by the barrier, most of the ordinary ones could escape successfully and the evacuation effect of the system is superior to that with barrier in the center

Figure 9. The states of forming fixed pedestrian flows

simulation experiments for 200 times, we could find that a certain clever agents were blocked in the barrier area, regardless of different amounts.

Reasons for that phenomenon root in the attributes of clever agents. Different from ordinary agents, clever agents are distinctly aware of the location and direction of exists, and they would stickily head for the direction of exists from then on. As the pedestrian flow situation shown in Figure 9(b), different from ordinary agents when approaching the barrier, clever agents would try to bypass the barrier at first, and they would reversely head for the barrier at the next time point because the barrier cut off the route of clever agents toward exists. And in the meanwhile, congestion happens as clever agents gather at the barrier area.

Referring to the simulation results of placing barrier on right side of the system, we can figure that because clever agents know exactly where exists are, the barrier blocks a certain clever agents and cause congestion with spread of reference of neighbors.

Figure 10 interprets that the evacuation effect of the system where the barrier is in the middle is inferior to that of the barrier deviated to one side. The simulation results also verify a right-side placement of barrier as a role of route management.

To sum up, the effect of barrier in the system depends on the specific position of the barrier. When it is in the middle of the system, the pedestrian flows will be shaped from two sides of the barrier to positions near the exits in the evacuating process. Thereby, the impact of the barrier located in the center is not significant, and if the barrier could be changed into a sign, the evacuation effect will be improved by reducing the individual blind spots without previous effect of evacuation.

Besides, the shape of exits and distribution of exit location would also have an influence on effect of evacuation. Those are also the topics for our further research. For example, the "arching" characteristic may occur under condition of large density of evacuating agents and small size of exits.

7. Discussion

Based on works of established theories on crowd evacuation, we notice that the rational decision and cooperation exists even in emergent evacuation: considerable observations of altruistic behaviors in evacuation suggest the probability of

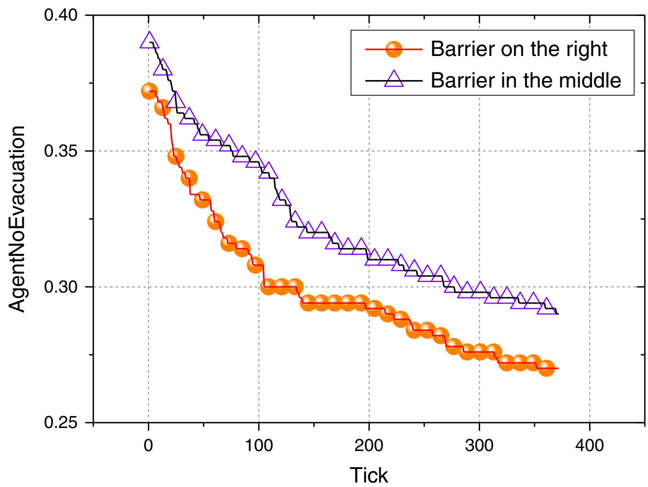


Figure 10.
The comparison of simulation results with different barrier positions

boundary rationality and rational thinking (Pan *et al.*, 2007; Ozel, 2001; Mawson, 2005; Sime, 1995). Especially in an environment of limit time and incomplete information, a rational thinking of average direction or following neighbors depends on evacuating time and the extent of seriousness, but without doubt both rational thinking and following neighbors exist with a certain probability in evacuation.

The models and mechanisms in this paper aims at discussing how ordinary agents utilize any information they could obtain for eventual escape efficiently, including information from clever agents, neighboring ordinary agents and the influence on information of a barrier. When absorbing "majority rule" and "average direction rule" into evacuation system, we eventually verified the diversity prediction theorem by Scott E. Page. Compared to a reference of "majority rule," a reference of "average direction rule" in simulation setting of this paper, evacuating agents can obtain better escape effects.

In reality, lacking in an effective "average choice" method of neighboring reference is one of the most important reasons for low efficiency of evacuation, with other factors unchanged. Thus in our further research, we would focus on discussing how agents allocate weights for available information for a highest probability of evacuation.

8. Conclusion

This paper combines individual-guidance mechanism with agent-based simulation model, and systematically studies the relationship between congestion phenomena and individual decision-making mechanism.

First of all, we study the autonomy for agents. As the simulation results show, the evacuating effect of random walk is superior to that of maintaining inertia. If agents maintain inertia, congestion reveal a characteristic of local-scale self-similarity, and even clever agents who maintain inertia would be congested near exists. However, an improved evacuating effect could be obtained if agents keep a probability less than 0.4 for random walk. And that's consistent with conclusion of Len Fisher's Panic Index.

Next, this paper focusses on the reference of neighbors of ordinary agents, under the consideration of individual-guidance mechanism of clever agents. The results show that taking average direction as reference of neighbors, the effect will surpass that following majority rule.

Furthermore, the simulation is carried out to figure out the influence of system density and the proportion of clever agents. Results would not significantly support that the evacuating effect could improve as the proportion of clever agents increases. However, an optimized ratio between the proportion clever agents and system density exists. For instance, when the proportion of clever agents is 0.6, the evacuating effect with the number of agents 1,000 is relatively good.

Finally, simulation is employed to verify the effects of route guidance brought by appropriate placement of barrier. The results illuminate that when the barrier is in the middle of the system, the evacuating effect is not significant. If the barrier could be changed into a sign conducing, it is beneficial to reduce agents' blind spots and have a better guidance on ordinary agents without influencing the previous effects. Besides, when the barrier is deviated to one side, though some clever agents are likely to be blocked, more ordinary agents could successfully escape from the exits. The overall effect of the system surpasses that with barrier in the medium.

The simulation results in this paper illustrate the individual-guidance mechanism would significantly improve evacuating effect of system, however, under a series of setting individual autonomy mechanism, reference of neighbors, system density, the proportion of clever agents and location placement of barrier. Generally speaking, a relatively acceptable evacuating effect could be obtained with 40 percent of agents insisting on random walk, 60 percent of taking average direction rule as reference of neighbors.

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