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Crowd Evacuation Optimization by Leader-follower Model

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Abstract: Emergency evacuation has been receiving increasing attention due to the widely concern of public security in recent years. It is a critical task to analyze how to evacuate large crowd in an efficient way. Evacuation leaders, described by a modified leader-follower model based on social force, areinvestigated in this paper aiming to reduce evacuation time, casualties and loss. Artificial system of Beijing South Station is established based on actual data to verify the lead-follower evacuation method, where a large number of simulations have been conducted. The results show that evacuation with evacuation leaders can effectively reduce the evacuation time and casualties in an emergency situation in public place with a large number of pedestrians.

Keywords: Evacuation, leader-follower model, emergency, computational experiment, social force.

1. INTRODUCTION

When emergency situation occurs, especially in places with large crowds, it may cause serious consequences and heavy casualties. This is really true in the field of rail transit for the highly concentrated passenger flow. On February 18, 2003, as a result of arson, a damage of 198 dead and 147 injured was caused in Daegu subway. On March 29, 2010, at least 38 people were killed and more than 60 injured in two suicide bomb attacks on the Moscow Metro during the morning rush hour. On September 27, 2011, a signal system failure incurred in Line 10 of Shanghai Metro, leading to more than 260 people injured when a train was chased by another. On September 30, 2013, a collision on the tracks of Chicago's CTA metro line sent over 30 people to the hospital.

Ensuring the safety of large crowds has been both a concern and challenge for specialists in a variety of fields ranging from security teams and emergency response specialists to architects and building designers. Various researches have been done and many modelling systems based on atomistic approach have been proposed. For example, Alizadeh (2011) proposed a dynamic cellular automation model to simulate evacuation with obstacles; Pelechano (2006) considers animating evacuation in complex buildings by crowds who might not know the structure's connectivity, or who find routes accidentally blocked by setting different kinds of agents such as trained personal, leaders and followers; Helbing (2000) worked with the social force model to simulate behaviours specific to escape panic situations; and Ji (2006) used a A*-based dynamic grouping algorithm to simulate the dynamic grouping phenomena of evacuation.

However, some evacuation models are not suitable to simulate crowd behaviour for the reason of different escape directions and means, and it would make difference between simulation results and the reality in evacuation. Considering that if people could be guided by leaders who know the evacuation path, the difference would be smaller and the simulation result would be closer to reality (Aubé (2004), Murakami (2002), Zhong (2008)). It is a rather common phenomenon that pedestrians are unfamiliar with the area in the neighbourhood and insensible of the position of exits. Chaos may occur in emergencies especially when people are too scared to keep sober-minded (Helbing (2002), Ji (2006)). Therefore, the role of a guide who rescues them from emergencies is very important for scared people. With the improving awareness of safety, many inspection staff, who may act as guiders in an escape, are arranged within a certain range of large-scale public places to be responsible for safety inspection.

In this paper, we proposed an appropriate evacuation method namely leader-follower model. It provides not only a practical method of crowd evacuation, but also a microscopic modelling method of pedestrian movement. The method can efficiently accelerate the evacuation process, which will be examined later. The remainder of this paper is organized as follows. Section 2 introduces the decomposition of a subway station with agent based modules, including the facilities and pedestrians. Section 3 describes the extended social force model, which reflects the guided crowd system. The model is verified later. Section 4 builds the artificial system of Beijing South Station, which run as the examination environment. Some verification results and computational experiments are shown in section 5. Section 6 concludes the paper.

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2. SUBWAY STATION MODEL

Based on the requirements that components and modules have autonomy, interactivity, and adaptiveness, agent-based method and programming technology are the first choice of the modelling approach. To study the evacuation of Beijing South Station, a well-defined model is needed. In this paper, different kinds of agents are introduced to realize different modules and to complete the experiments. Fig.1 gives the relationship among environment agents, facility agents and the pedestrian agents. Pedestrian agents are set based on social force model, which will be introduced in section 3. Here, we only pay attention on the autonomy, interactivity and adaptiveness of them.

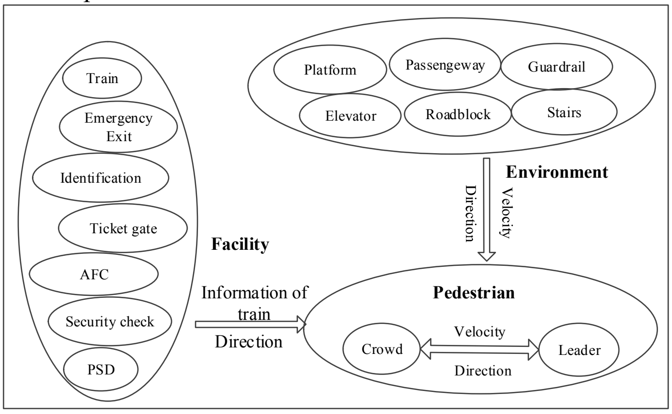


Fig. 1. Environment agents' and facility agents' affection on pedestrians

2.1 Pedestrian agents

The simulation focuses on the crowds' evacuation model with leader. Obviously, the pedestrian is the key part of the simulation. In real life, people behave in different ways and it's hard to sum up people-behaviours as a simple analytic expression. But in evacuation, two patterns of pedestrian behaviour are clearly shown, namely the behaviour of leader and the follower. The leaders represent the people who knows the route to the exit and tend to help others. And the followers represent the general crowds who don't know the route and have to follow the leaders to find the exit. In the simulation, the leaders find the evacuation path and the crowd follow them.

- *Leader agent:*

As the evacuation starts, the shortest path to the nearest exit is found for every leader. Leader leads people to evacuate after followers gathering around him. Each leader has an attracting area, which means pedestrian who is far away from the leader may not find and follow the leader.

- *Crowd agent:*

At the beginning of evacuation, people gather to the nearest leader as the followers. Followers and the leader form a group. Different groups have different leaders. Followers follow their respective leaders to evacuate to exit. The path information for followers can only be obtained from the leader.

2.2 Environment agents

In a subway station, movement of pedestrian is restricted by the environment. When emergency situation occurs, the evacuation path, direction and velocity of pedestrian will be directly determined by the space structure of the station. Space structure includes tunnels in the subway, entrance and exit, passageway, station hall and so on. They serve as the escape route. And they also determine the evacuation bottleneck of the entire station, due to the barrel effect.

2.3 Facility agents

According to the actual situation, we set up the on-site service model of the facility agents, which including Train control system related agent and emergency and service facility agent.

- *Train control system related agent:*

Train control system related facilities, including the train, platform and PSD (Platform Screen Door), affect the pedestrians' state, which includes the location, velocity and the direction of pedestrian. Operation of these facilities usually has a fixed schedule and process. In some emergency situations, trains can also be used as a tool for passenger evacuation.

- *Emergency and service facility agent:*

Emergency facilities such as evacuation signs and lights affect the direction of pedestrian. The ticket gates, AFC (Auto Fare Collection) and the security check machines restrict both the velocity and direction of pedestrian. These facilities are directly controlled by the security office.

3. LEADER-FOLLOWER MODEL

Behaviours of pedestrians can be modelled in many ways, among which, social force model is widely used in evacuation. Social force model (Helbing (1995)), which aims at explain the influence of social-psychological and physical forces on the behaviours of the crowd, is adopted to describe pedestrians' movement in the station in this paper. It assumes that the individual has some intelligence, and can respond to the change of surrounding environment. Pedestrians' subjective views, interactions between people and environment are described by Newton's second law. Social force model can reproduce many pedestrian traffic phenomena, such as self-organizing, arch obstruction, mass effect, etc.

3.1 The social force concept

Four characteristics of human behaviour are expressed by the model, they are: (1) Pedestrians tend to cross a fixed distance as soon as possible. (2) Pedestrians are easily distracted by bulletin board, acquaintance, big events, favorite things. Thus forming crowds. (3) Pedestrians will automatically accelerate to the desired speed, in the case of unhindered. Desired speed varies with the change of situations. (4) There are interactions between pedestrians. They wish to keep a certain distance to other pedestrians, namely "territorial effect", so as to walls and obstacles. When there is an obstacle ahead, pedestrians will slow down to avoid collision.

In Helbing's social force model, pedestrians are driven by a mixture force. Pedestrian *i* of mass m_i tends to move with a original speed $\vec{v}_i^0$ and adapts his instantaneous velocity $\vec{v}_i(t)$ in a desired direction $\vec{e}_i^{\,0}$ within a certain time interval τ_i. Meanwhile, the pedestrian tries to keep a distance from other pedestrian *j* and from the walls *w* using interaction force $\vec{f}_{ij}$ and $\vec{f}_{iw}$. The social force model is showed in Fig.2.

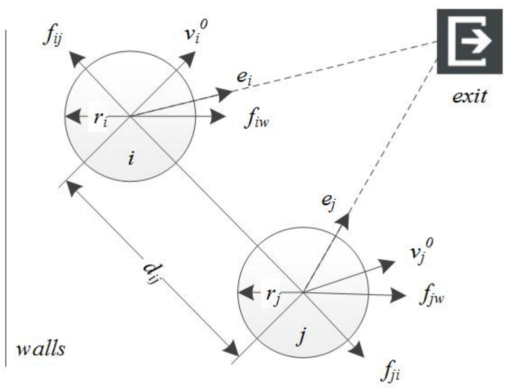


Fig. 2. The social force model

Helbing described the mathematical expression of pedestrian *i* in mechanic principle as:

$$m_i \frac{d\vec{v}_i(t)}{dt} = \vec{f}_i^0 + \sum_{j(\neq i)} \vec{f}_{ij} + \sum_{\omega} \vec{f}_{iw} \tag{1}$$

Here, $\vec{f}_i^0$, the desired force, reflects the willingness to achieve the desired velocity. It is formed as

$$\vec{f}_i^0 = m_i \frac{v_i^0(t)\vec{e}_i^0 - \vec{v}_i(t)}{\tau_i} \tag{2}$$

$\vec{f}_{ij}$, which contains socio-psychological force and physical force, can be expressed by

$$\vec{f}_{ij} = \vec{f}_{ij}^{\,s} + \vec{f}_{ij}^{\,p} \tag{3}$$

$$\vec{f}_{ij}^{\,s} = A_i \exp[(r_{ij} - d_{ij})/B_i]\vec{n}_{ij} \tag{4}$$

$$\vec{f}_{ij}^{\,p} = \vec{f}_{ij}^{\,p_1} + \vec{f}_{ij}^{\,p_2} = kg(r_{ij} - d_{ij})\vec{n}_{ij} + \kappa g(r_{ij} - d_{ij})\Delta v_{ji}^t \vec{t}_{ij} \tag{5}$$

where A_i, B_i, k, κ are constant parameters; $d_{ij}(t) = \left\|\vec{x}_i(t) - \vec{x}_j(t)\right\|$ is the distance between the centres of mass of pedestrians *i* and *j*, and $r_{ij} = r_i + r_j$ is the sum of their radii r_i and r_j; $\vec{n}_{ij} = (n_{ij}^1, n_{ij}^2) = (\vec{r}_i - \vec{r}_j)/d_{ij}$ is the normalized vector pointing from pedestrian *j* to *i*; $\vec{t}_{ij} = (-n_{ij}^2, n_{ij}^1)$ means the tangential direction, $\Delta v_{ji}^t = (\vec{v}_j - \vec{v}_i)\bullet\vec{t}_{ij}$ means the velocity difference in tangential direction. $g(x)$ is a piecewise function defined as

$$g(x) = \begin{cases} 0 & (x < 0) \\ x & (x \geq 0) \end{cases} \tag{6}$$

The expression of interaction force between pedestrian and the walls is similar to equation (3). It can be given by

$$\vec{f}_{iw} = A_i \exp[(r_i - d_{iw})/B_i]\vec{n}_{iw} + kg(r_i - d_{iw})\vec{n}_{iw} + \kappa g(r_i - d_{ij})\Delta v_{wi}^t \vec{t}_{iw} \tag{7}$$

3.2 Extension of social force model

As a supplement to territorial effect, pedestrians tend to react much stronger to what happens in front of them, which means theirs direction will be determined according to the ones in their vision field (Helbing (2002), Yu (2007)). Then the direction of socio-psychological force can be extended to:

$$\overrightarrow{n_{ij}}' = \overrightarrow{n_{ij}}\left(\lambda_i + \left(\frac{1}{2} - \frac{\lambda_i}{2}\right)\left(1 + \cos\left(\varphi_{ij}\right)\right)\right) \tag{8}$$

$\lambda_i < 1$ is a dynamic parameter of pedestrian *i*, which is used to determine the direction influence of pedestrian *j* on *i*. By choosing its value, we can reflect the anisotropic character of different kinds of pedestrians. $\varphi_{ij}(\mathrm{t})$ is the angle between the desired direction $\vec{e}_i^{\,0}(\mathrm{t})$ and the direction $-\overrightarrow{n_{ij}}(\mathrm{t})$ of the object exerting the repulsive force, i.e. $\cos(\varphi_{ij}(\mathrm{t})) = -\vec{n}_{ij}(\mathrm{t})\bullet\vec{e}_i^{\,0}(\mathrm{t})$.

Meanwhile, Pedestrians always have the psychological tendency of going with the crowd in emergency evacuation. The tendency of going with the crowd is not always harmful, the proper response can transfer the information effectively, resulting in more organized evacuation. In the process of evacuation, pedestrians often feel that they can find the exit by following others, especially when the field of vision is limited, e.g. in smoke and complex environment. In these situations, one may find no exit, he will decide his desired direction according to the pedestrians in his vision:

$$\vec{e}_i^{\,0\prime}(t) = \frac{\sum_j \alpha_{ij} \vec{e}_j^{\,0}(t)}{\left\| \sum_j \alpha_{ij} \vec{e}_j^{\,0}(t) \right\|} \tag{9}$$

where α_{ij} is a weight coefficient defined as:

$$\alpha_{ij} = \begin{cases} 0 & j \text{ is out of the vision of } i \\ \dfrac{1}{d_{ij}} & j \text{ is one of the followers in the vision of } i \\ +\infty & j \text{ is a leader in the vision of } i \end{cases} \tag{10}$$

The vision area can be changed according to situations, i.e. the more complex condition or the bigger smoke, the smaller field of vision. The vision area model is showed in Fig.3.

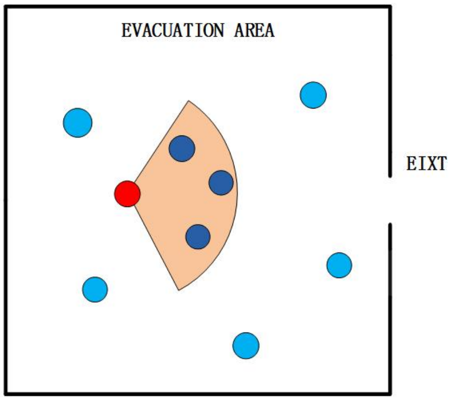


Fig. 3. The vision area model

In this way, the movement of pedestrian is formed as follows: they will move like a group; the one who know the exit will be in the front of the group, namely the leader; the one who can't find the paths will follow the leaders, namely the follower.

4. ARTIFICIAL SYSTEM OF BEIJING SOUTH STATION

Based on agent modelling method, we could clearly classify and show the interactions between different agents. Then to examine the leaders' affection on the evacuation, an underlying model is defined, namely the artificial system.

Beijing South Station is a comprehensive transportation junction. The passenger capacity ranks the third in the world and the safety insurance is very important. It is divided into three layers. The underground layer is the station of subway line 4, the ground floor is the transfer hall, and the elevated layer is the railway passenger transportation centre. Around the station, there are many public transportation transfer points. To make the model more reliable, we made a full investigate of Beijing South Station. Some surveyed parameters are shown in Table 1 and Table 2.

Table 1 shows the main facilities of underground floor: two stairs and elevators and two no-passing zones in the middle, two offices are established on separate sides. The waiting zones are the places near the doors of the arriving trains. Table 2 is the same with Table 1. The ground floor is more flexible than the underground floor. An oval area in the middle is directly connected with the following floor, and the outer part connects to the high speed railway entrance. Both north and south ends of the station have one exit.

Table 1. Surveyed parameters of underground floor

Underground Floor		
Name	Length (cm)	Width (cm)
Stairs	/	267
Elevator	/	114
Waiting area	/	260
Bench	150	140
Office	300	200

Table 2. Surveyed parameters of ground floor

Ground Floor				
Name	Length(cm)	Width(cm)	Height(cm)	Aisle(cm)
GATE_1	180	25	100	56
GATE_2	180	30	100	90
Security inspection	180	106	160	/
TVM_Rail[1]	90	90	180	/
TVM_Sub[2]	90	23	180	/
ATM	120	95	180	/
Billboard	180	35	213	/

[1] *TVM_Rail: the ticket vending machine for high speed railway*
[2] *TVM_Sub: the ticket vending machine for subway*

Based on these parameters and the CAD documents of Beijing South Station, we build the station's artificial system, which is accurately mirrored the real station, see Fig.4. The service time of ticket vending and security inspection in the system is set according to actual time. So is the capacity of ticket gate and the stairs. It is a parallel system with the real world, and many experiments which reflect the actual operation can be conducted based on it.

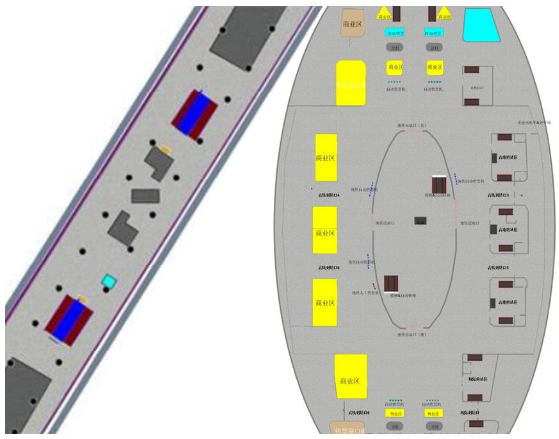
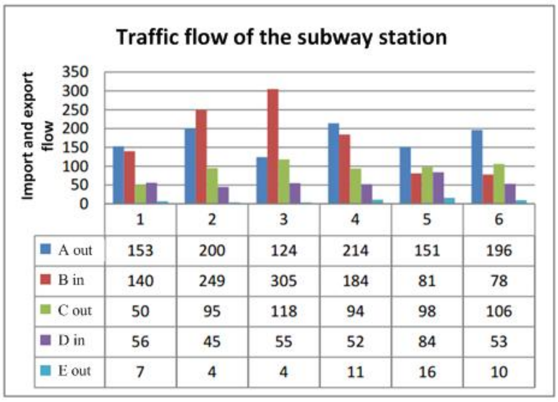


Fig. 4. The artificial system of underground and ground layer

Table 3. The subway station traffic flow



	1	2	3	4	5	6
A out	153	200	124	214	151	196
B in	140	249	305	184	81	78
C out	50	95	118	94	98	106
D in	56	45	55	52	84	53
E out	7	4	4	11	16	10

Later, computational experiments will be designed and executed based on the artificial systems. To make the result closer to real situations, we use the data comes from investigation. The investigated traffic flow is shown in Table 3, which shows the relevant distribution proportion of passenger flow. This would be the input of the model to represent the passenger flow in the station. So is the train schedule.

5. SIMULATION AND THE RESULT

Numerical simulations will now be carried out with the extended social force model. The parameters in the original social force model are specified as: pedestrian mass $m_i = 80kg$, pedestrian radius $r_i = 0.25m$, strength of social repulsive force $A = 2000N$, characteristic distance of social repulsive force $B = 0.08m$, coefficient of sliding friction $\kappa = 24000kg{\bullet}s^{-2}$, body compression coefficient $k = 12000kg{\bullet}s^{-2}$, desired speed $\vec{v}_i^0 = 1.5ms^{-1}$, and pedestrian reaction time $\tau = 0.5s$ (Helbing (2000)).

5.1 Computational experiment

Computational experiment is a series of computer simulations. Due to the complexity of an urban transit hub and the difference between the specific situations, a single simulation of evacuation makes little sense. But a series of carefully designed computational experiments will lead to some conclusions. In this paper, evacuation time was selected as the main indicator. Several simulations will be carried out according to a set of input, and the average evacuate time *T* is calculated as the result of this kind of situation. The calculation method is:

$$T = {T_{total}}/{N} \tag{11}$$

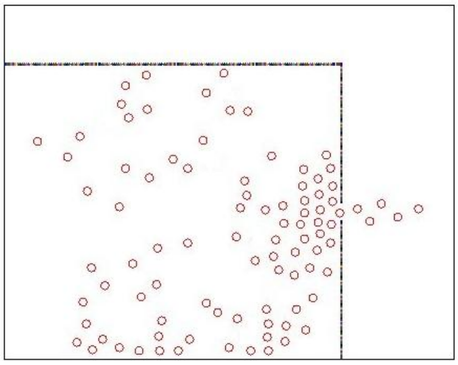
$$T_{total} = N\sum_{i=0}^{n} t_{divide} n(t_i) \tag{12}$$

$$n(t_i) = n_{walk}(t_i) + n_{wait}(t_i) \tag{13}$$

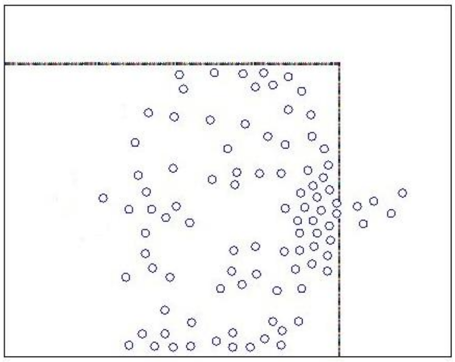
T_{total} is the sum of evacuate time of all simulations; N is the number of simulations; $n(t_i)$ is the number of pedestrian in artificial system at time t_i, including the walking ones and the ones in service; t_{divide} is the evacuate time of individual.

5.2 Model verification

Two validation simulations are performed to verify the model, setting 50 pedestrians evacuate from a $15m \times 15m$ room with an exit of 1.5m. When a pedestrian is close enough to the exit, i.e. the exit is in his vision field, he can escape from the fired room. Due to smog, the vision field is set to 2m. The result is showed in Fig.5. Fig.5 (a) reflects the process of evacuation with original social force model, and Fig.5 (b) the process of evacuation with extended social force model, i.e. evacuation with leaders. After 40s, pedestrians in Fig.5 (b) can all escape successfully, while in Fig.5 (a) only the ones near the exit can escape. This means that the extended social force model reflects the transmission of information, and that the leader-follower model accelerates the evacuation process.



(a) Evacuation with original social force model



(b) Evacuation with extended social force model (leader)

Fig. 5. The validation simulation

5.3 Leader Model with different number of leaders

It's proved that leaders can accelerate evacuation effectively. Then, another question comes: how many leaders are needed in an evacuation? It's obvious that evacuation with too few leaders may result in low efficiency and with too many may lead to chaos. Tests with different number of leaders have been conducted. The average result is shown in Table 4.

Table 4. Tests with different number of leaders

Leaders in subway	Leaders in transfer	Death	Evacuation number	Evacuation time (s)
1	2	4	725	645
2	3	5	705	576
2	6	3	721	440
3	8	3	701	702
4	9	2	697	745

From Table 4, we can find that evacuating 700 pedestrians in Beijing South Station only needs about 8 leaders: 2 leaders are needed in the subway and 6 in the transfer hall. If we set too many or too few leaders, the average evacuation time would be longer and even cause more casualties. The position of leaders also has a great impact on the results of evacuation. Through a series of computational experiments and actual inspection, it's found that setting leaders near stairs, corners and bottlenecks results in the best.

5.4 General evacuation and the Leader Model evacuation

When an uncontrolled situation occurs in places with a large crowd, chaos may appear which often cause severe casualties (Ji (2006)). This is especially true in subway station for the reason of the complicated internal structure and the limited exit paths. In addition, disasters may change the structure of a station and people will lose their mind because of fear. Thus, leaders are very important for evacuation. To verify this conclusion, experiments are carried out as follows:

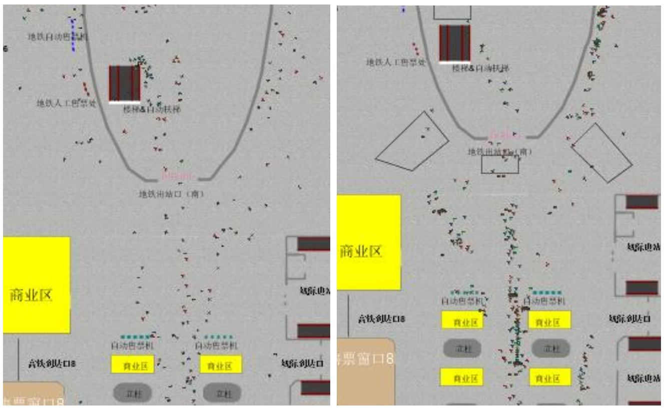


Fig. 6. The general evacuation and the leader optimized evacuation system

There are two scenes of evacuation in the figure: general evacuation (the left) and leader optimized evacuation (the right). When emergency situation happens, pedestrian moves around and finds a proper guider in his visual range. Both the distance with leader and the number of followers are under consideration. Then, the leader and the followers move to an exit as a group. From Fig.6, it's easily to find that general evacuation always cost more time and together with chaos. Relatively, evacuation with leader shows more coherent. More detailed experimental results are shown in Table 5.

Table 5. The results of the two evacuation systems

Item \ Result	General evacuation	Leader model
Dead Number	2	3
Evacuation Start	9:42:37	16:37:05
Evacuation Complicated	9:54:31	16:42:52
Evacuation Time	0:12:04	0:07:47
Evacuated Pedestrians	669	687

6. CONCLUSIONS

This paper has accomplished these works: An extended social force model is derived, namely leader-follower model. The artificial system of Beijing South Station is built based on fully investigation. The system mirrored the real station, and various experiments have been conducted on it. Evacuation via leader-follower model has been examined on the artificial system. Compared with general evacuation, leader-follower model shows more ordering and efficiency. According to a series of computational experiments, the suitable number of leaders is estimated. In Beijing South Station, if there exist 2 leaders in the subway and 6 leaders in the transfer hall, the evacuation time will be reduced when emergency situation occurs.

The proposition of leader-follower model is a start point of evacuation since the problem of evacuation within infrastructures in case of emergency is very difficult. The determination of the number or location of leaders depends on the specific scenario. A further step could be the application of the model to general situation, such as finding out the relationship between leaders' position and structure of building. Besides, the leaders are also influenced by the followers. If the leader is surrounded by a large amount of people in a group, he may also lose his way. It's also worthy of study that in which position should the leaders be in a group.

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