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Multi-objective Optimization Model Based on Steady Degree for Teaching Building Evacuation

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Abstract—**In this paper, the process of evacuation in teaching building is considered. The concept of steady degree based on cellular automata and potential field is introduced and it can describe the behavior tendency of evacuees during the evacuation process. With the help of steady degree, the model simulates the indoor evacuation behavior. To reduce the congestion and evacuation time, a multi-objective optimization model considering steady degree and evacuation clearance time is proposed. Finally, an experiment in the Teaching Building No.1 of Wuhan University of Technology is carried out. The results show that this model can reduce the clearance time of emergency evacuation in teaching building compared to other models.**

I. INTRODUCTION

Campus security is closely related to the students, teachers and the community, and it is a very important part of the social security work. A variety of dangerous factors (such as: earthquakes, chemical experiments, and other man-made disasters or accidents) have posed threat to campus security recent years. Establishment of effective campus emergency evacuation mechanisms is an important safety method to protect people's lives and property.

Recently a number of research work is completed by computer simulation to capture the evacuation behavior of crowd in the teaching building [1], and the proposed evacuation model is refined with the help of experiment data. Many international and domestic researchers have proposed several evacuation models [2]: Simulex, Exodus, Ggrafexitt etc., and some corresponding software such as Evacnet, Simulex, Hazard Egress Pro, Exit and Steps are developed. Some main evacuation models, including cellular automata model, lattice gas model and social dynamics model, etc., are also proposed. Because it is easy to simulate by computer, cellular automata model is widely used to simulate the pedestrian flow. With the help of micro-simulation personnel evacuation behavior, cellular automata model can directly reflect the people's interaction in buildings [3]–[5], and it can also describe and analyze the competitive behavior in emergency environment to find the points of congestion in the evacuation process [6][7], then the building structure can be optimized. But it cannot make route-planning optimization from macro level. Kou [8] proposed multi-objective evacuation routing optimization method, but it is not capable for indoor evacuation. Zhang [9] applied the improved adaptive ant colony algorithm to large public buildings and improved the route optimization. But he does not take into account the congestion factor in evacuation. Zhao [10] simulated and analyzed the evacuation in teaching building using Pathfinder, but it is hard for manually optimization.

In view of this situation, the purpose of our work is to propose a multi-objective optimization model based on heuristic ant colony algorithm for the emergency evacuation. The model we propose is here:

- Take into account the influence factor of exits, wall and other evacuees and propose the steady degree model based on cellular automata and potential field to find the rules of evacuation process.
- Improve the evacuation method in teaching buildings by considering the evacuation clearance time and steady degree.
- According to the fixed distribution of students with course schedules in teaching building, make the route-planning by multi-objective optimization model before emergency evacuation.

The paper is organized as follows. Firstly this paper proposes the concept of steady degree which can describe the behavior tendency of evacuees during the process of evacuation in teaching building, combining with the potential field and cellular automata. Next, multi-objective optimization for emergency evacuation is introduced to reduce the evacuation clearance time and congestion. Then, experiments are conducted in Teaching Building No.1 of Wuhan University of Technology using this model. Finally, we summary the work with our conclusions and future research directions.

II. STEADY DEGREE BASED ON CELLULAR AUTOMATA AND POTENTIAL FIELD

Cellular Automata (CA), firstly proposed by Stanislaw Ulam and John von Neumann [11] in the 1940s, is a discrete model widely studied in computability theory, mathematics, physics, complexity science, theoretical biology and microstructure modeling.) Because it is easy to simulate on computer, it is widely used to simulate pedestrian flow [12].

The teaching building room can be abstracted as a two-dimensional plane, so it is suitable for the establishment of a two-dimensional cellular automata model. Von-Neumann and Moore are two common neighbor types used in a two-dimensional grid of cellular automata model [13], as shown in Fig. 1 and formula (1).

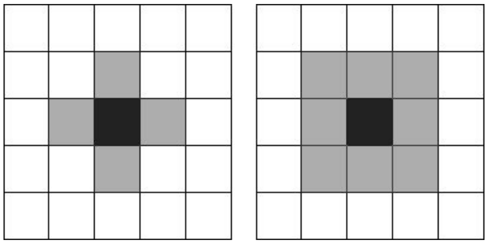

Fig. 1: Neighbor types commonly used in the two-dimensional cellular automata

Formula:

$$\begin{cases} Von.Neumann = \{(1,0),(-1,0),(0,0),(0,1),\\ (0,-1)\} \\ Moore = \{(1,0),(-1,0),(0,0),(0,1),(0,-1),\\ (1,1),(1,-1),(-1,1),(-1,-1)\} \end{cases} \quad (1)$$

For the characteristics of rooms and channels in teaching building, this paper adopts Moore cellular automata model as the selection for next step and it can enlarge the searching space during the emergency evacuation process.

Cellular automata is used to simulate the process of crowd movement under specific scene on computer. In this model, each floor of the teaching building can be divided into a series of square grids, and each grid is called a cell whose size is typically 0.5m $\times$ 0.5m. As a result, each grid represents the corresponding real scene in the real world, and each cell has different status and attribute.

Traditional cellular automata model can describe the simple process of evacuation, but the real environment includes more factors which makes the computation complicated. For this reason, potential field model is introduced and it can help solving the problem of lacking local information in cellular automata model.

The basic idea of the potential field model can be described as follows. There is a virtual potential field force influenced by the attraction of exits, the repulsion with other evacuees, and the repulsion by barriers(such as wall). The virtual potential field force drives the evacuees to escape from the building.

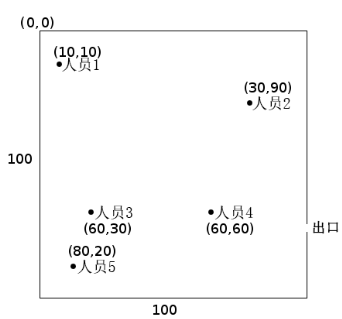

Fig. 2: Distribution of evacuees in the room

To make the question simple, the distribution of evacuees in the room can be shown as Fig. 2:

We suppose that evacuees prefer the shortest possible route to reach the exit during the evacuation process in the building. Then static potential field U_s can be expressed as the attractive force. People will move from the point with the higher potential field to the point with the comparatively lower potential field along the positive gradient of the potential field U_s. The route selected is the shortest one. U_s can be defined as follow:

$$U_s = \int_0^{D_s} kx dx \quad (2)$$

$$f_s = kx \quad (3)$$

Where U_s is the potential field generated by the exit, f_s is the attractive force generated by the exit and D_s is the shortest route to the exit. U_s is shown as Fig. 3.

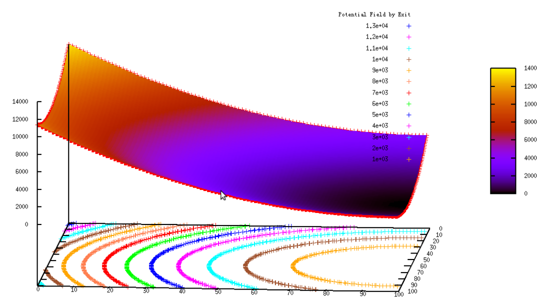

Fig. 3: Potential field produced by the exit

During the process of evacuation, evacuees will be influenced by the repulsive force from other evacuees and wall. With the help of social force model [14], the dynamic potential field generated among the evacuees can be defined as formula (4), and potential field generated by the wall can be defined as formula (6):

$$U_{ij} = \int_0^{d_{body}-d_{ij}} f_{ij} x dx \quad (4)$$

$$f_{ij} = A_i exp[(d_{body} - d_{ij})/B_i] \quad (5)$$

$$U_{iw} = \int_0^{R_i - d_{iw}} f_{iw} x dx \quad (6)$$

$$f_{iw} = A_i exp[(R_i - d_{iw})/B_i] \quad (7)$$

Where U_{ij} is the dynamic potential field generated by the evacuees and U_{iw} is the dynamic potential field generated by the wall, d_{ij} is the distance between evacuee i and evacuee j, R_i is the radius of evacuee's body and d_{body} is the diameter of evacuee's body. The U_{ij} and U_{iw} can be shown as Fig. 4 and Fig. 5 respectively.

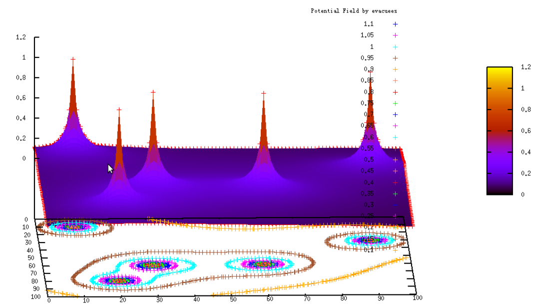

Fig. 4: Potential field generated by the evacuees

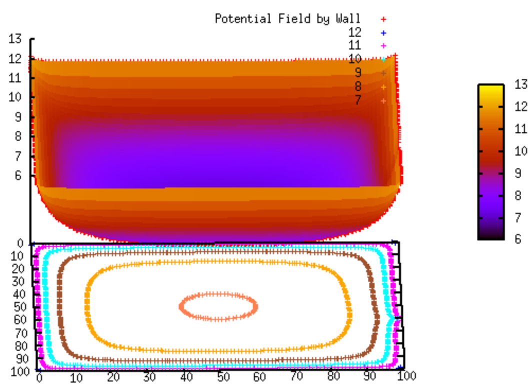

Fig. 5: Potential field generated by the wall

Then, the comprehensive potential field generated by kinds of factors can be expressed as follow:

$$U = \alpha U_s + \beta U_{ij} + \gamma U_{iw} \tag{8}$$

Where α, β and γ are weights that influence various different potential fields.

The final potential field model including U_s, U_{ij} and U_{iw} can be expressed as Fig. 6.

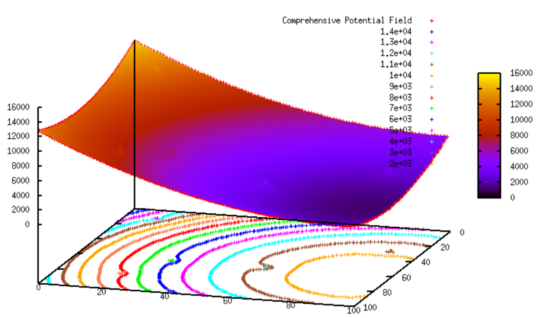

Fig. 6: Comprehensive potential field

The traditional evacuation model based on potential field is that every evacuee walks along the direction of gradient in the potential field. However, the process of emergency evacuation is the process of mutual cooperation by evacuees. Every evacuee will influence the distribution of potential field as well as the whole process. So it is necessary to find some laws to describe the process of evacuation.

Considering the formula (8), it can be known that U is constant during the process of evacuation (all evacuees are in the room and the impact of the border to the evacuee is ignored). Intuitively, we get that Fig. 7 is more "steady" than Fig. 6. So the process of evacuation is the decreasing process of the steady degree.

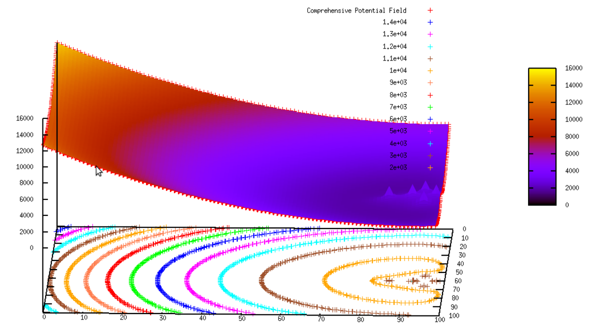

Fig. 7: The potential field while evacuees are close to door

The Steady Degree can be defined as follow:

$$S = \sum_{c \in C} U_c^2 = f(r_1, r_2, ..., r_n); \tag{9}$$

Where c is the cellular in the room and r_i is the position of evacuee i. There are n evacuees whose positions will influence the steady degree. While all evacuees are close to the door, S becomes smaller. It can be proved as following:

$$z = min(S) = U_1^2 + U_2^2 + ... + U_n^2 \tag{10}$$

st

$$U_1 + U_2 + ... + U_n = D \tag{11}$$

It can be concluded that when $U_1 = U_2 = ... = U_n = \frac{D}{n}$, z is the smallest. So while the potential of every cellular is more close to each other, the steady degree is smaller.

With the help of steady degree, the probability of evacuee r choosing the next cellular c_i follows the rule:

Define J_i as the set of neighbors of cellular i and jn_i is the number of its neighbors. Sort the set J_i according to steady degree S by ascending order, so the cellular with the lowest steady degree will be placed first.

Calculate the transition probability of cellular c_i as follows:

$$P_j = \frac{\frac{\theta^j}{s_j}}{\sum_{k=1}^{k \leq jn_i} \frac{\theta^k}{s_k}} \tag{12}$$

Where s_k is the steady degree while the evacuee chooses the cellular k. $0 < \theta \leq 1$ is the relative importance of the shortest path model versus the traditional roulette wheel model.

The steady degree based on cellular can help to simulate the scene of evacuation in teaching building. But it cannot optimize the route planning problem during emergency evacuation. According to the fixed distribution of evacuees in teaching building at a fixed time, with the help of the evolutionary algorithm, this paper proposes the model based on steady degree for teaching building evacuation.

III. Multi-objective Optimization Model Based on Steady Degree for Teaching Building Evacuation

Cellular automata model can reflect the position change of evacuees in evacuation from the micro-level by simulating the evacuation process. For the teaching building evacuation, there are fixed schedules which means fixed distribution of evacuees at a given time. So this paper proposes an multi-objective optimization model based on steady degree to optimize the route planning for teaching building evacuation.

Multi-objective optimization is the process of simultaneously optimizing two or more conflicting objectives subject to certain constraints [15]. The evacuation route problem in the teaching building belongs to routing optimization problems. Hence, the clearance time and steady degree sum are considered as the two objective functions of the multi-objective optimization model. The model treats stairs as nodes and corridors as links. So the path network in the teaching building can be expressed as Fig. 8:

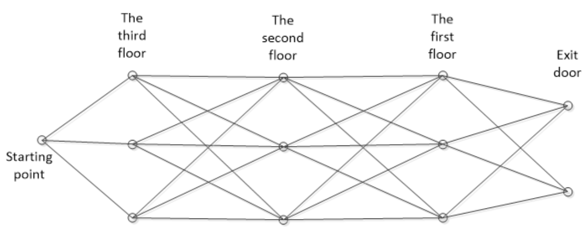

Fig. 8: Path network in teaching building

A. Notation

The notation used in the problem formulation is introduced below.

M: the total number of evacuees in the teaching building

i: the index of evacuee

K: the total number of floors in the teaching building

k: the index of floor

S_t^k: the steady degree of floor k at time t

C: the clearance time for teaching building evacuation

t_i: the time for evacuee i to evacuate from teaching building

RP_n: the Route-planning for teaching building evacuation

B. Methodology

According to the analysis of the emergency evacuation, the formulae describing the objectives and constraints can be represented as follows:

Objectives:

$$min f_1 = \max t_i \tag{13}$$

$$min f_2 = \int_{t=1}^{C} \sum_{k=1}^{K} S_t^k dt \tag{14}$$

Subject to the following constraints:

$$C = \max t_i \tag{15}$$

Where C means the time when the last evacuee leaves the teaching building.

As shown in Fig. 9, f_2 means the area formed by steady degree. While the area is smaller, the process of evacuation is more optimal.

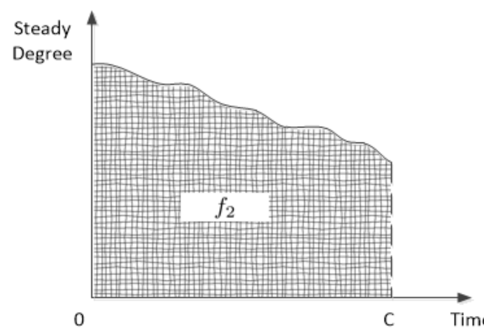

Fig. 9: Accumulation of steady degree

Based on the model above, the procedure of route-planning multi-objective optimization model is illustrated in Algorithm 1.

Algorithm 1 multi-objective optimization model based on steady degree

Initialization: Initialize the layout of the teaching building as well as the distribution of evacuees;
repeat
  Simulation: Place all evacuees in the specific classroom. Each evacuee chooses his route according to the route planning algorithm based on cellular automata model and potential field. Finally, make a statistics of the clearance time used to leave the teaching building and the total steady degree.
  Pareto optimal set determination: Calculate the objective funtions of f_1 and f_2. If RP_n is a non-dominated solution of the dominated set, add RP_n to the dominated set and remove the solutions which are dominated by RP_n.
until $noChange$ is $true$

C. Experiment

This model is validated in the Teaching Building No.1 of Wuhan University of Technology where there are 2939 evacuees and 50 classrooms. The distribution of classrooms in third floor of the Teaching Building is shown as Fig. 10.

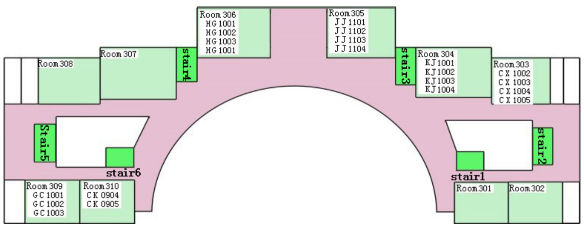

Fig. 10: Distribution of classrooms

According to the formula (2) and formula (6), the distribution of static potential field is shown as Fig. 11.

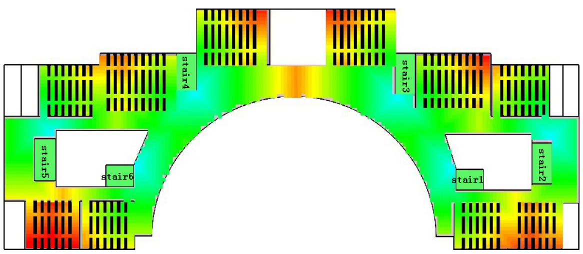

Fig. 11: Distribution of static potential field

Taking into account the actual situation, the multi-objective optimization model based on steady degree and cellular automata (MOSD) makes route planning for evacuees grouped by which classroom they are in. That is to say, evacuees in the same classroom will follow the same route.

Table 1 shows the final result of route planning and it lists all the choices of stairs for evacuees in every classroom on each floor.

To further validate the experiments of this model, this paper makes a comparison between this model and other route planning models on the platform of Pathfinder.

Pathfinder is an emergency egress simulator that includes an integrated user interface and 3D results visualization. Pathfinder allows you to evaluate evacuation models more quickly and produces more realistic graphics than other simulators.

The 3D model is shown as Fig. 12. There are five floors in this building, with 10 classrooms on each floor. And there are two exits (0.8-meter wide doors) in each classroom, which can accommodate about 100 evacuees. In total, there are 2939 evacuees in the entire teaching building.

Fig.13 shows the Pareto solution set with 2939 people. From the picture, It can be seen that there are many solutions with different objectives such as total evacuation time and steady degree. It is useful for decision maker to decide which solution is better for a certain evacuation.

TABLE I: Stair choices for teaching building evacuation

Classroom	Floor5	Floor4	Floor3	Floor2
room508	6	6	6	6
room507	5	5	5	5
room506	3	3	3	3
room505	4	4	4	4
room504	2	2	2	2
room503	1	1	1	1
room502	1	1	1	1
room501	2	2	2	2
room407		5	5	5
room405		4	4	4
room404		2	2	2
room403		4	4	4
room402		6	6	6
room401		1	1	1
room308			5	5
room307			6	6
room305			4	4
room304			3	3
room303			5	5
room302			1	1
room301			2	2
room206			2	4
room205			2	4
room204			2	3
room203			2	2
room202			2	1
room201			2	1

Fig. 12: The evacuation model based on Pathfinder

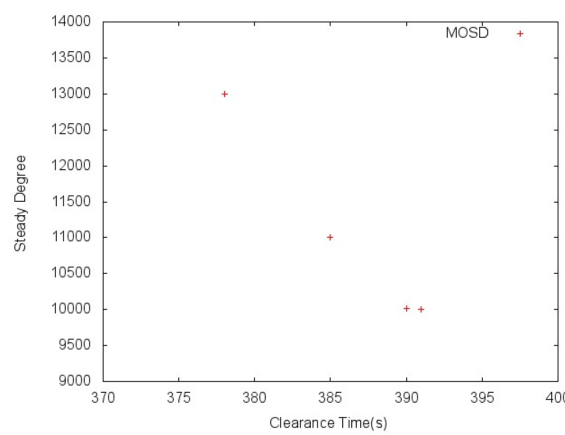

Fig. 13: The evacuation routes of evacuee in teaching building

The fig.14 shows the distribution of evacuated number of evacuees in different floors. It shows that the clearance time is the shortest when all the stairs in the teaching building are fully exploited.

To verify the MOSD model, we compare it with Pathfinder model and the traditional ACO model. The comparison of the clearance time among three evacuation models is shown as Fig.15. It can be seen that the MOSD model is better than the

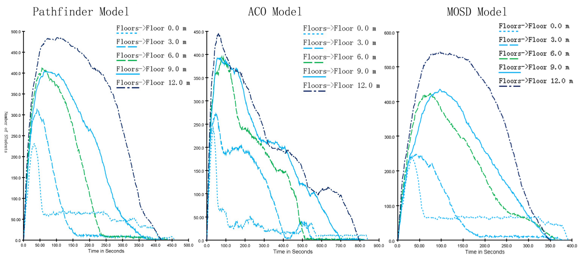

Fig. 14: Distribution of evacuees in different floors

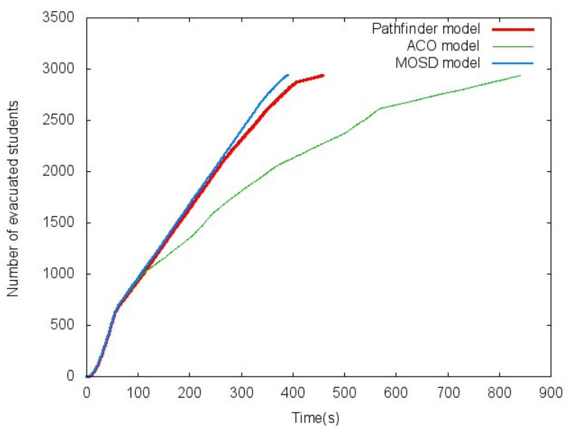

Fig. 15: The results of Pathfinder/ACO/MOSD

other models. As shown in Table 2, if the evacuees get out of the building according to their own choice, the clearance time is probably 460s. But if they follow the global optimal route planning, the clearance time will be reduced to 385s and the steady degree sum is lower, which means there is less congestion. The clearance time will be longer if all the evacuees follow the shortest route ACO model.

TABLE II: Comparison of the clearance time among the models of ACO/Pathfinder/MOSD

Model	Clearance(s)	Steady Degree
ACO	843	23478.92
Pathfinder	459	12736.30
MOSD	391	9987.49
	385	11003.36
	393	9802.27

IV. Conclusion

Since the distribution of evacuees in the teaching building is fixed at a given time, this paper proposed multi-objective optimization model based steady degree for emergency evacuation in teaching building. It makes a pre-evacuation planning for the entire teaching building and reduces the clearance time of the evacuation.

However, the factors influencing emergency evacuation are extremely complicated, such as building construction factors, physiological and psychological factors. So it needs more factors to refine the potential field and consider more objectives to improve the evacuation route-planning.

Acknowledgment

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