

Social Force 3D Evacuation Model based on Improved Ant Colony Algorithm

Yunliang Zhu ^a, Baoyu Ding ^b, Junfeng Bao ^c, Zisen Mao ^d and Xinghu Teng ^{e, *}

The Army Engineering University of PLA, Nanjing 210000, China.

^a15051801667@163.com, ^b1292876208@qq.com, ^c2967116271@qq.com, ^dmaozisen@126.com, ^{e, *} tengxh3121@163.com

Abstract. This paper proposes a social force three-dimensional dynamic crowd evacuation model by combining the ant colony algorithm with the social force model, improving the heuristic function and updating method of pheromone, as well as adding the target heuristic function and the fallback strategy. Compared with the traditional ant colony algorithm, the operation efficiency has been improved and the searching time of path in the crowd evacuation process to some extent has been shortened. The three-dimensional environment modeling of the Louvre is carried out by using the grid method according to the real three-dimensional structure of the Louvre. The grid unit is used as the minimum moving unit in the path planning to divide the Louvre floor plan into evacuation nodes. By using the improved ant colony algorithm in the social force three-dimensional dynamic crowd evacuation model, the evacuation route in the emergency is planned as well as the bottleneck point, the shortest path in the evacuation process and the new optimal path when some exits cannot be used is obtained. The model fully considers the interaction force between individuals in the evacuation process. It has higher efficiency and applicability than the traditional model, and can solve evacuation problems under emergencies in complex building groups. The simulation results of the model are also verified based on the simulation software Pathfinder. Through setting the parameters of evacuated visitors and building in the software, the simulation of crowd evacuation behavior under emergencies is realized, and the effects of different visitors' density and visitors' types on evacuation path and evacuation time are simulated. Simulation results demonstrate the effectiveness of the model strategy in three-dimensional dynamic evacuation. Finally, the advantages and disadvantages of the model are analyzed, and the applicability of the model in the crowded large building structure is discussed.

Keywords: Louvre; Ant colony algorithm; social force model; simulation.

1. Introduction

The Louvre is one of the largest and most visited art museums in the world, receiving more than 8.1 million visitors in the 2017. The increasing number of terror attacks in France requires a review of the emergency evacuation plans at many popular destinations. We need to help design the evacuation plans at the Louvre in Paris, France. The number of guests in the museum varies throughout day and year, which provides challenges in planning the regular movements within the museum. The diversity of visitors -- speaking a variety of languages, groups traveling together, and disabled visitors -- makes evacuation in an emergency even more challenging. In general, the goal of evacuation is to have all occupants leave the building as quickly and safely as possible. Upon notification of a required evacuation, individuals' egress to and through an optimal exit in order to empty the building as quickly as possible.

2. Problem Analysis

One of the commonly used methods of path planning is the social force model. We often refer to the non-linear interaction between individuals in the population and between individual and the environment (obstacles, such as doors or walls) as social forces. This force can cause changes in individual behavior. The movements of individual are subjected to three forces in the scene: the driving force that guides the movement of the individual, the force of the safe distance between individuals, the force of the safe distance between individual and obstacle or others. As shown in the figure, assuming that the quality of individual A is M, it will be affected by both the psychosocial

force and the physical environment force in the entire evacuation environment. The psychosocial force is reflected in the self-driving force generated by the individual's expectation of the target, which can be illustrated in the following formula:

$$f'_A(t) = \frac{1}{t} (v'_A(t)e'_A(t) - v_A(t))M \quad (1)$$

Wherein, $v'_A(t)$ is the expected velocity of evacuated individual A, which is positively correlated with the degree of danger of the environment; $e'_A(t)$ indicating the expected movement direction of individual A, is affected by factors such as the location of the safe exit, or the diffusion trend of danger; and $v_A(t)$ is used to express the actual movement velocity of individual A, generally smaller than the expected velocity $v'_A(t)$.

The physical environment force consists of two parts: the force between the individuals, f_{AB} . And the force between the individual A and the obstacle, f_{AW} . The force between individuals is mainly expressed as repulsive force, which can be showed in the following formula:

$$f_{AB} = \alpha \exp\left(\frac{\gamma_A + \gamma_B - d_{AB}}{\beta}\right) \vec{\lambda}_{AB} \quad (2)$$

Where α and β are the constants of the social force model, which respectively represents the strength of the repulsive force and the variation range of repulsive force which varies with the distance between the individuals; γ_A , γ_B , is respectively, the radius of the individual A and the individual B; and d_{AB} , indicating the distance between the individual A and individual B, is the repulsive force unit vector generated by the individual A to the direction of individual B, and is related to the size of the $\gamma_A + \gamma_B$. Similarly, the force between an individual and an obstacle can be written as:

$$f_{AW} = \alpha \exp\left(\frac{\gamma_A - d_{AW}}{\beta}\right) \vec{\lambda}_{AW} \quad (3)$$

Where d_{AW} is the distance between an individual and an obstacle; it is the unit of the repulsive force between the individual and the obstacle.

In summary, in the social force model, the social force exerted upon the individual A can be expressed by the following dynamic formula:

$$F_A = f'_A + \sum_{B \neq A} f_{AB} + \sum_W f_{AW} \quad (4)$$

In the social force model, it is considered that there is absolutely equality between people, and there is no corresponding relationship between the force and speed of movement between individuals. The relative speeds between individuals and between individual and obstacle in the case of contact affect the speed of evacuation, which is obviously unrealistic. Therefore, we improve the original social power model to overcome the shortcomings, and add the emergency algorithm to the social force model. The emergency algorithm can plan the path for the individual. After the improvement, there is no collision when the environment has obstacles, in this way the social force model can more accurately simulate the movement process of the crowd.

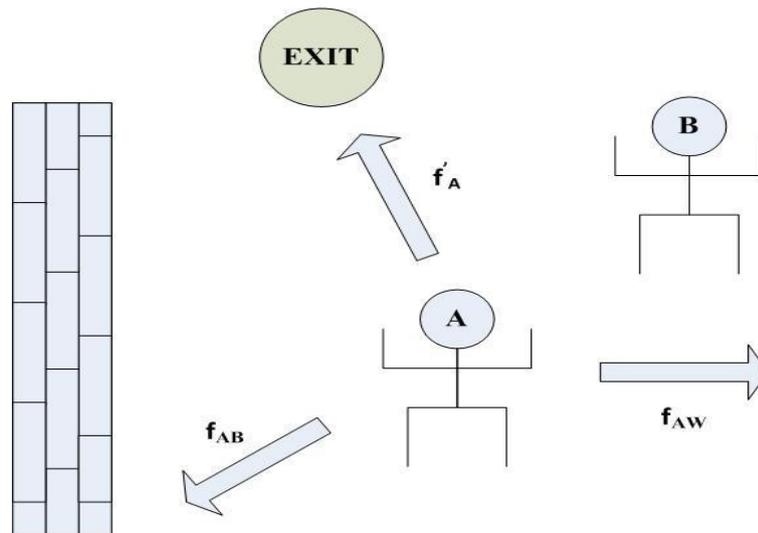


Figure 1. Three forces that individuals receive in crowd evacuation

In summary, we have established a three-dimensional evacuation model based on improved ant colony algorithm (ACO), which marks visitors as independent cells, and modifies the ACO algorithm's heuristic function, updating method of pheromone and forbidden rules to describe the crowd behaviors in evacuation, such as retrograde motion, circumambulation, obstacle avoidance, and conformity. The results show that the model can simulate the "arched distribution" phenomenon in the actual evacuation process, and the resulting evacuation time is similar to that of the commercial software Pathfinder; compared with Pathfinder, the model can automatically obtain main evacuation path. We propose a three-dimensional emergency dynamic evacuation strategy based on an improved emergency algorithm model to solve the problem of evacuation under emergencies in complex building groups. This strategy uses the grid method to model the three-dimensional environment of the designed building; then uses the improved bio-heuristic emergency algorithm to automatically plan the evacuation route in the event of an emergency to get the shortest evacuation path; at last, according to the characteristics of point dynamic diffusion of fire disaster, plan the best evacuation route in real time.

3. Model Establishment and Solution

3.1 Improvement of Ant Colony Algorithm

Combined with a single forbidden rule to simulate the evacuation process of the crowd, the optimal evacuation path of the CA based on the ACO algorithm is obtained. This path is better than the optimal evacuation path based on the classical cellular automatic evacuation model. According to the replication idea of genetic algorithm, the updating method of pheromone of ACO algorithm is improved, and the optimal evacuation path of the specified individual is obtained according to the dynamic change of people in the field combined with a single forbidden rule. For the CA evacuation model with the improved ACO algorithm, we mainly reflect the following three aspects:

1) Improve the heuristic function.

The heuristic function in the traditional ACO algorithm is usually the reciprocal of the distance between nodes, and the distance between adjacent nodes in the CA model is a constant value, which causes the value of the heuristic function to be a constant, thus the function loses the heuristic effect and cannot be well applied to a gridded evacuation model. In this problem, we mark each visitor as an independent cell, and the heuristic function happens to reflect the expected value of the individual selection of each candidate node. The static field reflects the distance from the node to the exit. Generally, the closer the node is to the exit, the larger the expected value is. This characteristic is consistent with the essence of the heuristic function. Therefore, the static field of the candidate node

is added to the heuristic function. The improved heuristic function can be represented by the following formula:

$$\eta_{ij} = \frac{1}{|X - X_i| + |Y - Y_i| + 0.1} \quad (5)$$

Where X, Y are the abscissa and ordinate of the exit; X_i, Y_i are the abscissa and ordinate of the cell to be selected (the addition of 0.1 in the denominator is to prevent the meaningless of heuristic function of the exit coordinates). When an exit occupies multiple cells, the coordinates of the exit cell are selected by roulette.

2) Improve the updating method of pheromone

The ACO algorithm needs to update the pheromone after each iteration, corresponding to the evacuation problem in an emergency situation, that is, the pheromone needs to be updated after each evacuation. The ant-cycle model can use global information to update the amount of pheromone on the path. Considering the impact of retrograde motion on crowd evacuation, we improve this model.

The pheromone concentration function reflects the updating method of pheromone and the improved pheromone concentration. The function is as follows:

$$\tau_{ij}(t+\Delta t) = (1 - \rho) \times \tau_{ij}(t) + \sum_{k=1}^m \tau_{ij}^k(t + \Delta t) \quad (6)$$

$$\Delta \tau_{ij}^k(t+\Delta t) = \frac{1}{L_k} \times \left(\frac{1}{2}\right)^{n-1} \quad (7)$$

Where $\eta_{ij}(t + \Delta t)$ is the amount of pheromone on path (i, j) at time $t + \Delta t$; ρ is the coefficient of volatilization; $\tau_{ij}(t)$ is the amount of pheromone on path (i, j) at time t ; $\Delta \tau_{ij}^k$ is the pheromone increment left by visitor k on line (i, j) during the period Δt ; L_k is the number of cells passed by the visitor k in this tour; n is the number of times the visitor k passed the path (i, j) in this tour, path (i, j) and path (j, i) are the same path. The value of ρ ranges from 0 to 1. Therefore, as the number of iterations increases, the pheromone concentration on the path where visitors rarely pass and the path with long evacuation time will become lower and lower, and the attraction to visitors will become smaller and smaller; The pheromone concentration will increase after positive feedback, and visitors will increasingly prefer to paths with shorter evacuation time.

3) Improve the forbidden rules

We propose a two-stage forbidden rule. The first phase refers to the first iteration, the second phase refers to the 2nd iteration to the last iteration. At the same time, the suboptimal placeholder is introduced in the forbidden rules of the first stage, so as to avoid the visitors getting into the local optimum in the path selection and improve the convergence speed of the ACO algorithm.

Considering the state of the surrounding cells, the probability calculated by the following formula is used to select the next place.

$$p_{ij}^k(t) = \frac{[\tau_{ij}(t)]^\alpha \times [\eta_{ij}(t)]^\beta}{\sum_{\omega \in J_i} [\tau_{i\omega}(t)]^\alpha [\eta_{i\omega}(t)]^\beta}, \quad j \in J_i \quad (8)$$

Where $\tau_{ij}(t)$ is calculated according to equations (6) and (7), $\eta_{ij}(t)$ is calculated according to equation (5), $p_{ij}^k(t)$ is the probability of selecting path (i, j) for the visitor k at cell i , α is the pheromone influence factor, β is the influence factor of the heuristic function, J_i is a collection of vacant cells near cell i , ω is an element in set J_i .

3.2 Three-dimensional Emergency Dynamic Evacuation Strategy

In order to clearly describe the working principle of the algorithm, the plane environment model of the two-dimensional emergency evacuation path planning is first described, and then extended to

the actual three-dimensional space model to plan the three-dimensional evacuation route of the Louvre.

3.2.1 Two-dimensional Emergency Evacuation Environment Model

The emergency evacuation work environment is discretized into a two-dimensional grid map, and the state of each grid is defined as "free point", "obstacle point" or "emergency point", as shown in Figure 2. On the basis of the raster map, a neighborhood model related to its motion is established. The moving trail of the human during the evacuation process corresponds to the grid on the map, as shown in Figure 3. When a person is in the grid i , the adjacent 8 grids in the circular area are the optional evacuation positions of the next moment. The specific evacuation direction depends on the size of the pheromone concentration between the two grids and the value of the heuristic function.

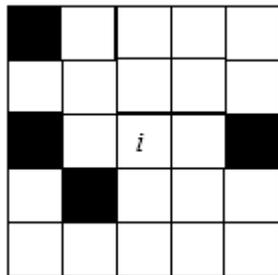


Figure 2. two-dimensional raster map

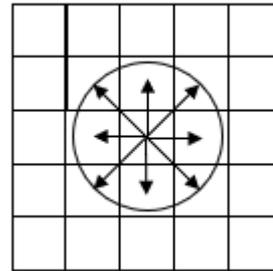


Figure 3. motion neighborhood model

3.2.2 Three-dimensional Emergency Evacuation Environment Model

For the two-dimensional grid model in Figure 1, adding one dimension in the vertical direction we would get the actual three-dimensional environment model. The three-dimensional space is evenly divided into $n \times n \times n$ equal-sized units, and the grid unit is used as the minimum moving unit in the path planning. Each grid is numbered according to the principle from left to right and from bottom to top, with each grid being a unique code among $1 \sim n^3$. The coordinates of each grid in the three-dimensional space model are represented by its center point position, the grid number and the coordinate position is determined by equations (9). In the three-dimensional fire evacuation environment, there are six degrees of freedom of movement (up and down, left and right, and forward and backward) when crowd are evacuated. The structural model is shown in Figure 5. Taking the model $n=3$ as an example, the raster coding and forward coding of the bottom floor are shown in Table 1. In this model, the human activity area includes three floors. When the position is not at the stairway, the next possible movement position would be limited to 8 positions in the plane; when at the stairway position, the direction of upwards and direction of downward are added, and the neighborhood range would be expanded to 10 positions. The evacuation direction is the same as the two-dimensional model, depending on the pheromone concentration between the two grids and the heuristic function value.

$$\begin{cases} x = \text{mod}(G - 1, n) + 0.5 \\ y = f(\text{mod}(G - 0.1, n^2) / n) + 0.5 \\ z = c \times G / n^2 - 0.5 \\ G = (z - 0.5) \times n^2 + (y - 0.5) \times n + x + 0.5 \end{cases} \quad (9)$$

In the formula, G is called the grid number in the 3D model; (x, y, z) is called the 3D coordinate corresponding to the grid G ; f is the bottom floor of the building; c is the top floor of the building.

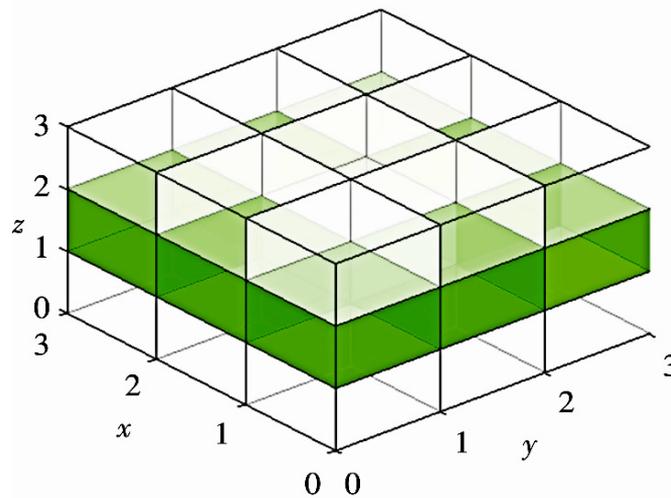


Figure 4. 3D illustration of evacuation direction

Table 1. Grid Numbering Diagram of Building

Number	Bottom grid numbering sequence	Forward grid numbering sequence
1	1-2-3	1-2-3
2	4-5-6	10-11-12
3	7-8-9	19-20-21

3.3 Three-dimensional Emergency Dynamic Evacuation Strategy based on Improved Ant Colony Algorithm

The implementation steps of the improved three-dimensional evacuation model of the ant colony algorithm are represented by a general program flow chart and a subroutine flow chart, in the Pathfinder environment, the evacuation model is applied to the evacuation scene by using the drawing function programming.

The input and to-be-output are as follows:

Input: Initial evacuation number $m=22658$ and various parameters of the improved ant colony algorithm, including the maximum number of iterations in the probability transfer formula, the number of moving steps S , the specified number of iterations ($2 < N_{ap} < N_{max}$), and the specified number of moving steps S_{ap} .

Output: The initial distribution state of the visitors, the evacuation state of the specified number of moving steps S_{ap} in the specified number of iterations N_{ap} , the number of time and steps required to complete the evacuation of the 100th iteration of visitors, and the main evacuation path.

3.3.1 Principles for the Division of Personnel Evacuation Nodes

Due to the limitation of the running speed of the computer, only a certain scale of the network can be calculated. Therefore, when the evacuation nodes are divided according to the internal structure of the building, if the size of the building is too large, the number of nodes may be too many. The program cannot run under such circumstances, so the nodes should be reasonably merged to reduce the number of network nodes. The basis of the node combination is to merge the nodes connected to the same node, and the relevant characteristic parameters need to be changed accordingly after the new node is formed.

Sometimes due to the large range of the unit, the division into just one node cannot specifically reflect the details of its people flow, thus the one node should be split into more nodes. For example,

the aisle inside the building may be too long, sometimes the width of the aisle is inconsistent, and there are too many nodes leading to the aisle. At this time, the aisle should be divided into sections, and it is more reasonable to treat each section as a different node. The principle of detailed division of aisle is showed as follows:

(1) When the aisle is forked or turned halfway, mark the bifurcation or corner position as the division boundary of nodes;

(2) When the width of the aisle changes (expanded or narrowed), the position where the width changes is set to the division position of the nodes.

According to the principle of node division, the Louvre building plan is divided into nodes, and the evacuation exits are 1, 2, 12, 13, 14, 34, 35, 36. The specific nodes are divided as below:

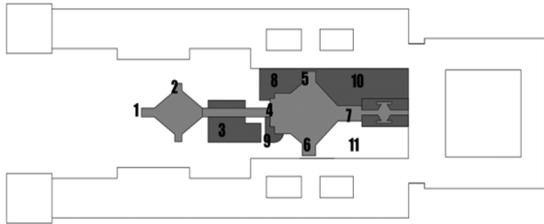


Figure 5. Floor plan of the Napoleon Hall

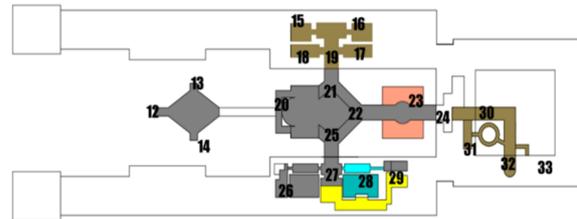


Figure 6. Floor plan of the Lowerground floor

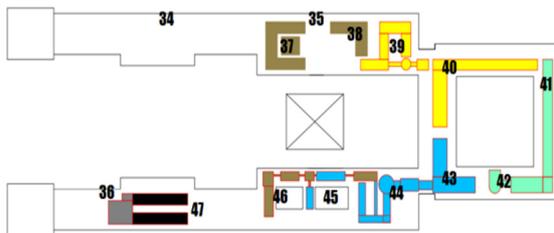


Figure 7. Floor plan of the ground floor

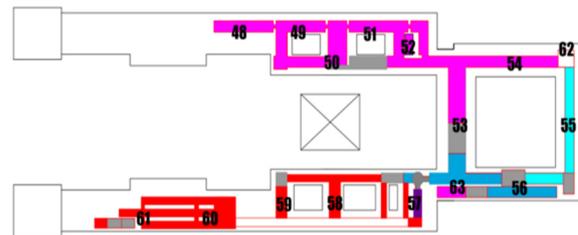


Figure 8. Floor plan of the first floor

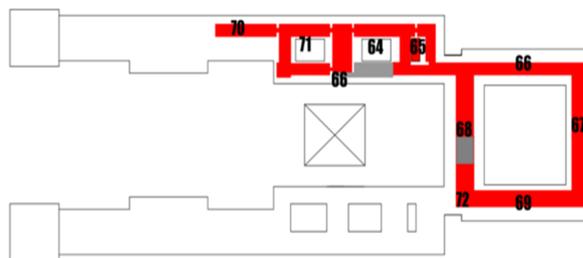


Figure 9. Floor plan of the second floor

This paper uses the social force 3D model based on the improved ant colony algorithm to stimulate, and obtain the following table which shows the optimal path for each node:

Table 2. Optimal path of each node

Node	Optimal path	Node	Optimal path
1	exit	2	exit
3	2	4	3→2
5	4→3→2	6	4→3→1
7	4→1	8	5
9	4→3→1	10	5
11	7	12	exit
13	exit	14	exit
15	16→35	16	35
17	16→35	18	16→35
19	16→35	20	12
21	20→13	22	20→14
23	20→12	24	23→20→12
25	22→20→12	26	25→22→20→12
27	25→22→20→12	28	25→22→20→13
29	25→22→20→13	30	23→21→16→35
31	23→21→16→35	32	23→21→16→35
33	23→21→16→35	34	exit
35	exit	36	exit
37	34	38	34
39	35	40	35
41	35	42	35
43	35	44	36
45	36	46	36
47	36	48	50→35
49	50→35	50	35
51	50→35	52	50→35
53	63→44→45→36	54	62→39→38→35
55	62→39→38→35	56	63→44→45→36
57	61→36	58	61→36
59	61→36	60	61→36
61	36	62	39→38→35
63	44→45→36	64	62→50→35
65	62→50→35	66	62→39→35
67	66→62→39→35	68	66→62→39→35
69	72→63→45→36	70	62→50→35
71	62→50→35	72	63→45→36

4. Model Verification

To further demonstrate the accuracy of the model, we used the Pathfinder crowd evacuation simulator developed by Thunderhead Engineering to verify.

4.1 Pathfinder Tool

Pathfinder, a simulator based on personal movement of entry and exit, is developed by Thunderhead Engineering of the United States. It provides graphical interface for users to simulate design and execution, as well as the analysis results of the 3D visualization tool. It is a simple, intuitive and easy-to-use intelligent emergency crowd evacuation evaluation system.

4.2 Establish Pathfinder Personnel Evacuation Model and Evacuation Scene Design

4.2.1 Establishing the Pathfinder Personnel Evacuation Model

First, use AutoCAD to simplify the floor plan of the Louvre Museum offered in the problem and then, use the 1:1 scale to model the simplified Louvre in Pathfinder. Figure 10 is a CAD schematic diagram of the floor plan of the Louvre Museum, and Figure 11 is a 3D rendering of the Pathfinder crowd evacuation model of the Louvre. All walls and floors are made of concrete.

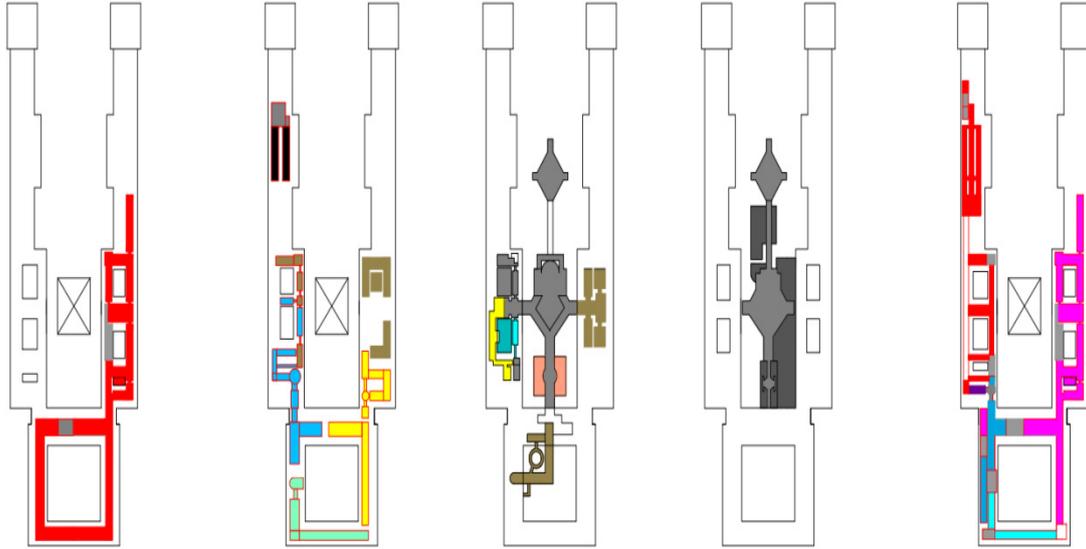


Figure 10. A flat tour of the Louvre Museum.

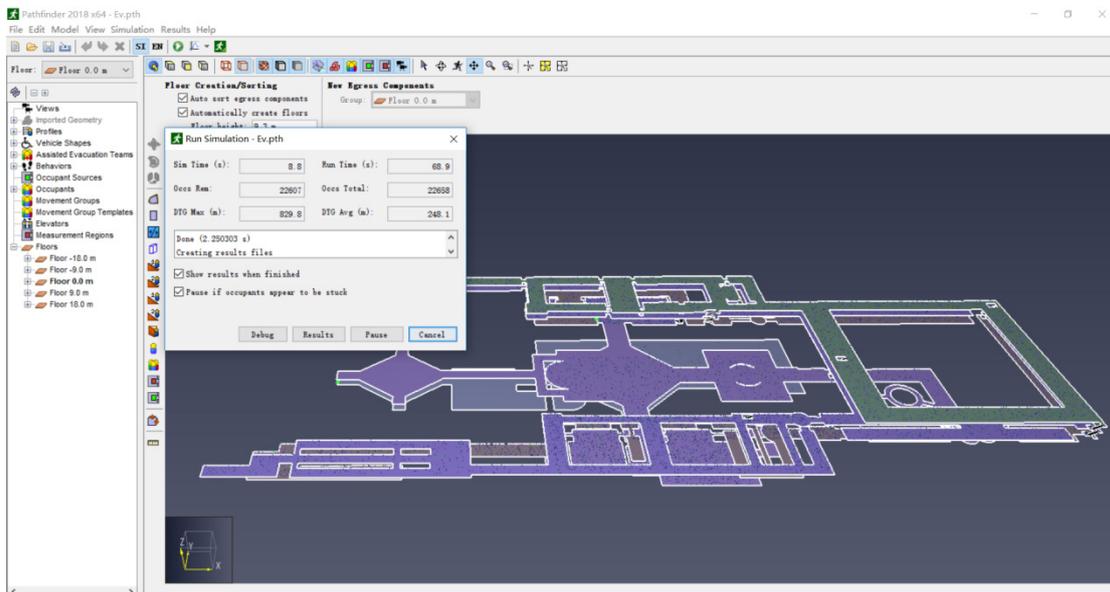


Figure 11. 3D rendering of the Pathfinder personnel evacuation model of the Louvre

4.2.2 Evacuation Scene Parameter Design

Set the data for occupants inside the building, such as the type of visitors and the walking speed, as well as the shoulder width of different people, etc., see in Table 3. The walking speeds of the visitors are determined by referring to the evacuation parameters given by the SFPE Handbook of Fire Protection Engineering.

Table 3. Personnel evacuation parameters

Personnel type	Personnel composition ratio	Walking speed m/s	Shoulder width (cm)
Adult lady	40%	1.02	45
Adult men	40%	1.2	50
Old man	10%	0.82	50
Child	10%	0.92	32

The evacuation scene is designed in combination with the scenario of the terrorist attack. The scenario with the most unfavorable evacuation is used to set up the following evacuation scene. See in Table 4.

Table 4 .Evacuation scenarios

Evacuation strategy	Evacuation number (person)	Specific evacuation plan
Overall evacuation	22658	All floors, at the same time evacuate

4.3 Simulation Results

When a terrorist attack occurs, people in the area where the terrorist attack occurred would be the first to detect and evacuate, and people in other areas will take some time to start evacuation. Before they escape, there would be some internal alarm time of the mall and visitors' response time. Formula (1) can represent the entire evacuation time inside the museum, T_A indicates the alarm time; T_R indicate the visitors' response time; T_M represents the evacuation walking time.

$$T_{REST} = T_A + T_R + T_M \quad (10)$$

The alarm time refers to the period of time when the terrorist attack occurs until the terrorist attack alarm system issues an alarm. The program designed in this paper is equipped with an automatic alarm system, so the time for warning of terrorist attacks (T_A) is 60 s; the response time of visitors refers to the period when the visitors hear the terrorist attack alarm until they start to escape and evacuate. The designed program has a broadcasting system. Therefore, the visitors' response time (T_R) is valued as 120s; the evacuation walking time of the visitors (T_M) is calculated by simulation calculations, the results are shown in Table 5. The calculation results are shown in Table 6.

Table 5 .evacuation time

Evacuation strategy	Evacuation number (person)	Evacuation time (s)
Overall evacuation	22658	1979.3

Table 6 .Final evacuation time

Evacuation strategy	Alarm time T_A (s)	Response time T_R (s)	Action time T_M (s)	Evacuation time T_{REST} (s)
Overall evacuation	60	120	1979.3	2159.3

Evacuate personnel at 5, 15, 25, 45, 55, and 65 nodes are respectively observed to observe the evacuation path. The results are as follows:

Table 7 .The results of Evacuate personnel

Node	Path	Node	Path
5	4→3→2	15	16→35
25	25→22→20→12	45	36
55	62→39→38→35	65	62→50→35

The simulation results are in agreement with Table 2, and the feasibility of the model is verified.

4.4 Personnel Evacuation Simulation Screenshot



Figure 12. Personnel evenly distributed on each floor 0.0s Screenshot

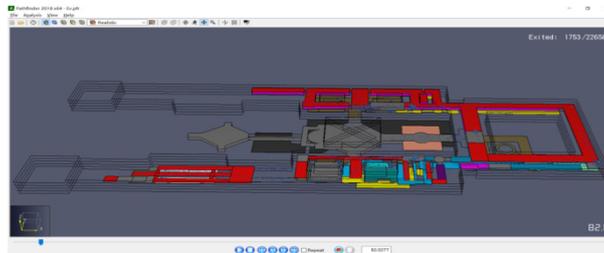


Figure 13. Personnel evenly distributed on each floor 82.0s Screenshot

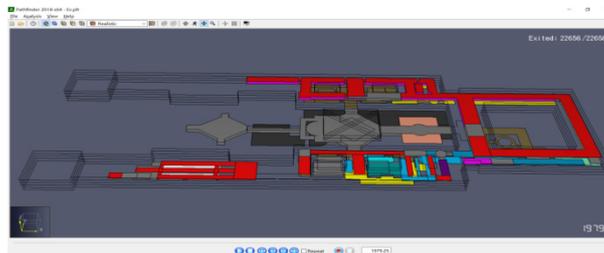


Figure 14. Overall evacuation completed 1979.3s screenshot

4.5 Analysis of the Impact of Personnel Density on Evacuation

A large number of on-site conditions has demonstrated that due to the excessive density of occupants in the building, the stairway is often severely congested, which makes the evacuation time significantly longer. Therefore, reasonable occupants' density within the building is critical to evacuation. This time, Pathfinder was used to simulate the evacuation in the building with different visitors' densities. The experimenter density settings are :

Table 8. Personnel density settings

Floor	Experiment 1	Experiment 2	Experiment 3
-2	0.45	0.22	0.88
-1	0.40	0.20	0.80
0	0.50	0.25	0.96
1	0.48	0.24	0.96
2	0.44	0.22	0.90
Number of people	22658	10324	42634
Evacuate time(s)	1979.3	852.3	4564.6

The following table shows the relationship of evacuation personnel over time:

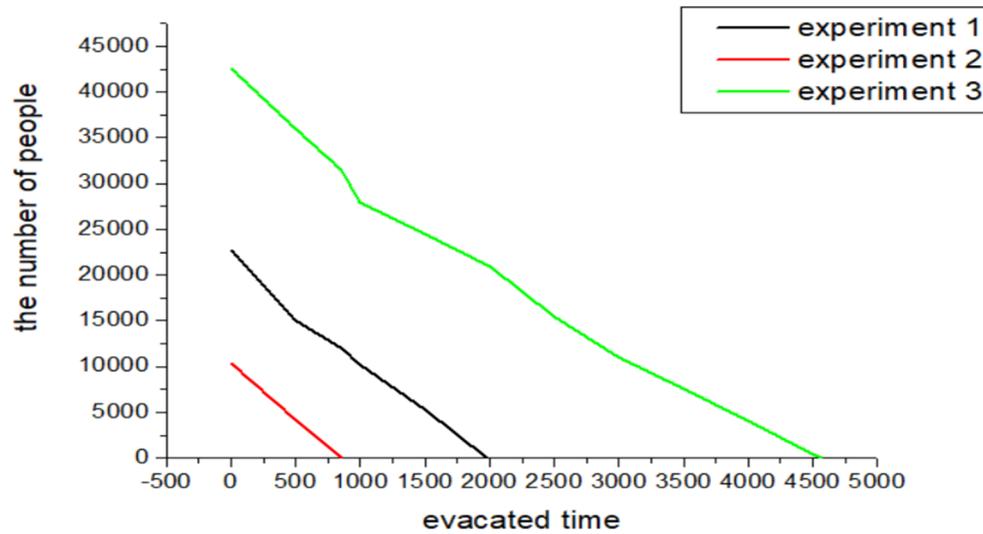


Figure 15. Diagram of personnel changes over time

It can be concluded that as the density of visitors increases, the same number of people increases, and the increase in evacuation time will be more, so the reasonable occupants' density in the building plays a vital role in evacuation.

5. Summary

One advantage of this model over pathfinder is that it can automatically generate the main evacuation path, which can provide a basis for the arrangement of small movable obstacles in the room and the work of intelligent evacuation indication system, which is of great significance for improving evacuation efficiency and reducing casualties.

In the future, models and algorithms should be continuously improved, such as the familiarity of personnel with the environment and the influence of the pressing force between people in the evacuation process on evacuation, so as to achieve better application of casualties.

In the future, the area within the building can be finely meshed, hoping to reproduce individual differences in pedestrians and details of pedestrian behavior.

References

- [1]. Varas a, Cornejo M D, Mainemer D, et al. Cellular automaton model for evacuation process with obstacles[J]. *Physica A Statistical Mechanics & Its Applications*, 2006, 382(2): 631-42.
- [2]. Kirchner A, Nishinari K, Schadschneider A. Friction effects and clogging in a cellular automaton model for pedestrian dynamics[J]. *Physical Review E Statistical Nonlinear & Soft Matter Physics*, 2003, 67(5 Pt 2): 056122.
- [3]. Stutzle T, Hoos H H. Max-min ant system[J]. *Future Generation Computer System*, 2000,16 (8):889- 914.
- [4]. Leguizam N G, Coello C A C. An Alternative ACO Algorithm for Continuous Optimization Problems [M]. Springer Berlin Heidelberg, 2010.
- [5]. Wang Ru, Zhou Lei, Liu Jun. Research on Cellular Automata Evacuation Model Based on Improved Ant Colony Algorithm[J]. *Chinese Journal of Safety Science*, 2018, 28(01): 38-43.