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Summary Sheet

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Type a summary of your results on this page. Do not include the name of your school, advisor, or team members on this page.

Time to leave the Louvre

Abstract

In this paper, we make a series of explorations on the design of the Louvre emergency evacuation plan, and construct a comprehensive revenue model and an equilibrium flow model based on cellular automata for the evacuation of the ground floor and the evacuation between floors. Finally, pathfinder software is applied to simulate and verify the optimal paths of the model solution.

We first consider that the evacuation is evacuated from the building process, define the comprehensive benefit as the principle of ideal choice evacuation of personnel evacuation path, based on cellular automata thought, set the maximum comprehensive benefit grid for the direction of the cellular state transition, which based on cellular automata evacuation path model of comprehensive income.

For the selection of evacuation path between floors, an equilibrium flow model is constructed to balance the flow of people in different paths and realize the reasonable distribution of people in public sections, so as to reduce the degree of evacuation congestion and evacuation time.

Cellular automata simulation by matlab to explore the influence of different factors on the evacuation rules, which determine the gain coefficient of different evacuation situation of optimal value range, using the three-dimensional evacuation simulation software pathfinder to various circumstances evacuation path for simulation model, and compared with the short circuit model to determine the evacuation route, found that the present model to determine the evacuation efficiency of path is optimal; In addition, a three-dimensional model of the Louvre is built by pathfinder, and the corresponding evacuation paths are obtained through simulation.

Finally, the models are evaluated and generalized, and the policy and procedural recommendations for Louvre emergency management are given based on the research conclusions of this paper.

Key Words: Emergency evacuation; Comprehensive income; Cellular Automata; Equilibrium flow; Pathfinder simulation

Contents

1 Introduction

1.1 Background

From students killed in Toulouse to soldiers attacked outside the Louvre museum in Paris[1], there have been at least a dozen terror-related attacks in France since 2012. The increasing number of terrorist attacks in France has forced a review of emergency evacuation plans in numerous popular destinations. Reduce casualties from terrorist attacks by using reasonable emergency evacuation plan to allow all occupants to evacuate the building as quickly and safely as possible and to empty the building as soon as possible.

The Louvre in Paris is part of the world's largest and most visited art museums, with more than 8.1 million visitors in 2017[2]. Considering the diversity of visitors, such as different languages, disabled visitors, etc., and the number of visitors in the museum varies from day to day and from year to year, this poses a challenge to the planning of emergency evacuation plans for the museum.

The Louvre has five floors, two of which are underground. There are 4 main entrances, of which the pyramid entrance is the main public entrance[3]. Export quantity and only emergency personnel and museum officials know the total number of actual usable exit point, although the public awareness of the exit point can provide additional power for evacuation plan, but compared with the four main entrance security level, due to the security of the exit is limited, may cause security issues, this makes the case of an emergency evacuation is becoming more challenging.

1.2 Our Work

Problem requires us to develop on the Louvre museum in terrorist attacks in the safety of personnel evacuation model, it is concluded that the optimal evacuation path, and making a series of different cases of the Louvre safety evacuation plan for the Louvre managers for reference, require evacuation model can make the visitors quickly safely out of the Louvre, and allow relief and emergency personnel as soon as possible into the Louvre museum in directing visitors to withdraw. In addition, the building can be used to solve a variety of factors and the adaptability of various may affect the potential threat of evacuation model, and applies the model in the Louvre museum visitors safe evacuation of the project, at the same time for large congestion structure adjust the evacuation model, finally, according to the research conclusion, put forward Suggestions about the Louvre emergency management policies and procedures.

In this article, we give full consideration to the crowd density, communication action team, exit width, obstacle of language, tourist quantity, population characteristics, such as gender, age, disability, etc factors on the impact of the Louvre museum visitors safe evacuation, evacuation time to be shortest as the goal, in the most short distance as the basic principles, respectively separate influence factors is built and the comprehensive influence visitors safe evacuation of the basic movement rules, to establish the optimal evacuation path based on cellular automata model, combining with the results and Affluences procedures, standards for different influence of various factors, the optimal evacuation strategy, In order to verify the practicality of the model, the model was simulated in 3d by using Pathfinder software. In addition, due to the large crowd density and the small number of exits in the large congestion structure, the model coefficients were adjusted accordingly to obtain the model of personnel safety evacuation suitable for the large congestion structure. Finally, combined with the research conclusions of this paper. Suggestions were put forward for the Louvre managers on relevant policies and procedures for emergency management.

2 Symbols and Definition

Symbols	Definition
S_i^t	the state of the ith cell at time t.
V	the evacuation speed of personnel.
ε	the coefficient of speed influence.
$R_{(i,j)}$	the integrated return of the cellular grid.
k	the factor of influence factors.
$\rho_n(t)$	the density of the nth exit at time t.
$a_{i,j}$	the rate of return of the cellular grid is adjusted.
M	the floor set.
Q_L^M	the all possible paths for evacuation.
T_L^M	the evacuation time of each feasible path.
G_L^M	the flow rate of each feasible path.

3 Assumptions

In order to simplify the analysis of the performance, we set some assumptions.

- It is assumed that the evacuation is carried out in full compliance with the command, and the influence of psychological activities and other principal factors on evacuation path selection is not taken into account;
- It is assumed that all personnel have the same volume and remain the same in the evacuation process;
- It is assumed that the potential exist only has the effect of reducing the evacuation speed of evacuees through this exit and increasing the evacuation cost.

4 Model Establishment

4.1 Tourist Evacuation Model at the Exit of the Louvre Museum Based on Cellular Automata

(1) Model Framework Construction

Safety evacuation is happened in a particular place, under the specific environment of certain people flow phenomenon, therefore, location characteristics, environmental characteristics, population characteristics determine the personnel safety evacuation of the optimal path, contained three factors on the effect of evacuation process to build the basic framework of evacuation model, model of frame as shown in Figure 1:

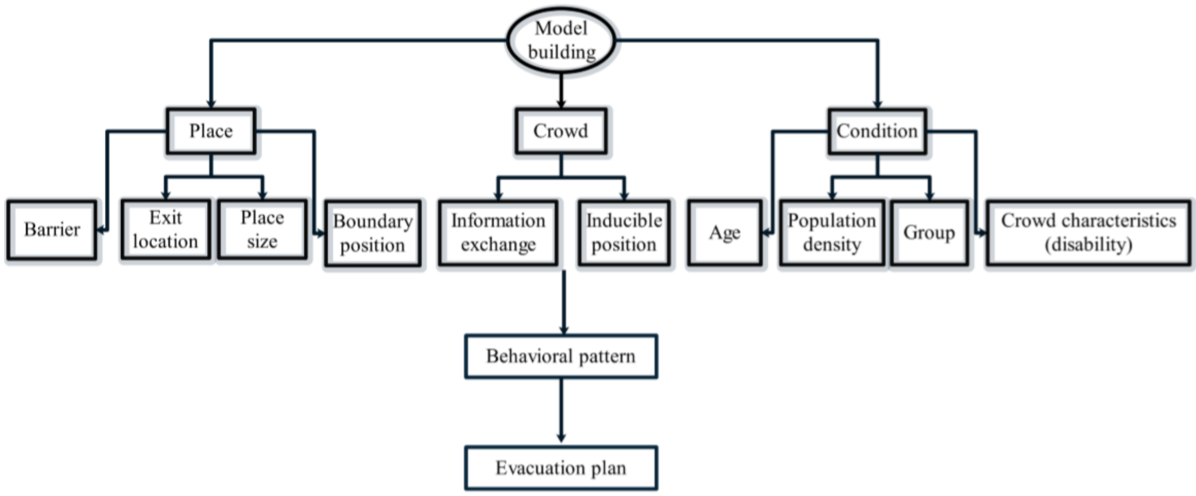

Figure 1: The basic frame of evacuation model

(2) Model Description

In order to facilitate the use of cellular automata to simulate the evacuation model, the simulated environmental conditions are described as follows:

1) Grid division: the building plane is divided into grids, and the size of each grid is defined as 0.5m X 0.5m according to the typical space allocation standard of the United States on dense flows of people. Each grid corresponds to a cell.

2) Grid state: each grid may be empty or occupied by personnel, obstacles and walls, which will affect the evacuation direction of personnel in evacuation simulation.

3) Evacuation speed: we use the Frunin model[4] to calculate the basic speed of personnel evacuation. The Frunin model divides the evacuation speed V_1 into the evacuation speed V_2 on the plain road and the evacuation speed on the stairway.

$$V_1 = 1.427 - 0.3549\rho \tag{1}$$

$$V_1 = 0.6502 - 0.0972\rho \tag{2}$$

For different groups of people, considering the difference in evacuation speed, we introduce the speed difference coefficient, and the final evacuation speed is $V = \varepsilon V_{1(2)}$, As shown in Table 1:

Table 1: The Average Energy Consumption Per Mile and Ownership

The crowd	The elderly	Young men	Young women	The child	Disabled person
coefficient ε	0.7	1.1	1	0.9	0.5

In addition, when opening the potential exit of the Louvre, taking into account the safety requirements, the speed attenuation coefficient ε', ε', is introduced, that is, evacuation speed of the potential exit is $V = \varepsilon' \varepsilon V_{1(2)}$.

4) Possible direction of movement: for the direction of cellular state transition, adopts Moore type neighborhood, and there are 8 possible directions of movement.

5) Information communication: consider coming to visit the Louvre museum visitors generally come from different countries, language communication barriers in the evacuation process exists, information about emergency personnel evacuation instructions there understand delay, so for non-native English speakers tourists evacuate speed, introducing evacuation lag caused by the language communication speed influence coefficient ε'', the value of ε'' is 0.9.

(3) Rules for the Movement of Evacuees

In cellular automata, all individuals on the basis of their state of the grid and the surrounding grid implement state of individuals in the next target mobile grid, at the same time, the CA in each grid cell, can only be one yuan when a grid is multiple cellular mobile target, is decided by the competitiveness of the various F cellular its moving direction, define competitiveness $F = \frac{D}{V}$, distance D for cellular target of grid, V for cellular movement speed.

Since personnel evacuation is affected by many factors, we define the grid return level $R_{(i,j)}$ here to represent the possibility of each cell moving to a certain grid in the next step. The grid return level is determined by the time return $T_{(i,j)}$, direction return $D_{(i,j)}$ and information return $I_{(i,j)}$ of the target grid, and the definition is as follows:

$$R_{(i,j)} = a_{i,j}[k_t T_{(i,j)} + k_d D_{(i,j)} + k_i I_{(i,j)}] \tag{3}$$

$$k_t + k_d + k_i = 1 \tag{4}$$

Where $a_{i,j}$ is the adjustment coefficient of grid income level determined by grid attributes, and the value of $a_{i,j}$ is as follows:

$$a_{i,j} = \begin{cases} 1 & \text{, The target grid is empty;} \\ 0 & \text{, The target grid is occupied.} \end{cases} \tag{5}$$

k_t, k_d, k_i respectively represent the influence coefficients of time return, direction return and information return. The definitions and calculations of the three kinds of returns are as follows:

Time returns:$T_(i,j) = \frac{t_(i,j)}{\sum_{k=1}^{8} t_{k(i,j)}}$.

Where $t_{k(i,j)}$ is the time required for the individual to move from the kth grid point (i_k, j_k) to the nearest evacuation exit M.

Considering the Louvre museum is an international tourist visiting a museum, visit this is usually a group tour, and because each channel of the museum are not familiar with, plus a bandwagon effect, therefore, out in the crowd density the hours generally also submit action team, to this, we translate them into personnel in retreat will give preference to view direction within the scope of the direction of more mobile, define the type as follows:

Directional return:$D_(i,j) = \frac{N_k}{\sum_{k=1}^{8} N_k}$.

Where N_k is the total number of people moving in the k direction within the range of vision. The vision is defined as the rectangular range from the grid where the individual is to the five surrounding grids.

Information return refers to the personnel in the process of evacuation received information about guide to retreat, for example the stairs to escape marks, fire, etc., such information is usually indicates a safe path for evacuation personnel, to this, we according to the type safety path direction and Moore neighborhood eight may be shown in the Angle between the direction of evacuation, define the earnings information expression is as follows:

Information return： $I_(i, j) = \frac{\pi - \theta_k}{\pi}$.

Where θ_k is the Angle between the direction of the kth lattice point and the direction of the path indicated by the indicating information.

4.2 Equilibrium flow model for the evacuation of tourists between floors

Tomonori Sano et al. [5] studied the influence of pedestrian combination on evacuation time of each floor on stairs. The basic rules for the evacuation of tourists between floors are basically the same as those for the safe evacuation of ordinary single-storey large shopping malls. However, as the flow of people between floors may exist on a public road section during the evacuation, the reasonable distribution of the flow of people on a public road section is the key to planning the optimal path for the evacuation of people between floors.

(1) Model Construction

The construction of the evacuation model between floors is composed of three parts, namely, evacuation source, evacuation path, and crowd allocation of public road section. According to the principle of short board, we will withdraw the longest floor, under the same circumstances define its withdrawal as the highest priority, at the same time, convergence in distribution sections of stream of people, should first meet high floor personnel flow, and on the same floor to find the shortest path between withdrawals, model construction of mind mapping as shown in Figure 2.

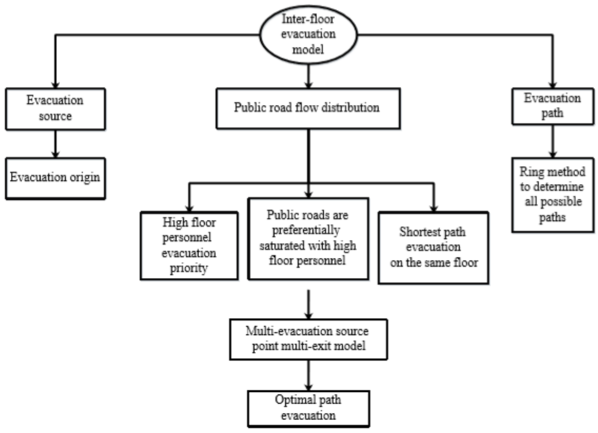

Figure 2: The Model Builds Mind Maps

(2) Model Algorithm

Step 1: define the floor set M, the arc set E between each node, the time t_{ij}^{l} through each arc, the maximum capacity c_{ij} allowed to pass through arc e_{ij} in unit time, and the length of each arc is l_{ij}.

Step 2: The possible feasible path Q_L^M at all times is traversed by the loop method, and the evacuation time $T_L^M = \sum\limits_{e_{ij} \in Q_L^M} t_{ij}$ of each path is calculated and sorted.

Step 3：Initialize the starting data set of each parameter to ϕ, and let's $l = 1$.

Step 4: The evacuation model at the Louvre exit can determine the path set $Q = Q_l^m$ that actually participate in the evacuation, Evacuation time $T = T_l^m$, Human traffic $G = G_l^m$.

Step 5: when the top floor of m_r, makes the floor set to $M = M \cup M_r$, the path set is $Q = \{Q_l^m \cup Q_l^{m_r}\}$, and remember that the maximum evacuation time of the building is $T^{m_r} = max\{T_{m_r} | m_r \in M\}$, otherwise execute Step 4.

Step 6: public path traffic update:

$$g_l^m(t) = \begin{cases} g_l^m & T_{q_l^{m_r}} \le t \le T^{M_r} \\ 0 & else \end{cases} \tag{6}$$

$$T = T - T^{M_r}$$

$$G = G - g_l^m$$

Step 7: Let the shortest path of layer M_r be $Q_l^{m_r}$, and the location path of the remaining layers be $Q_l^{m_s}$. When there is no public road section during the evacuation process between two floors, that is, set $\{e_{ij} | e_{ij} = Q_l^{m_r} \cap Q_l^{m_s}\} = \phi$, the flow of people is independent of each other, and evacuation according to single source point. Model processing can be obtained: $g_l^m(t) = min\{c_{ij} | e_{ij} \in Q_l^m\}$. If the set is a non-empty set. Enter Step 8 and perform the flow distribution of the public road segment.

Step 8: Let evacuation start from path $Q_l^{m_r}$ and $Q_l^{m_s}$ respectively. $Q_l^{m_r}, Q_l^{m_s} \in Q_L^M$. According to the literature[6], there is one and only one intersection point between $Q_l^{m_r}$ and $Q_l^{m_s}$. The time taken to evacuate along these two paths are $T_l^{m_r}, T_l^{m_s}$, obviously $T_l^{m_r} \geqslant T_l^{m_s}$, so Priority should be given to evaluating M_r-level personnel. The following is a discussion of the flow of people on these two paths:

- If $t < min\{T_l^{m_r}, T_l^{m_s}\}$, $g_l^{m_r}$与$g_l^{m_s}$ are both 0, the flow of the two paths is not evacuated.
- If $T_l^{m_s} \le t \le T_l^{m_r}$, knowing $g_l^{m_r}(t) = 0$, at this time, only the person who starts the evacuation of the route from the source point of the floor s has $g_l^{m_s}(t) = min\{c_{ij} | e_{ij} \in Q_l^{m_s}\}$. Similarly, if $T_l^{m_r} \le t \le T_l^{m_s}$, there is $g_l^{m_s}(t) = 0$, $g_l^{m_r}(t) = min\{c_{ij} | e_{ij} \in Q_l^{m_r}\}$.

- If $max\{T_l^{m_r}, T_l^{m_s}\} \leq t \leq T_l^{m_r}$, both paths $Q_l^{m_r}$ and $Q_l^{m_s}$ are evacuated, and the flow of people is the flow rate of the two sources of evacuation source points, with $g_l^{m_s}(t) = min\{c_{ij}|e_{ij} \in Q_l^{m_s}\} and g_l^{m_r}(t) = min\{c_{ij}|e_{ij} \in Q_l^{m_r}\}$.

5 Model Simulation and Countermeasures Analysis

5.1 Analysis of influencing factors of evacuation time

Generally speaking, when there is no external interference, people will give priority to the exit nearest to them for evacuation. At this time, the expression of comprehensive income is:

$$S_{(i,j)} = a_{i,j}T_{(i,j)} \tag{7}$$

Set based on the foregoing CA model, an area of 35×35 m rectangular plane area, on the basis of the foregoing rules on grid, the grid size for $0.5 \times 0.5m$, a total of 70×70 grid, set the export occupies 3 grid, each cell holds a grid, cellular mobile speed of 1 m/s, the initial random distribution in the system, personnel status update on the basis of comprehensive income expression, simulation scene layout as shown in Figure 3.

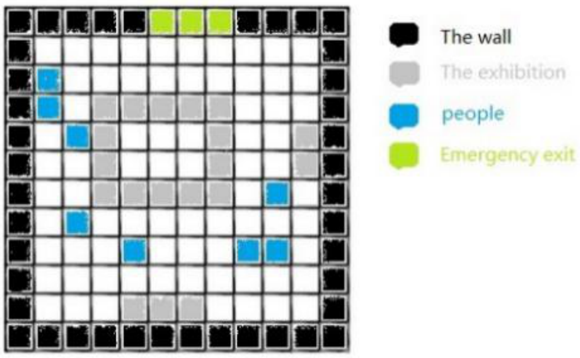

Figure 3: Illustrates the Layout of the Simulation Scenario

(1)Influence of Crowd Density on Evacuation Time

The number of people in the control system increased from 200 to 2000, and the exit was one, occupying three grids. The simulation of cellular automaton was carried out by matlab, and the simulation of evacuation behavior between 1000 and 2000 people in the system was listed, as showed in Figure 4.

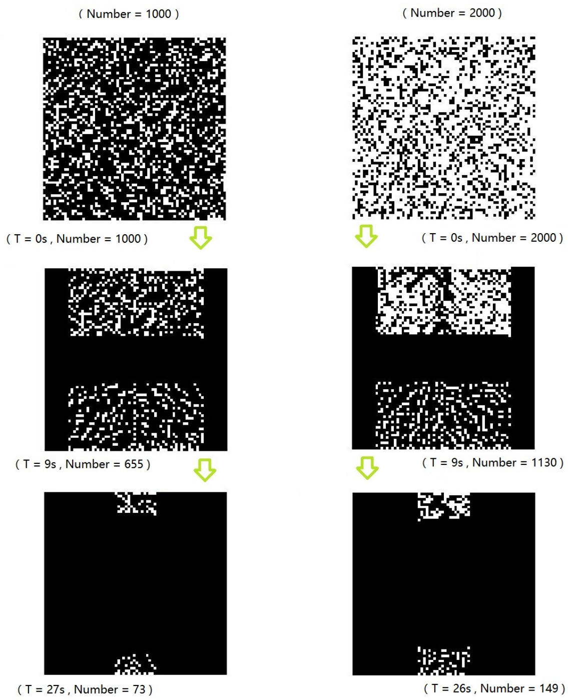

Figure 4: Simulation of Cellular Automaton Evacuation Process

As can be observed in the simulation diagram of cellular automaton evacuation process shown in Figure4, at the beginning of evacuation, people are randomly distributed, and at the beginning of evacuation, people are evacuated in accordance with the shortest path principle. After a period of time, people flow into two streams and are evacuated to exits on both sides, which are in line with the actual general evacuation process.

With 100 as the gradient, the matlab cellular automaton program was used for simulation, and the systematic evacuation time under different crowd densities was calculated. The statistical results are shown in Figure 5.

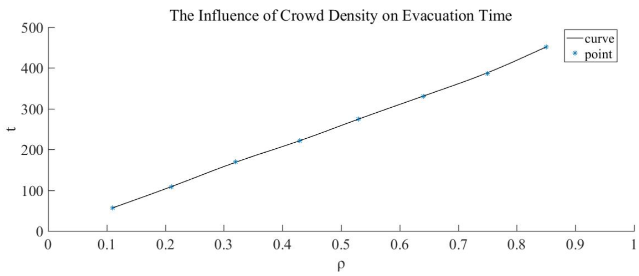

Figure 5: Influences of Crowd Density on Evacuation Time

The Figure 5 shows that in the process of evacuation in the most short circuit principle, in the case of other conditions unchanged, evacuation time and population density approximation linear relationship, will be happened at a certain moment in crowded stampede, suggesting that only based on principles of export shortest path distance is not reasonable, it is easy to close at a certain distance eventually export channel traffic jams, considering the single coefficient of factors in the model of comprehensive income represents the meaning of, must increase appropriate direction in the evacuation situation factor coefficient values, in order to avoid local export through big crowded.

(2)Influence of Crowd Characteristics on Evacuation Time

Population characteristics including many ways, here we only consider the crippling effect on the evacuation time, using 3D simulation evacuation software Pathfinder single floor of building $35m \times 35m$ structure, floor, there are exhibition hall and other kinds of obstacles is added to the population available channel area is about $938m^2$, set the number of disabled number/normal number $= \lambda$, define rule 1: barrier-free access for people sharing, rule 2: Barrier-free access is preferred for disabled people, and Pathfinder software is used to simulate the evacuation process with different λ under the two rules, and the evacuation time results under the two rules are shown in Figure 6.

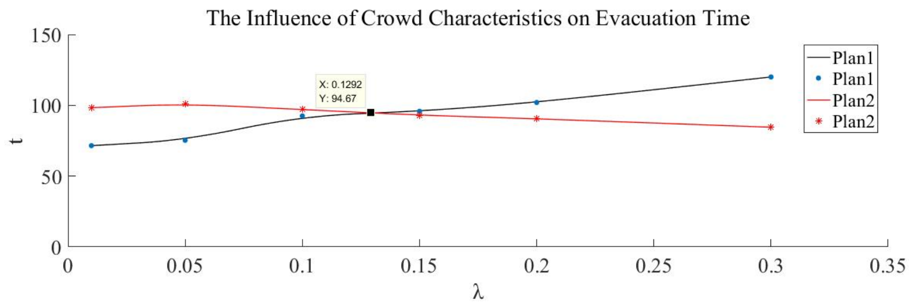

Figure 6: The Influence of Crowd Characteristics on Evacuation Time

According to Figure 6, when $\lambda < 0.13$, the evacuation time of rule 1 is short, and when $\lambda > 0.13$, the evacuation time of rule 2 is the shortest. Therefore, we need to determine whether the disabled channel can be used by normal people according to the value, so as to select an optimal evacuation path.

(3)Influence of Opening Potential Exits on Evacuation Time

There is potential exists in the Louvre, and whether the potential exits are open or not has a great influence on the evacuation time. The basic parameters of the Pathfinder 3D model are the same as the above, and two safety exits and a potential exit (red exit in the figure) are set. The number of people in the system is 500, and the behavior parameters of people are the same as the above. Through simulation of Pathfinder, the change of human flow at each exit can be obtained as showed in Figure 7.

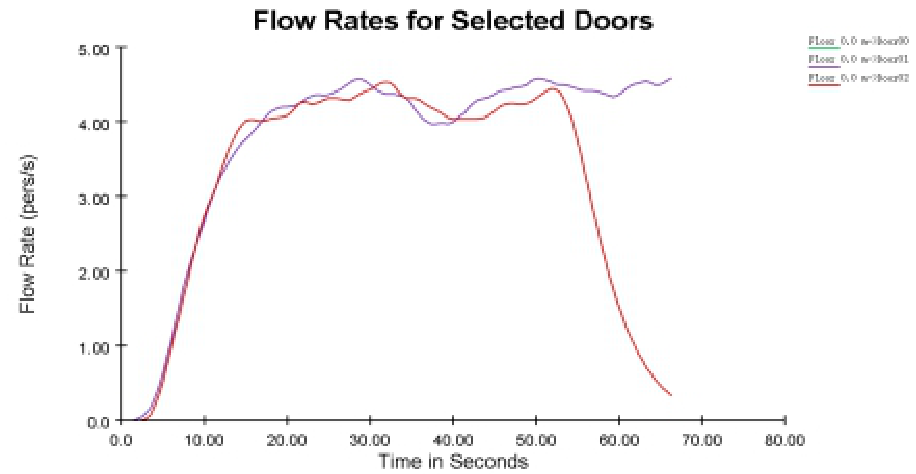

Figure 7: Variation Diagrams of Human Flow at Each Exit

It can be seen from the observation in Figure 7 that when the time is around 32s, the human flow at the two exits starts to drop sharply, and then starts to rise after a period of time. It is speculated that the crowd-crowding degree of evacuation is the highest at this time, and the crowd-crowding cloud chart of evacuation place when t=32s can be obtained by Pathfinder is shown in Figure 8.

Figure 8: Congestion Clouds of Evacuation Site When t=32s

According to literature[7], trampling may occur when the crowd density is greater than 0.59. Therefore, when $max\rho_n(t) > 0.59$ potential channel m nearest to the safety exit is opened, where $S_{nm} = min\{S_{n1}, S_{n2} \cdots S_{nm}\}$,$\rho_n(t)$ is the density of the nth gate at time t, and S_{nm} is the distance from the nth gate to the mth gate. It can be known from the foregoing that the evacuation speed of the potential exit is $V = \varepsilon' \varepsilon V_{1(2)}$. When the potential exit is opened, the change of human flow at each exit is simulated by Pathfinder, as showed in Figure 9.

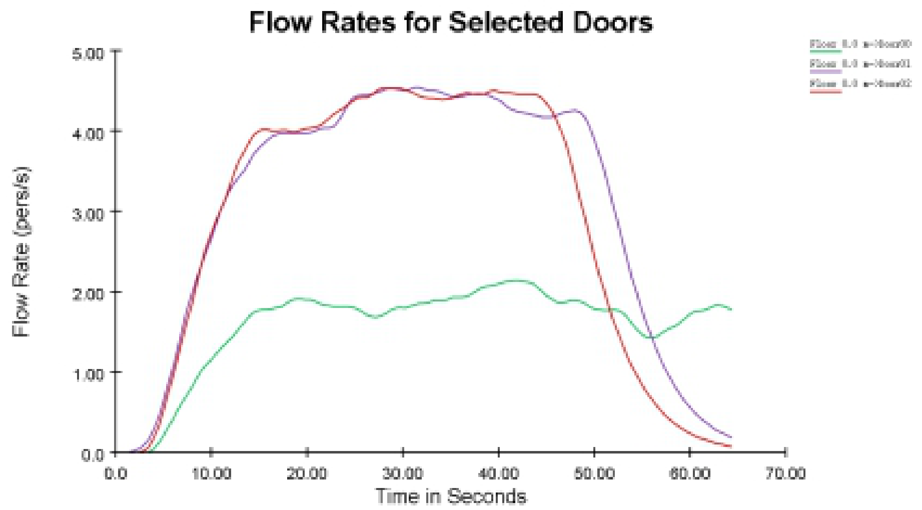

Figure 9: Changes of Human Flow at Each Exit When Potential Exits Are Opened

As can be seen from Figure 9, when potential exits are opened, the total evacuation time decreases, and the flow of people at each exit presents a small fluctuation state without significant fluctuation, indicating that no serious congestion accidents occur at this time.

5.2 Model simulation and countermeasures analysis

In are analyzed in detail the influence law of various influencing factors of evacuation time for buildings, it is not difficult to learn that the path of moving the optimal evacuation of personnel should be determined comprehensively by the model of comprehensive benefit and the following principles, to fully embody the comprehensive benefit of applicability of dynamic route choice model, in the last analysis the influence factors for the effect of evacuation time in the building, on the basis of various factors in some cases on the size of the evacuees effect is ideal, the comprehensive benefit model under different circumstances can be obtained in the best value range of coefficient of factors as shown in Table 2.

Table 2: The Value Table of Factor Coefficients in the Comprehensive Benefit Model in Each Case

	General evacuation	Differentiated crowd evacuation	High density crowd evacuation
k_t	$0.6 \sim 0.9$	$0.5 \sim 0.8$	$0.5 \sim 0.8$
k_d	$0.1 \sim 0.2$	$0.2 \sim 0.3$	$0.3 \sim 0.5$
k_i	$0.1 \sim 0.2$	$0.2 \sim 0.4$	$0.1 \sim 0.2$

Note: general evacuation refers to evacuation situation with low crowd density and small difference between groups; In the case of high-density crowd evacuation, the directional return should be negative, because in this case, evacuees should choose the direction with lower crowd density for evacuation under other conditions being the same.

In the following, this model is used to find the best evacuation path in different evacuation situations of buildings, and the comparison between the solution result and the general shortest path optimization method is made to illustrate the applicability of this model, and the evacuation strategy of the corresponding situation is given according to the solution result of the model.

(1) Evacuation of Different Groups

Take the general multi-storey museum as the prototype, and use Pathfinder to build a three-layer 3D solid model of 50×50. Various kinds of obstacles such as exhibition hall are added into the floor. The setting of passage parameters and crowd's own behavior parameters is the same as before, and two exits are set for each floor, as shown in Figure 10.

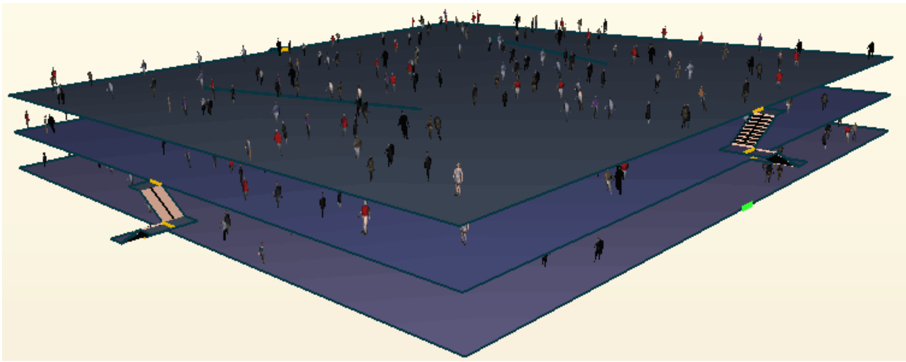

Figure 10: Pathfinder Model Diagram

Set to 150 the number of layers, using the Pathfinder to single layer model of comprehensive income and the balance between floor flow model for the optimal path specified simulation.

There are many differences among actual evacuees. Only gender, age and disability are taken into consideration here, and the population is divided into five categories: elderly, young male, young female, child and disabled. The value of speed of each type of population is determined by the following equation:

$$V = \varepsilon' \varepsilon V_{1(2)} \tag{8}$$

The factor value coefficient of the single-floor comprehensive income model refers to Table 2, where $k_t = 0.6, k_d = 0.1 and k_i = 0.3$. The simulation results obtained by using pathfinder are shown in Figure 11 and Figure 12.

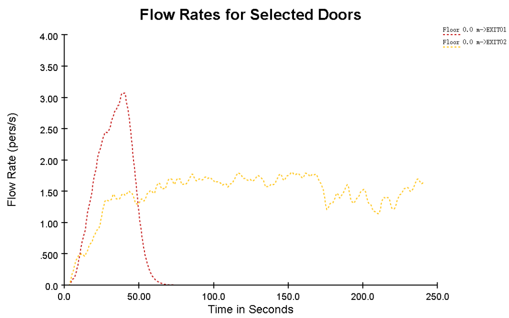

Figure 11: Comprehensive Model for Different Populations

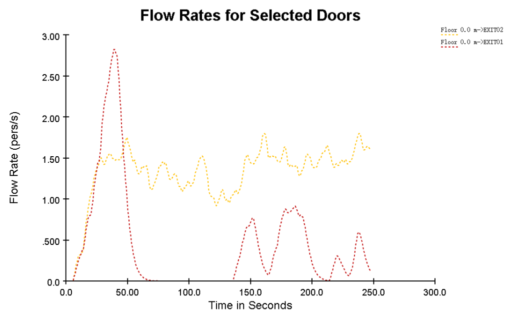

Figure 12: Shortest Path Algorithm Evacuation Simulation

The Figure 11 and Figure 12 respectively show the change of the outlet utilization rate with time in the evacuation process of the comprehensive model and the shortest circuit model. It is not difficult to see from the peak point of the curve in the figure that the outlet utilization rate in the comprehensive model is higher than that in the shortest circuit model. In integrated models, export 1 to 2 maximum instantaneous pass rate of 3.24 per/s respectively, and 1.86 per/s, compared with the short circuit model of two export the maximum instantaneous pass rate of 2.82 per/s and 1.76 per/s is higher, and the total evacuation time under the two models were 240.8 s, 248 s, the appropriate increase in different crowd evacuation instructions for routing can reduce the influence of evacuation time.

(2) High Density Crowd Evacuation

In high density evacuation cases, prone to stampede, this case it is necessary to open the potential exports to reduce the evacuation congestion level, improve the efficiency of evacuation, moreover, considering the possible exit off accident, so it is necessary to dynamically adjust the evacuation route, according to the model of dynamic traversal search for the optimal evacuation path, and compared with the short circuit optimization path, set to 300 the number of layers, using Pathfinder for simulation, the simulation result is shown in Figure 13 and Figure 14.

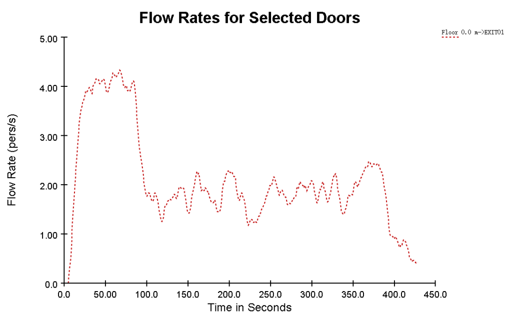

Figure 13: Comprehensive Model with High Population Density

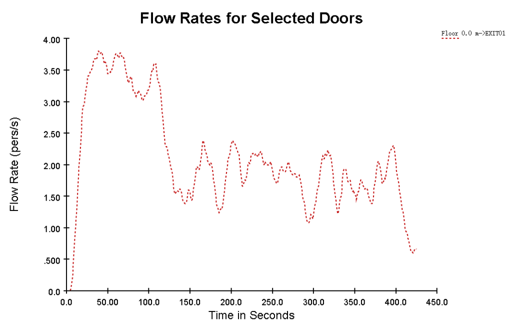

Figure 14: Shortest Path Algorithm Evacuation Simulation

According to the simulation results, the evacuation time under the two models is 425.5s and 436s, respectively. The peak value of the export utilization rate is 4.3per/s and 3.8per/s, respectively. In comparison, the evacuation efficiency under the comprehensive model is relatively high.

6 Model Application – Three-dimensional Simulation of Safe Evacuation of Louvre Staff

(1) Modeling of Louvre Pathfinder

The Pathfinder supports two moving simulation modes: the Steering and SFPE. As the Steering mode used a combination of path planning, Steering mechanism and collision treatment to handle the movement mode, we used the Steering mode to simulate the evacuation of the Louvre.

(2) Basic Information of the Building Model

According to the Louvre museum construction drawings and the building standards (ANSI building standards) using Pathfinder to construct 3D model: the building area of 72735 square meters of the Louvre, three layers on the ground, underground 2 floors, considering the Louvre about 28 meters height, so we design the height of 9.0 m, 0 layer has four security exit, each layer has safe passage, and is equipped with emergency staircase. There are hall, exhibition hall and other obstacles inside. The evacuation door leading to the safety exit on each floor is 5m wide, and the width of the safety exit on the first floor is 5m. The established 3d model is shown in the Figure 15.

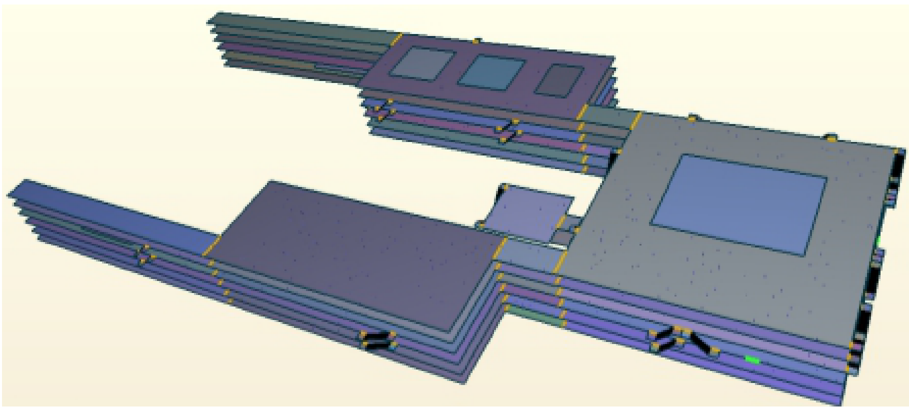

Figure 15: Three-Dimensional Structural Model of the Louvre

(3) Basic Information of Personnel

In the model, 25 disabled people were randomly defined, with an evacuation speed of 0.8m/s, a normal population of 1675, an evacuation speed of 1.25m/s, an average height of

1.75m, a shoulder width of 0.45m, an acceleration response time of 1.1s, a duration of 1.0s, a collision response time of 1.5s, an evacuation minimum distance of 0.08m, and a crowd reaction coefficient of 1.0.

(4) Analysis of Simulation Results

Through the establishment of the above model, 88 people in the site were completely evacuated through software simulation, requiring 89.3s. The simulation results show the relationship between evacuation number and time.As shown in Figure 16.

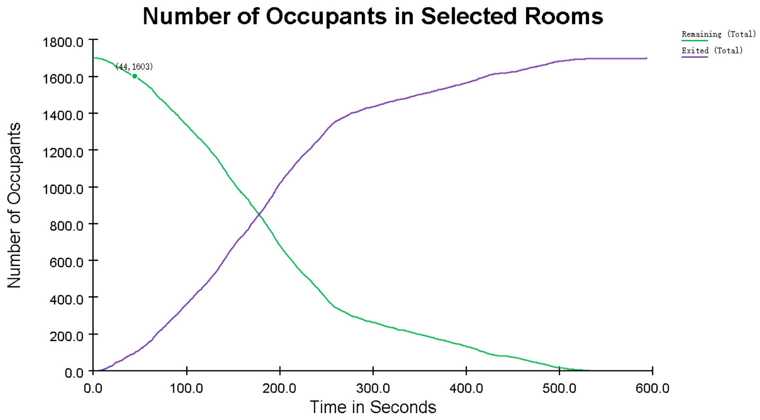

Figure 16: Relationship Between the Number of Evacuees in the Louvre and the Time

As shown in the Figure 16, 0 250s is the peak of evacuation speed, and around the 250s is the inflection point of evacuation. At this time, the number of evacuees begins to slow down, and at this time, most of the evacuees arrive at the evacuation stairs, leading to the crowding of the evacuation stairs.The utilization rate of the safety exit obtained through simulation is shown in Figure 17.

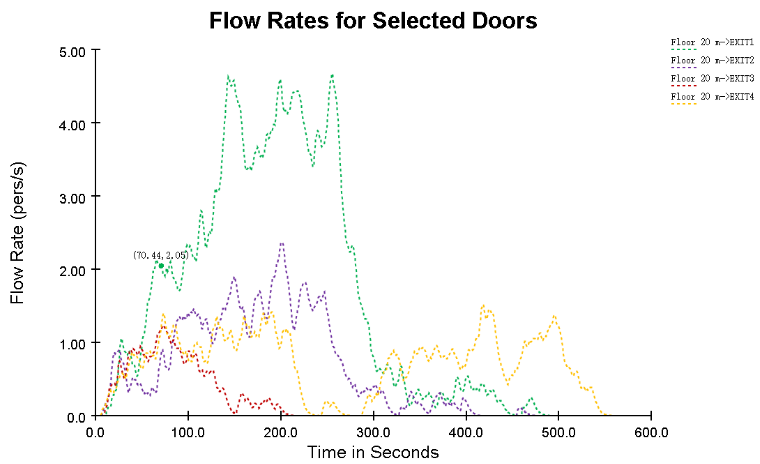

Figure 17: Utilization Rate of Louvre Exits

According to the analysis of the Figure 17, among the 4 safety exits on floor 0, EXIT01, the one nearest to the evacuation stairs, has the highest utilization rate, and the utilization rate drops sharply at 250s, and the peak of EXIT02 is 200s. The peak of safety exit EXIT03 is around 1990s. After 205s, there is no longer a crowd to evacuate from this place. The peak of safety exit EXIT02 is at 200s, and the utilization rate drops sharply at 250s.

Through the simulation of the evacuation behavior of the people in the model built, the following conclusions can be drawn: after the terrorist event, due to panic and other factors, the direction of evacuation of the trapped people is multi-directional, but the really safe evacuation should be unidirectional, that is, trapped room evacuation aisle stairs safety exit. People's action mode directly determines whether the evacuation route is safe and effective. Therefore, in steer-ing mode, people's behavior is instructive, and there is no ”retrograde” in the direction of evacuation. However, the model person's behavior pattern is just ideal, in reality, to achieve, personnel must clearly grasp their position and the nearest safe exit.

7 Model Promotion

This paper built the evacuation path model both for large single layer construction personnel, such as large supermarkets, shopping malls, or multi-story buildings (e.g., museum), has a strong applicability.For the evacuation situation of large congestion structure, we introduce the congestion coefficient to represent the degree of congestion at a certain entrance and exit. The congestion coefficient is defined as:

$$\xi = \frac{\mu}{\mu_s} \tag{9}$$

Where,μ represents the number of people passing through the entrance and exit in unit time under the crowded condition;μ_s represents the number of people passing through the entrances and exits in unit time under normal full flow condition. Here, we assume that in a highly crowded structure, the general exits are full flow, and considering that congestion will slow the flow rate at the entrance and exit, the greater the congestion ξ, the smaller the degree of a certain entrance and exit, and the higher the utilization efficiency. According to the above model, the optimal path for evacuation of personnel is selected as a comprehensive expression

$$R_{(i,j)} = a_{(i,j)}[k_t T_{(i,j)} + k_d D_{(i,j)} + k_i I_{(i,j)}] \tag{10}$$

Considering the impact of congestion on the selection of evacuation path, meanwhile, in the highly crowded structure, the path direction with low population density should be selected as the priority for personnel movement. The expression for the selection of the optimal evacuation path for the highly crowded structure is as follows:

$$R_{(i,j)} = a_{(i,j)}[k_t T_{(i,j)} - k_d D_{(i,j)} + k_i I_{(i,j)} + k_\xi \xi_{(i,j)}] \tag{11}$$

Where, k_ξ and $\xi_{(i,j)}$ are congestion impact coefficient and congestion benefit respectively. This formula indicates that people in ideal evacuation should first evacuate in the direction with the largest comprehensive benefit.

8 Strengths and Weaknesses

8.1 Strengths

- In the process of model construction, the effects of various objective factors on crowd evacuation are considered and summarized into three types of benefits that affect the selection of evacuation path by personnel. The optimal evacuation path in different evacuation situations can be obtained by adjusting the benefit coefficient, and the model is of good universality ;
- Could be divided into the building evacuation multi-storey building evacuation and evacuation between floor two parts, and set up evacuation at the bottom of the model of comprehensive income and the balance between floors flow model, starting from the overall level, by adjusting the evacuation of the priority between different floors and public road distribution of stream of people, in order to reduce the total evacuation time, fully consider problem;
- The Pathfinder 3d simulation evacuation software is used to simulate the evacuation path of the model in various evacuation situations, and the comparison between the model and the ordinary shortest path optimization shows that the model is reasonable and practical.

8.2 Weaknesses

- As there are many factors affecting the evacuation path of personnel in real life, the model only considers the impact of some objective factors on personnel evacuation. If subjective factors can be considered, the model will be more practical ;
- In the process of model construction, the risk cost of potential exit and the positive guidance effect of emergency personnel entering the building are not taken into account, resulting in a certain deviation between the solution result of the model and the actual evacuation.

9 Model Inprovement

In the model construction, the guiding planning function of emergency personnel and computer application program to evacuation is considered to enhance the applicability of the model. In addition, the comprehensive revenue model is combined with heuristic algorithm for global optimization in single-storey evacuation, and the minimum cost equilibrium flow model is built in the flow distribution between floors to achieve the dual goals of reducing evacuation cost and reducing total evacuation time.

10 Recommendations on Emergency Management Policies and Procedures for the Louvre

(1) At the beginning of evacuation, the phenomenon of crowd retention generally appeared in the small area of stairs of large buildings and multiple exits. This phenomenon lasted until the evacuation was basically completed. Therefore, the location, quantity and effective width of stairs and exits needs to be considered

(2) The total evacuation time in a large building depends on the reaction time and action speed of the panics in the crowd. If panics can reduce the reaction time and increase the active power to a certain extent, the evacuation time can be greatly reduced. At this time, the correct and effective guidance of personnel is required.

(3) It can be seen from the conclusion of this paper that there is a threshold value for the influence of the exit number on evacuation time. Under the threshold exit number, the ”maximum value” in the comparative sense of evacuation efficiency will increase the cost if the number of exits continues to increase. Therefore, the number of threshold doorway is the number of exits that managers should control. The opening time of the potential channel shall be the time determined by the evacuation congestion degree $\rho_n(t)$, and the potential channel nearest to the exit of the maximum congestion degree shall be given priority to be opened; In addition, in order to reduce the evacuation time, when the proportion of λ between the disabled and the normal is less than 0.13, the barrier-free channel can be used as the public evacuation channel, on the contrary, the barrier-free channel should be first passed by the disabled.

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Appendices

Here are simulation programmes we used in our model as follow.

```
clear;clc
plotbutton=uicontrol('style','pushbutton',...
    'string','Run',...
    'fontsize',12,...
    'position',[100,400,50,20],...
    'callback','run=1;');
erasebutton=uicontrol('style','pushbutton',...
    'string','Stop',...
    'fontsize',12,...
    'position',[300,400,50,20],...
    'callback','freeze=1;');
number=uicontrol('style','text',...
    'string','1',...
    'fontsize',12,...
    'position',[20,400,50,20]);
z=zeros(70,70);
xx = [1,1,1,80,80,80,80,80,80,80,80,80];
yy = [65,66,67,35,36,37,85,86,87,125,126,127];
cells=z;
weith=70;length=70;
x0=1;y0=35;
x1=70;y1=35;
peoplemidu=0.6;

pd = zeros(length,weith);
pd = profit(pd,xx,yy,cells);


for i=1:weith;
    for j=1:length;
        choice{i,j}=[0 0];
    end
end

for  i=1:weith;
    for j=1:length;
        if(rand<=peoplemidu)
            cells(i,j)=1;
            pv(i,j)=1;
            choice{i,j}=[i j];
        end
```

```
    end
end
imh = imshow(cat(3,cells,cells,cells));
axis equal
axis tight
stop= 0;
run = 0;
freeze = 0;
for  i=1:weith;
    for j=1:length;
        if(j==35 && i>=35)
            pd(i,j)=70-j;
        end
        if(j==35 && i<35)
            pd(i,j)=j-1;
        end
        if(j>=34 && j<36 && i==weith)
            pd(i,j)=0;
        end
        if(j>=34 && j<36 && i==1)
            pd(i,j)=0;
        else
            if(i<35)
                pd(i,j)=sqrt((i-x0)^2+(j-y0)^2);
            else
                pd(i,j)=sqrt((i-x1)^2+(j-y1)^2);
            end
        end
    end
end
step=0;

while (stop==0)
    if(run==1)
        for i=1:weith;
            for j=1:length;
                if(cells(i,j)~=0)
                    if (j>=10&&j<13&&i==1)
                        choice{i,j}=[0 0];
                        cells(i,j)=0;
                    else
                        [newi,newj]=findnew(i,j,pd);
                        if(pd(i,j)>pd(newi,newj))
                            if(same(newi,newj,choice)~=0)
                                choice{i,j}=[newi newj];
                            else
                                choice{i,j}=[i j];
```

```
                end
            end
            if (pd(i,j)==pd(newi,newj))
                if(same(newi,newj,choice)~=0)
                    if(rand>=0.5)
                        choice{i,j}=[newi newj];
                    else  choice{i,j}=[i j];
                    end
                else
                    choice{i,j}=[i j];
                end
            end
            if (pd(i,j)<pd(newi,newj))
                if(same(newi,newj,choice)~=0)
                    if(rand>0.2)
                        choice{i,j}=[i j];
                    else
                        choice{i,j}=[newi newj];
                    end
                else
                    choice{i,j}=[i j];
                end
            end
        end
    end
end
end
for i=1:weith;
    for j=1:length;
        if(choice{i,j} ~= [0 0])
            m=choice{i,j};
            ii=m(1);jj=m(2);
            cells(ii,jj)=1;
            cells(i,j)=0;
        end
    end
end
for i=1:weith
    for j=1:length
        if(cells(i,j)~=0)
            choice{i,j}=[1 1];
        else choice{i,j}=[0 0];
        end
    end
end
step = step + 1;
ans = 0;
```

```
        for i = 1:weith
            for j = 1:length
                if(cells(i,j)~=0)
                    ans = ans + 1;
                end
            end
        end
        fprintf('%d : %d\n',step,ans)
        if(ans==0)
            run=0;
        end
        pause(0.05);
        set(imh, 'cdata', cat(3,cells,cells,cells) )
        stepnumber = 1 + str2num(get(number,'string'));
        set(number,'string',num2str(stepnumber))
    end

    if (freeze==1)
        run = 0;
        freeze = 0;
    end
    drawnow
end
```