Optimal Louvre Evacuation Method based on Cellular Automata

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Abstract: The main purpose of this paper is to figure out a plausible scientific evacuation system for the Louvre Museum. First of all, we build a basic model considering only the single floor with stairs using the Cellular Automata. Then, we try to use the Electric Field Force Formula and the Ant Colony Algorithm to evaluate the attraction level of different exhibits, and thus decide the relative moving speed of the visitors. At the end, we complete the entire Louvre evacuation model, calculating the shortest possible evacuation time using the Target Planning Model.

1. Introduction

Nowadays, with the increasing amount of the human population, crowd congestion becomes normal, especially in the public places like the subway stations, shopping malls, office buildings, and tourist attractions. The potential danger behind this situation is hard to be perceived in usual. However, when an unexpected accident like a fire, gas leak, or even terrorist attack happens, effective evacuation immediately becomes an essential problem for the sake of public safety. As a result, researchers from different fields—the psychologists, sociologists, physicists, computer scientists and transportation scientists started to research about the issue of the evacuation (Helbing & Johansson, 2009).

Three major streams, different but also interrelated, are commonly chosen by these researchers. The first flow focuses on the empirical studies of the pedestrian behavior and the crowd dynamics; the second branch pays attention to create the mathematical models to imitate the realistic pedestrian movements (Teknomo, 2016); the third research orientation aims to use the optimization-based methods to develop models for the optimal evacuation plans (Abdelghany, Abdelghany, Mahmassani, & Alhalabi, 2014). However, most studies still fall in the first two categories. Schadschneider (2009) summarized the empirical results; research and theoretical models have been done with two examples of possible applications. Helbing and Johansson (2009) gave a similar overview while discussing the studies of the panic and critical population conditions. Schadschneider et al. (2011) studied the quantitative data of pedestrian dynamics for the calibration of evacuation models. Papadimitriou and Yannis and Golias (2009) evaluated the path selection model and crossover behavior model, which focuses on how pedestrians cross the street under different traffic conditions. Gwynne and Galea and Owen and Lawrence and Filippidis (1999) classified 22 evacuations. Zheng and Zhong and Liu (2009) distinguished seven methodologies methods based on agency, game theory models, experiments and animal behaviors. Moreover, Duives and Daamen and Hoogendoorn (2013) identified 8 basic facts of sports and six self-organizing crowd phenomena and simulation models. Again, Kalakou and Moura (2014) concluded the models from different research fields and analyzed the design of pedestrian facilities, while Lee and Kim and Park and Park (2003) focused on ship evacuation models. Bellomo and Piccoli and Tosin (2012) talked about the mathematical properties of pedestrian behavior models. For the third type of research, as far as we know, the work of Hamacher and Tjandra (2001) is the only review about the optimization models of evacuation problems; most of the models they discussed are network models with a constant travel time (density-independent).

In this research paper, we want to establish an evacuation model for the Louvre museum using the cellular automata; all different exhibition rooms and stairs are evenly divided into square grids of equal size. Each grid, or a cell, can be occupied by either visitors or obstacles. The model intends to divide the evacuation space of this floor into two parts, the exhibition room and the stairs, and then discuss the details respectively. In the exhibition room, the danger matrix of cell location is included due to the distance between each cell; the location of desk cell and wall cell are also given. In the corridor, we assume that visitors can walk in parallel on the stairs, with other rules being same as those in the exhibition room.

2. Louvre Coordinate System and Specific Entrance Conditions

2.1 Establishing the Louvre Coordinate System

The Louvre museum has five floors, with two floors being underground and three floors above the ground. A simplified schematic of the first floor is shown in Figure 1.

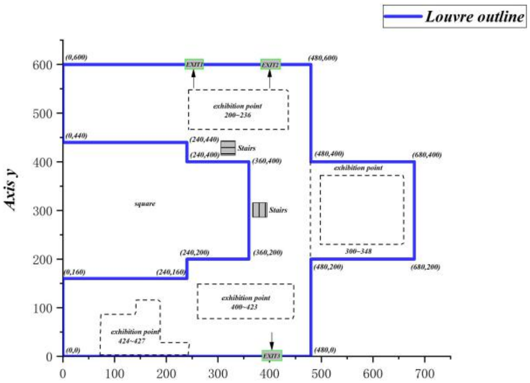

Figure 1. first floor coordinate chart

There are 4 exits on the first floor, the pyramid entrance and the three entrances reserved for groups and individuals having a museum membership. Based on the length of the 480-meter flank of the Louvre's building, other length of sides of the Louvre are estimated by proportion.

2.2 Estimation of the Specific Entrance Conditions of the Louvre

Affluences is an online app for the Louvre. This app can reflect the queue time for each public entrance of the Louvre museum. Therefore, by recording the queue time for each entrance per hour, we can have an approximate estimate of the number of the visitors in the Louvre at each moment.

Table 1. Queue Time

P	C	P	C	P	C	P	C	P	C	P	C	P	C
10	5												
10	5												
10	5	10	20										
10	5	5	5										
10	10	5	5	20	15								
10	15	5	5	20	15								
10	10	10	5	15	10	15	5						
10	10	5	5	15	15	10	10						
10	5	5	5	15	10	10	10	10	5				
10	5	5	5	15	5	5	5	10	5				
10	5	5	5	15	5	5	5	15	10	10	5		
5	5	5	5	10	5	5	5	15	10	5	5		
10	5	5	5	10	5	5	5	10	5	10	5	15	5

In fact, the width of the main entrance should be larger than the other entrances, but we only use relative widths in this simulation experiments. The more people queue up at an entrance, the more crowded this entrance would be, and smaller the relative entrance width is.

According to the history record, the average queue length of the pyramid gate is twice than that of the other entrances. However, we can't assume a proportional relationship between the waiting time and the width of different doors, since an exit is not conducive for evacuation if people get stuck in it, so we have

$$\frac{D_{d1}}{D_{d2}} = \frac{\overline{T_{d2}}}{\overline{T_{d1}}} \tag{1}$$

$$\overline{T_{di}} = \frac{1}{n}\left(\frac{\sum_{j=1}^{k_1} t_{dj}}{k_1} + \frac{\sum_{j=1}^{k_2} t_{dj}}{k_2} + \cdots\cdots + \frac{\sum_{j=1}^{k_{12}} t_{dj}}{k_{12}} \right) = \frac{1}{n}\sum_{k=1}^{12}\sum_{j=1}^{k}\frac{t_{dj}}{k} \quad i = 1,2,3,4 \tag{2}$$

where D_{d1} is the width of the gate named d_1; D_{d2} is the width of the gate named d_2; $\overline{T_{d2}}$ is the average all-day queuing time for the entrance named d_2; $\overline{T_{d1}}$ is the average all-day queuing time for the entrance named d_1; n is the number of times we recorded; k is the symbol for the time point that can be reserved.

From these equations, we know that $\frac{D_{dpyramide}}{D_{dcarrousel}} = \frac{D_{d1}}{D_{d2}} = \frac{\overline{T_{d2}}}{\overline{T_{d1}}} \approx \frac{1}{2.257}$.

Therefore, we can consider the ratio of the pyramid door to other small doors as 1:2 for convenience (for all the following computations).

3. How to Escaping from the Louvre Through Exhibition Room and Corridor

3.1 Single-floor Basic Adaptive Evacuation Model

In order to establish the evacuation model for the Louvre museum, we first use the Cellular Automaton model to construct a universally adaptable model for an individual floor such that the general situation can presented. In this section we only focus on the evacuation problem of two separate floors, the 0F and -2F.

3.1.1 Model Preparation

In order to simplify the actual structure of the Louvre, we must add several assumptions.

Regardless of the specific three-dimensional shape of the Louvre. It is considered as a cube composed of five same cuboids.

Ignore the attraction of exhibits to tourists. Visitors are completely randomly distributed on each floor.

Visitors on each floor are evacuated in a unified manner.

The stairs on each floor are close to the wall.

3.1.2 Model Establishment

The pedestrian evacuation simulation model is built in a two-dimensional discrete cellular grid system of size $W \times W$, in another word, the moving area of the pedestrian evacuation space is divided into $W \times W$ discrete cell spaces of equal size. The obstacles occupy the boundary cells to form the room wall, and the space cells left around the wall are the safe exits of the room; each space cell can only accommodate one person, vice versa.

The whole pedestrian simulation process is also discretized into equal time intervals. During each time interval, the visitors are allowed to only move one cell. Pedestrians cannot cross the wall, the only way for them to leave the room is through the safe exit.

In order to complete the qualitative research of real human evacuation, in this model, we also add a two-dimensional discrete cellular network system with a size of 4080 $(W_1 = 60, W_2 = 68)$, in which the specific locations of the three exits in the 0F are indicated and determined proportionally.

The position determination results of the three entrances in the first floor are shown in the table2.

Table 2. entrance and it's coordinate

Entrance	Real position	Relative position
Pyramid	(300,200)	(30,20)
Passage Richelieu	(410,600)	(41,60)
Carrousel du Louvre	(240,600)	(24,60)
Portes Des Lions	(450,0)	(45,0)

Visitors tends to run in a specific direction rather than run aimlessly during the evacuation process; they will naturally choose a position close to the safe exit as their next target location. And the closer a cell is to a safe exit, the stronger its attraction to the pedestrians. The formula of this tendency is presented by

$$S_{xy} = \begin{cases} \min_m(\min_n(\sqrt{(x-x_n^m)^2+(y-y_n^m)^2})), & Cell\,(x,y)\,is\,a\,space \\ B_c, & Cell\,(x,y)\,is\,the\,wall \end{cases} \tag{3}$$

where S_{xy} is the shortest distance from the cell (x, y) to the security exit; (x, y) is the coordinates of any cell; (x_n^m, y_n^m) is the coordinates of the nth cell in the mth gate; B_c is a very large positive number which is used to indicate that the wall is not attractive to the people.

Based on information given above, we can obtain a calculation formula for the direction parameter matrix

$$D_{i,j} = \begin{cases} \dfrac{S_{00}-S_{ij}}{1}, & Vertical\ and\ horizontal\ direction, i+j=1,-1, \\ \dfrac{S_{00}-S_{ij}}{\sqrt{2}}, & Diagonal\ direction, \quad i+j=0,-2,2, \end{cases} \tag{4}$$

where S_{00} is the shortest distance from the center of the entire movable area to the security exit; S_{ij} is the shortest distance from the Cell(x, y) to the security exit.

The space dynamic parameter matrix value can be indicated as following

$$E_{ij} = \begin{cases} 1, & Empty\ cell\ position \\ 0, & Central\ cell\ position \\ -1, & Cell\ position\ already\ occupied\ by\ pedestrian \end{cases} \tag{5}$$

The values of the two variable parameters are based on the shortest distance between the cell from the safe exit to that around the pedestrians.

The evacuation steps for each visitor in the room are as follows:

Each visitor can move from one cell to another in the unit time.

A visitor is set to the cell that can be accessed as shown in Figure 2 (Yue, Hao, Chen, & Shao, 2007).

When multiple people compete for a position, the system randomly selects a visitor to occupy this position.

Visitors choose to move to the position where mobile revenue is greatest

We provide a strategy that the formula of mobile revenue is given by

$$P_{i,j} = D_{i,j} + E_{i,j} \tag{6}$$

where $P_{i,j}$ is the mobile revenue; $D_{i,j}$ is the direction parameter and $E_{i,j}$ is the space parameter. Mobile revenue is shown in Figure 3 (Yue, Hao, Chen, & Shao, 2008).

Since we need to compare the effects of different evacuation methods, it is important to know how visitors move when an accident occurs. Usually, the terrorist attacks will lead to fires or blasts, therefore, we will study the movement of visitors through the smoke caused by terrorist activities. The following equations showing the relationship between the personnel density and the evacuation speed came from Roytman's finding (Predtechenskii & Milinskii, 1978).

$$v_p = v_0(\varepsilon A + \theta B + \gamma) \tag{7}$$

$$A = 1.32 - 0.82\ln(\rho) \tag{8}$$

$$B = 3.0 - 0.76\rho \tag{9}$$

where v_p is the evacuation speed; ε and θ are weight coefficients: $\varepsilon \in [0.25, 0.44]$, $\theta \in [0.014, 0.088]$, $\gamma \in [0.15, 0.26]$; σ is the horizontal correction factor: $\sigma \in [0.36, 1.49]$.

We use the following initial conditions to determine the constant visibility (Roytman, 1975).

$$D = \frac{C}{MK_m} \tag{10}$$

where C is an empirical constant, $C = 4.4$; M is the mass concentration of the smoke particles; K_m is the light elimination rate of smoke particles. From the Fire engineering, we know that $K_m = 7.6\mathrm{m}^2 / g$.

Therefore, from (8), we gain next formula:

$$V(D) = \begin{cases} -2.52 \times e^{-\frac{D}{4.22}} + 1.126 & 4.7 \le D \le 30 \\ 0.3 & 0 \le D \le 4.7 \end{cases} \tag{11}$$

Putting (5)(8)(10) together, we can obtain:

$$v_0 = \begin{cases} \mu(-2.52e^{-\frac{D}{4.22}} + 1.126)(\varepsilon A + \theta B + \gamma) & 4.7 \le D \le 30 \\ 0.3\mu(\varepsilon A + \theta B + \gamma) & 0 \le D \le 4.7 \end{cases} \tag{12}$$

where μ is an empirical constant, $\mu = 1.21$.

During the designing process, we can get different population density by changing the parameters in the MATLAB. To make the measurement easier, we define the population density equals 4 people per square meter.

Firstly, we take the median of the above various parameters as the general situation. Then, we plug (6)(7)(8)(9) into the equation (10), so that we can obtain the evacuation speed— $v = 2.5\mathrm{m/s}$.

To find evacuation time, we can use the following formula:

$$T_{\max} = r(\frac{P \times L_m}{V_p}) \times \frac{S_t}{S_s} \tag{13}$$

where $T_{\max}$ is the maximum time it takes for all visitors on the same floor to evacuate; P is the total number of the moving steps; L_m is the length of each cell; S_t is the actual floor area for one floor in the Louvre; S_s is the assumed floor area in the simulation model; r is a parameter used to reduce the distance traveled farthest. Therefore, we can use the formula to estimate the evacuation speed of visitors after we choose the parameters reasonably.

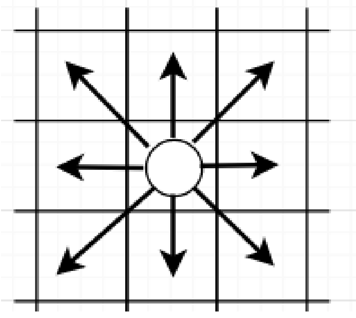

Figure 2. Visitor action area

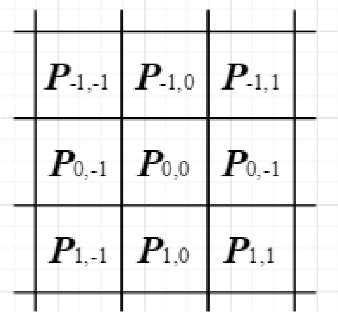

Figure 3. mobile revenue

3.1.3 Single-floor Evacuation Model Results

We use MATLAB to simulate the evacuation of all people. When we choose the density of visitors to be four people per cell, we know that the time it takes for visitors to evacuate from 0F is 4.37min, and the time it takes for visitors to evacuate from second floor underground is 3.64min from the formula (11).

The evacuation process of 0F can be taken apart into three phases**.** The Figure 4 shows the initial state and the Figure 5 shows the situation at the end of evacuation**.**

Figure 4. Initial state

Figure 5. End state

During the simulation process, we can see that the crowd will automatically be classified into three categories during the evacuation. For the visitors near the safe exit, they can easily make choices. But for those who are far from the safe exit or at the center of the room, they can't find the most appropriate route as quick as an element in the simulation system.

Therefore, in order to help visitors quickly find the nearest safe exit, we can divide different areas according to the simulation results from the Cellular Automaton model, and then install some signs on the border of the area to help confused people to find the nearest exit.

3.2 Evacuation between Stairs Model

We design the simulation model in an ordinarily ideal state to observe the distribution and movement of the visitors during the evacuation process. To find the approximate width of the bend of the stairs we use

$$W_s = W_t - W_{b1} - W_{b2} \tag{14}$$

The result is shown in Figure 6 and Figure 7. We can intuitively conclude that the visitor will choose to be close to the stair railings when they go down stairs. And we can simulate the curvature of the stairs and the existence of some on-stairs sculptures by adding obstacles to the model stairs. Figure 13 is a real picture of the stairs in the Louvre.

Figure 6. real picture

Figure 7. End State

Then, we can increase the number of obstacles and adjust the position of the them. As the degree of bending increases, the evacuation time also changes. As shown in the Figure 7, the change in the bending level of the stairs and the evacuation time of the visitors are not linear –visitors' evacuation time changes faster than the curve of the stairs.

Therefore, we recommend that the Louvre should try to avoid sharp bending; if the adjustment of the stairs is hard to achieve, the museum should avoid placing any art work on the corners of the stairs.

4. How to Evacuate Effectively

4.1 Non-public Entrances and Exits on Evacuation Model

In fact, there are many non-public entrances besides the four public entrances (service doors, employee entrances, VIP entrances, emergency exits, and old secret entrances built by the monarchy, etc.). However, these non-public entrances also have some security risks; for example, a narrower channel may cause congestion and hinder evacuation, and the increasing number of the possible evacuation paths may mislead visitors as well.

4.1.1 Model Building

We use probability to reflect that a non-public entry may be dangerous. When visitors arrive at a non-public entrance, there is a certain probability that they need to re-find other entrances when this non-public entrance doesn't work. We have the following formula

$$S_{xy} = \begin{cases} \min_m(\min_n(\sqrt{(x-x_n^m)^2+(y-y_n^m)^2})), & t \in (\frac{1}{p}(N-1), N\times\frac{1}{p}-1) \quad Cell\,(x,y)\,is\,a\,space \\ M, & t \in (N\times\frac{1}{P}-1, N\times\frac{1}{p}) \quad Cell\,(x,y)\,is\,the\,wall \end{cases} \tag{15}$$

where p is the probability that a non-public door is damaged.

4.1.2 Results

Without the non-public entrance, the total time that the visitor evacuated from the Louvre through a certain plan is a certain value. Compared this fixed time with the corresponding damage probability, we gain the result as shown in the Figure 8.

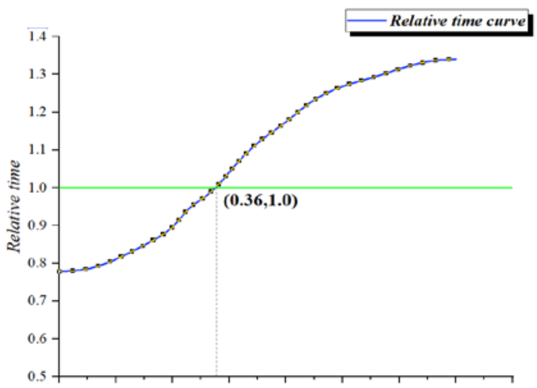

Figure 8. Damage probability and relative time

The abscissa of the intersection point is about 0.36, which means that the non-public portals work only if they have at least 64% of availability. So, the Louvre must pay attention to the routine maintenance of these entrances to ensure that they can come in handy in an emergency.

4.2 The Emergency Personnel Model

When a terrorist attack occurs, the external rescuers will also enter the Louvre to rescue the art collections and protect the safety of the visitors.

4.2.1 Problem Analysis

Based on the assumption that when the emergency personnel enter the Louvre, they must reach specific locations and rescue rare collections while evacuating in the shortest time, we can regard the issue of rescuers entering and leaving the Louvre museum as a TSP problem.

In fact, the attractiveness of various collections is different, so the density of people around the attractive collections must be significantly higher. The movement of emergency personnel in the Louvre may also be affected by the evacuated visitors; we believe that the speed of movement of the emergency personnel around the attractive art works will be slower.

4.2.2 Model Building

According to our hypothesis and basic principle, we can establish the following model as the action plan for the emergency personnel.

First, we need to define some variables,

$$a_{di} = \begin{cases} 1, & Entering\ from\ di\ door \\ 0, & Do\ not\ enter\ from\ di\ door \end{cases} \quad i = 1,2,3 \tag{16}$$

If the emergency personnel enter the Louvre from the d_i door, then $a_{di} = 1$, otherwise $a_{di} = 0$.

$$C_{ij} = \begin{cases} 1, & From\ i\ to\ j \\ 0, & Not\ from\ i\ to\ j \end{cases} \tag{17}$$

If the emergency personnel go from the i position to the j position, then $C_{ij} = 1$, otherwise $C_{ij} = 0$.

Next step, the goal of the emergency personnel is to leave the Louvre in the shortest time after entering the Louvre for rescue. Our objective function is

$$Min\ T_e = \sum_{d=1}^{m} a_d \sum_{i,j \in E}^{n} [\frac{(x_i - x_j)^2 + (y_i - y_j)^2}{v}] \tag{18}$$

Subject to:

$$\begin{cases} \sum_{i=1}^{n} C_{ij} = 1 \quad \sum_{j=1}^{n} C_{ij} = 1 \\ \sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij} = n \\ \sum_{d=1}^{m} a_d = 1 \end{cases} \tag{19}$$

Where

$Min\ T_e$ is the shortest time for emergency personnel to enter the Louvre to complete the mission and leave.

$\sum_{i=1}^{n} C_{ij} = 1$ are emergency personnel can only choose one path from i to j.

$\sum_{j=1}^{n} C_{ij} = 1$ are emergency personnel will definitely go to each of the specified locations.

$\sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij} = n$ are locations that must be arrived.

$\sum_{d=1}^{m} a_d = 1$ are emergency personnel can only choose one entrance to enter.

The exhibits with a higher attractive level can allure more visitors, who may hinder the actions of emergency personnel. Thus, the speed of the emergency personnel is determined by the attraction level and distance to the closet exhibits; we obtain the relative motion speed of the emergency personnel by referring the formula of the electric field force.

The formula for calculating the electric field force is

$$F = qE = \frac{1}{4\pi\varepsilon_0}\frac{q^2}{R^2} \Rightarrow v = \frac{R^2}{q^2} \tag{20}$$

When calculating the speed of the emergency personnel, we do not consider $4\pi\varepsilon_0$; we use the amount of charge as the attractive parameter for the exhibits and define R as the distance between the emergency personnel and the closet exhibits. According to the negative correlation between the density of people and the speed, we can get the formula for the relative speed of the emergency personnel.

4.2.3 Model Test and Results

Combined with the constraints in the formula (19), we can get the motion path of the emergency personnel in the simulation area we designed using the ant colony algorithm. (Figure 9 to Figure 11).

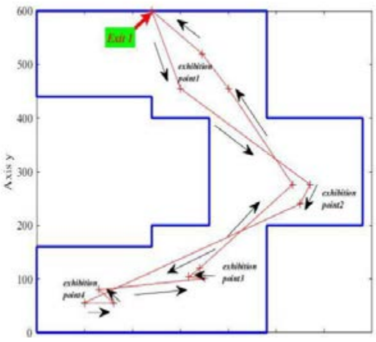

Figure 9. Carrousel du Louvre

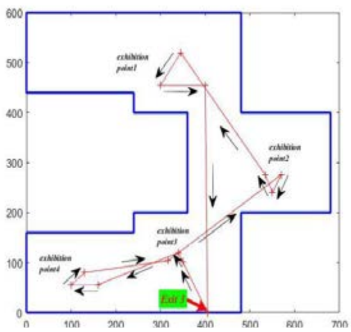

Figure 10. Portes Des Lions

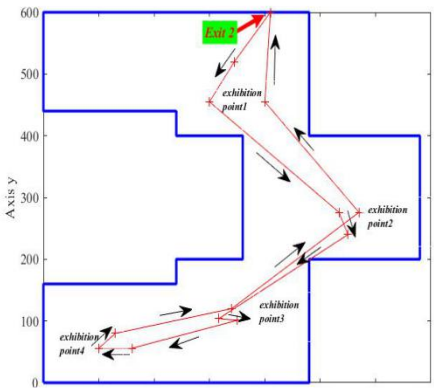

Figure 11. Passage Richelieu

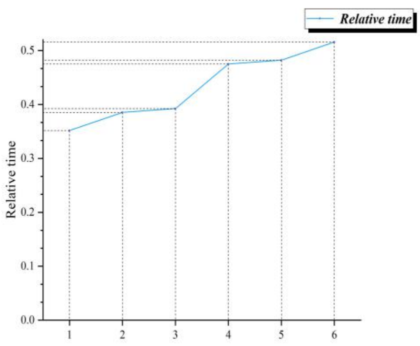

Figure 12. Relative time

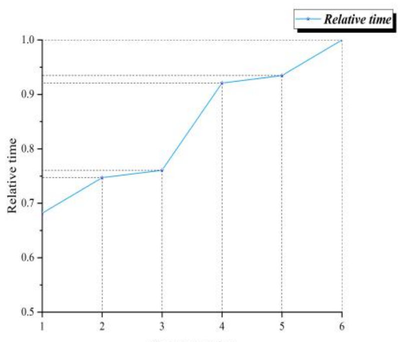

Figure 13. Adjusted relative time chart

We can calculate the relative time the emergency personnel spend in rescue based on the above six choices. The time corresponding to the six different schemes is shown in Figure 12.

We treat the maximum relative time as a standard unit and process other data to get Figure 13; the emergency personnel can achieve missions and evacuate at the fastest speed when they are in a place where the exhibits with different attraction level are spaced apart.

Based on the above analysis, we advise that the Louvre Museum should avoid intensive placement of the attractive exhibits; the emergency personnel should choose the entrance close to the lower attraction exhibits.

5. The Overall Louvre Evacuation Model

5.1 Problem Analysis

The above parts discussed the local optimal problem for different areas in the Louvre. The total time for evacuation using the barrel principle is usually gained from special cases. Therefore, in this section we will further analyze the result of the partial optimal combinations, with individual difference being considered.

5.2 Model Building

Putting all the local optimal time together, we have

$$T_{e\min} = T_{F\min} + T_{S\min} + T_{E\min} + T_{O\min} - T_N \tag{21}$$

Where $T_{e\min}$ is the shortest time for the entire building to be evacuated; $T_{F\min}$ is the shortest time for evacuation on a single floor; $T_{S\min}$ is the shortest time to evacuate on the stairs; $T_{E\min}$ is the shortest time for the emergency personnel to evacuate; T_N is the role of the non-public doors;

$$T_O = T_d + T_l \tag{22}$$

T_O is the extra evacuation time caused by other factors. Here we only consider the disabled people and tourists with a language barrier.

In a cellular automaton, each individual has the same competitiveness for the same cell while moving. On the other hand, the competitiveness for disabled people is significantly less than that of the healthy ones. Therefore, we need to set an obstacle coefficient in the speed of the disabled people to reflect their weakness; the formula to calculate their evacuation time is

$$t_{d1} = c_d \cdot \frac{\rho x_{d1}}{v_{d1}} \tag{23}$$

$$t_{d2} = \frac{x_{d2}}{v_{d2}} \tag{24}$$

$$T_d = t_{d1} + t_{d2} = c_d \cdot \frac{\rho x_{d1}}{v_{d1}} + \frac{x_{d2}}{v_{d2}} \tag{25}$$

Where t_{d1} is time for disabled people to leave a single floor; c_d is obstacle coefficient for the speed of the disabled people; ρ is visitor density; x_{d1} is shortest distance between the disabled people and the entrance; v_{d1} is speed of the disabled people on the level ground; t_{d2} is the time for the disabled people to leave a stair; x_{d2} is length of the stairs; v_{d2} is the speed of disabled people on the special passages. T_d is the total time used by disabled people to leave the Louvre.

For visitors facing a language barrier, we design a fixed reaction time, which is negatively related to the proportion of tourists having a same language background to the total visitors. The formula for calculating the reaction time for the visitors is

$$T_l = \frac{D_c}{r} \tag{26}$$

where T_l is reaction time; D_c is a fixed average reaction time; r is the ratio of the number of the tourists speaking same language to the total number of the visitors.

$$T_O = T_d + T_l \tag{27}$$

where T_O is the evacuation time caused by other factors, disability and language obstacle in this case.

5.3 Model Test and Results

In fact, the distribution of visitors in a museum would not be completely random; therefore, let's assume that the probability of a visitor in the exhibition area is 0.6826 and the probability for him to stay in the other areas is 0.3174. We can reflect this probability by the flow diagram, as following:

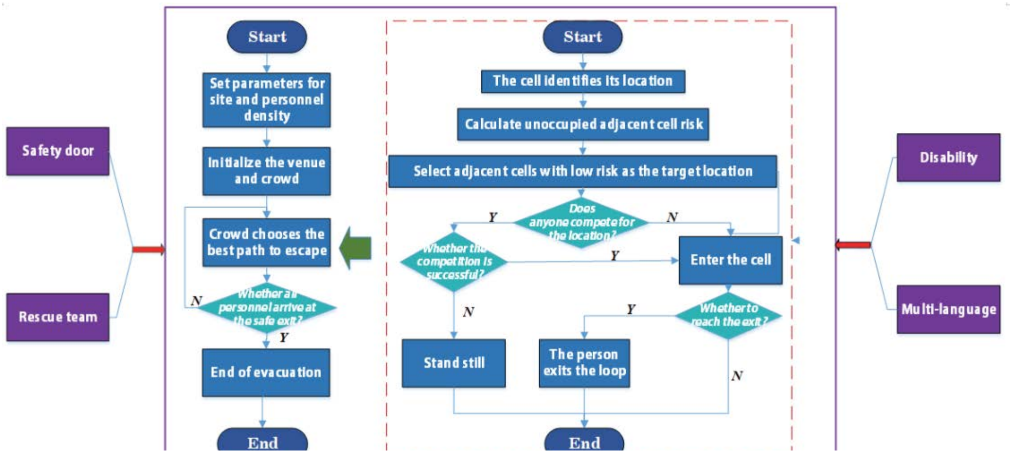

Figure 14. Flow Diagram

Based on the above flow diagram, we use the pathfinder to simulate the evacuation situation in two cases. The first case is that the visitors indeed act according to the best routes; the remaining number change is shown in Figure 15. The second one is that we first use the K-means Cluster Algorithm to calculate the cluster center of the visitors, and then formulate the same action strategy for visitors in the same area:

$$E = \sum_{j=1}^{k} \sum_{x_j \in w_j} \left\| x_j - m_j \right\|^2 \tag{28}$$

where x_i is the average of the abscissa and the ordinate for visitors; w_j is the entire point set; k is the number of the operation iterations.

When E reaches the minimum, the clustering process ends. The time needed for the visitors to first assembly and then uniformly evacuate is shown in Figure 16.

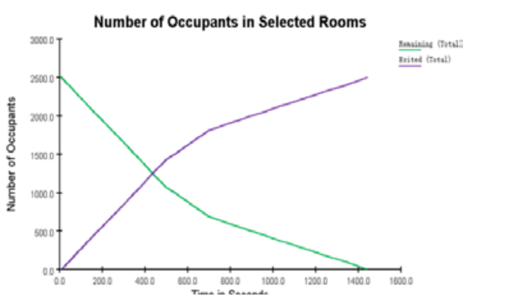

Figure 15. General Evacuation Result

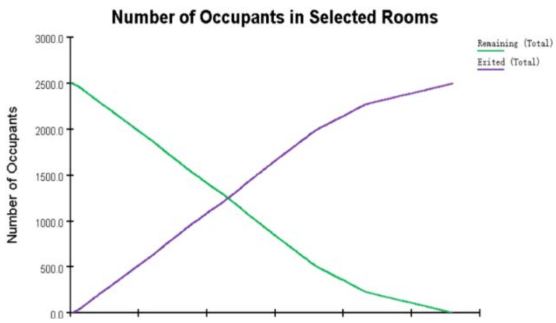

Figure 16. Cluster Evacuation Result

As is shown in the Figure 15 and the Figure 16, the evacuation of visitors without organization has a better effect at the beginning. But when we consider the total time required for visitors to evacuate, the cluster evacuation is more effective. Thus, we suggest that the Louvre should estimate the cluster center based on the actual tourist distribution data and arrange its staff in the needed areas to handle emergencies.

6. Conclusion

From the above model construction and analysis, we can conclude that the evacuation process of the Louvre is influenced by several factors. Therefore, to increase the evacuation efficiency and safety, the museum staff can choose to put clear signs on the border of the area, leading visitors to the nearest exits. This approach is essential in enhancing the survival rate of visitors when an emergency happens, especially for people far from the safe exit or at the center of the room. In addition, according to the K-Means Clustering, assembling all visitors together to evacuate saves the overall evacuation time.

During the research process, the Cellular Automaton model is vital in helping us to analyze the crowd evacuation situation. However, when comes to the problems like Ghost Jam in a large area, the basic model is less effective; by limiting the moving speed v_i for some cells and reducing the competitiveness C_d between adjacent cells, we can thus optimize the CA model to adapt to the larger space.

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