

Emergency Evacuation: Dynamic Network Diversion

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Abstract. Under the dangerous conditions, rapid evacuation of large public spaces is critical to the safety of visitors. Taking the Louvre as an example, this paper comprehensively considers the characteristics of tourists, the internal structure of Louvre, the dangerous situation and the openness of some secret exits. At the same time, based on the improved Cellular Automaton model and Network Flow model, this paper constructs the Dynamic System Optimal model. By applying the Frank-Wolfe algorithm, this model is simulated in MATLAB to simulate the evacuation of visitors in the emergency situations. Through the simulation results, we can find out the potential bottleneck position that restricts the movement to the exits and make the system's optimal evacuation program. It can be verified that the evacuation efficiency of the Louvre has increased by 21.3% after using the system's optimal evacuation plan. In addition, our model also has a broad application prospect. It can be extended to the evacuation of people in other large buildings by changing the parameters of initialization to improve the evacuation efficiency and protect people's safety.

1. Background

An increasing number of accidents such as terrorist attacks in France arouse the need of effective emergency evacuation plans for many popular tourism destinations. When designing the evacuation plan for the Louvre in Paris, France, it is important to consider that the number and the diversity guests in the Louvre vary from day to day and from year to year. Multilingual groups of tourists and cases of disabled tourists make evacuation in emergencies an challenging task. At the same time, different security issues brought by different exits are also attracting our attention.

Located on the north bank of the River Seine in the heart of Paris, the Louvre is one of the largest and most visited art museums in the world, attracting more than 10.2 million visitors in 2018. In 2018, the number of foreign tourists increased significantly to nearly 7.7 million [1]. According to the Louvre official website, in 2017, shows that tourists from the United States accounted for 18.6% of the total number of the foreign visitors, China accounted for 11.4%, Brazil accounted for 5%, Britain 5%, Germany 4.6%, Spain 4% [2]. There are five main entrances and exits and other non-main entrances with low levels of security and low public attention. As shown in the figure below, the red circle marks the main entrance and exit on the second floor of the underground, the blue is the main entrance and exit of the basement, and the rest is the main entrance on the ground.



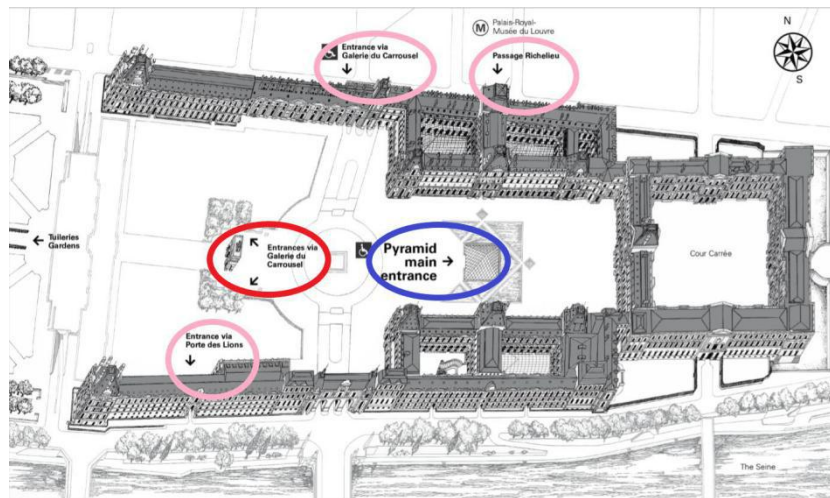


Figure 1. Map of the Louvre.

2. Introduction

This paper develops a model of visitors' attribute generation based on variable parameters, sets visitor's different attributes after considering the environment factor and physical condition. Assuming without guidance, all visitors will leave along the shortest path at the beginning of the evacuation. Through the simulation of our improved Cellular Automaton model simulation, we can determine the location of the bottleneck. After that, based on the system optimization model of Wardrop Principle, we construct the flow network of Louvre architecture. By applying the Frank-Wolfe algorithm, we can obtain the optimal capacity of each path and the congestion coefficient of the section at the minimum total evacuation time. Finally, we can obtain the specific fastest evacuation route.

At the end of the article, we propose the following evacuation plan: Firstly, dispatch officials to the nodes near the bottlenecks. Secondly, officials should guide visitors based on the fastest evacuation route. Thirdly, the open of secret exits depends on whether the overall congestion of the road network. Considering that model input relies heavily on real-time data, we develop a corresponding evacuation plan based on the number of visitors and adopt high-tech as a monitoring segment traffic tool.

The test of the improved Cellular Automaton simulation shows that the evacuation time was reduced by 21.3% after adopting our evacuation plan. In a word, after expanding the scope of application of the model and considering a wide range of factors, our model can effectively find the Louvre's fastest evacuation plan and can be applied to other large crowded occasions with high stability and high fault tolerance.

3. The Math Models

3.1. The Basic Models

3.1.1. Evacuation Path Model Based on Network Flow.

One of the most important data structures in dynamic human traffic distribution based on the Network Flow model [3] is the topology of the road network [4]. The main elements of the composition are nodes and road segments, where the nodes include intersections and OD points. The road segments connect two nodes and have different geometric characteristics (such as length) and road segment characteristics (such as maximum capacity). Characteristics have dynamically variable properties (such as crowding, traffic) in the road segment.



Figure 2. Road Network Structure.

(1) Dynamic system optimal model

When an emergency occurs in the Louvre, pedestrians will choose the path that is most beneficial to them to escape. Congestion often occurs in actual situations, which increases the overall evacuation time. According to the user optimal principle [5] all utilized paths have equal or less impedance, and the unused paths have equal or greater impedance. It is also known that the impedance encountered by a pedestrian on a connection is determined by the actual travel time spent.

In the system optimal model, pedestrians will choose to follow the guidance of the devised plan to maximize the overall efficiency of evacuation and minimize the evacuation time. At this time, the pedestrian escape route is mainly formulated by the relevant staff. During the evacuation process, pedestrians are given guidance to achieve the shortest total evacuation time. In designing the evacuation path, it is necessary to find the optimal solution for the total time that each region reaches the exit, which the following can be solved by the F-W algorithm.

$$\min \{z\} = \sum_a t_a(x) x_a \quad (4.1)$$

s.t

$$\sum_k f_k^{rs} = q^{rs} \quad (4.2)$$

$$x_a = \sum_k \sum_s \sum_v \delta_{a,k}^{rs} p_k^{rs} \quad f_k^{rs} \geq 0, x_a \geq 0 \quad (4.3)$$

$$h(G, k_v^0, k_v^n) = 0, v \in V \quad (4.4)$$

Here q^{rs} is the traffic demand between OD pair $r(r \in R)$ and $s(s \in S)$; x_a is the flow on road section a and f_k^{rs} is the flow on path k OD pair r and s ; If the road section a is part of the path k between OD pair r and s $\delta_{a,k}^{rs} = 1$, otherwise $\delta_{a,k}^{rs} = 0$; k_v^0 is the path that tourists v originally choose; k_v^n is the tourists' new path selection; G is the adopted boot plan.

Equation 4.2 represents the total flow conservation constraint between OD pair r and s ; Equation 4.3 indicates that the traffic on segment a is equal to the sum of the number of visitors for all new paths through path a between all OD pairs; Equation 4.4 represents flow non-negative constraints; Equation 4.5 represents the induction scheme G for the vehicle path.

(2) Principle of the Frank-Wolfe algorithm

In the process of exploring the minimum evacuation time in the Louvre, the evacuation model can be transformed into the optimal solution to the population's arrival and leaving in each region. The general form of the constraint optimization problem based on the Frank-Wolfe algorithm is:

$$\min \{f(x)\} \quad (4.5)$$

s.t

$$g_i(x) \geq 0, i = 1, 2, \dots, n \quad (4.6)$$

If $g_i(x)$ is a linear function, then the constraints of the linear programming are the same, only the objective function becomes nonlinear. The Taylor function is approximated by Taylor and linearized [6]. Expand $f(x)$ at x_k , there is

$$f(x) \approx f(x_k) + \nabla f(x_k)T(x - x_k) \quad (4.7)$$

Therefore, the original problem is similar to

$$\min \{f(x)\} \approx \nabla f(x_k)T(x - x_k) \quad \text{s.t} \quad x \in m \quad (4.8)$$

Let the optimal solution of this problem be y_k , then $p_k = y_k - x_k$, which is the feasible downward direction of the original problem. An iterative can be done by doing a one-dimensional search along this direction. In order to prevent the result of the one-dimensional search exceeding the feasible domain, the step size is $0 \leq \lambda \leq 1$.

At first a feasible point is initialized in the planned network flow area. When the feasible point $x \in g_i(x)$ is known, the optimal solution can be obtained by solving the feasible linear programming. If $\nabla f(x_k)T(y_k - x_k) = 0$, the K-T point in the region can be known from the F-W convergence theorem. Otherwise, it can be established in the feasible descent direction $p_k = y_k - x_k$ of $x \in g_i(x)$. Starting

from point x_k , a one-dimensional linear search is performed along the direction p_k . That is, λ_k is obtained, so that

$$f(x_k + \lambda_k p_k) = \min \{f(x_k + \lambda p_k)\} \quad 0 \leq \lambda \leq 1 \quad (4.9)$$

Since x is a convex set, the next iteration point $x_{k+1} = x_k + \lambda_k p_k$ can be obtained. And thus iteratively iterative, a K-T point satisfying the planning condition can be obtained.

3.1.2. Simulation Model Based on Improved Cellular Automaton.

When an accident occurs in a large building that requires evacuation of the crowd, collisions between pedestrians, friction and panic often lead to differences in evacuation speed. Therefore, based on the traditional Cellular Automaton model, we lead into the social force model. We also take the factor of knowledgeable person into consideration, combining the situation of the Louvre during the crowd's moving. In other words, during the evacuation process, pedestrians can tell the people around them what they know.

So, we adopt an improved Cellular Automaton model. The Cellular Automaton model divides the two-dimensional space in the region into square grids of the same size and each grid represents a cell. In the traditional Cellular Automaton model, the cell can only move one grid per unit time, and the speed remains the same. Each grid has two states, one is occupied and the other is not occupied. The mobile type of the cell selects the Moore type field. In the same time, the cell has a total of 8 moving directions [7]. Cellular individuals can choose to stay in the same place or move to the surrounding 8 grids during the evacuation process by judging the surrounding environment.

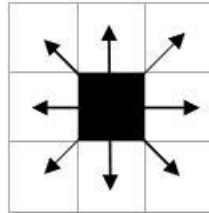


Figure 3. Cell diagram.

Under the improved Cellular Automaton model, the movement of the cell is affected by collision repulsive force (Details in 4.2.3), friction and panic emotions, which cause the pedestrian to change direction and speed during the evacuation process.

In order to make the simulation closer to the actual situation, we make the following improvements to the Cellular Automaton. First, the distance that pedestrians are allowed to walk in a unit time is not limited to one grid. And it can be changed depending on the actual conditions. Second, in the event of exclusion, pedestrian will slow down or turn around to find other paths in order to complete the evacuation in the shortest possible time. Third, when a pedestrian goes through a path and arrives at a place, he will tell the nearby pedestrian the situation of the path in order to find the shortest path.

3.2 Other Sub models

3.2.1. Speed Model

In the event of an accident, the evacuation of people from large buildings to safe areas is an important guarantee for reducing the number of casualties. According to V.M Predtechenskii and A.I Milinskii's study of the flow velocity in different situations, and taking the impact of personal physique into account, we consider different speed of people on the straight roads, walking along the stairs, and in the event of an accident [8].

(1) On the straight roads

On the straight roads, the average evacuation rate is a function of the density of people.

$$V_{L1} = 1.867(\rho_1 + \alpha)^4 - 6.333(\rho_1 + \alpha)^3 + 7.233(\rho_1 + \alpha)^2 - 3.617(\rho_1 + \alpha) + 1.502 - 0.13 \leq \alpha \leq -0.09 \quad (4.10)$$

α is related to the attribute generation model, which will be explained in 4.2.2

$$\rho_1 = \frac{N * S}{W * L} \quad 0.15 < \rho_1 < 0.95 \quad (4.11)$$

Here N is the total tourist number of the flow.

(2) When walking along the stairs

When the crowd walks along the stairs, the crowd speed needs to be modified.

$$V_{D1} = X_{\text{down}} V_{L1} \quad \#(4.12)$$

$$X_{\text{down}} = 0.775 + 0.44e^{-0.92\rho_2} \sin(5.16\rho_2 - 0.224) \quad \#(4.13)$$

(3) In the event of an accident

In the event of an accident, people will suddenly speed up due to the spread of panic in the crowd in the same situation.

$$V_{L2} = U_{\text{down}} V_{L1} \quad \#(4.14)$$

$$V_{D2} = U_{\text{down}} V_{D1} \quad \#(4.15)$$

Here V_{L2} is the evacuation speed under straight roads in the event of an accident; V_{D2} is the evacuation speed along the stairs in the event of an accident.

3.2.2. Attribute Generation Model

(1) Language attribute

Assuming that the number of native speakers of French, English and other languages in the Louvre is A , B , C respectively.

The total number of tourist M is get from the Louvre's report in the past two years. The number of tourists in the several countries with the most tourists is m_i ($0 \leq i \leq im$). Assuming that the total population of the world is Np , the total population of all the above countries is np and the population of other country is n_i ($0 \leq i \leq im$). The number of tourists whose mother tongue is French is n_{lan1} . The number of tourists whose mother tongue is English is n_{lan2} . Let the first language attribute is $m_i.lan$. When the native language of the tourist is French, $m_i.lan = 1$. When the native language of the visitor is English, $m_i.lan = 2$. When the native language of the visitor is other languages, $m_i.lan = 3$.

$$\begin{cases} A = \frac{1}{M} \sum_{k=0, m_k.lan=1}^{im} m_k + \frac{n_{lan1}}{Np - np} \\ B = \frac{1}{M} \sum_{k=0, m_k.lan=2}^{im} m_k + \frac{n_{lan2}}{Np - np} \\ C = 1 - A - B \end{cases} \quad \#(4.16)$$

According to the above-mentioned total proportion of the whole year, we assume that the proportion of the native speakers of French, English and other languages in the Louvre at a certain moment are a , b , c respectively.

$$\begin{cases} a = A + x \\ b = B + y \\ c = 1 - a - b \end{cases} \quad \#(4.17)$$

The values of x , y are subject to a uniform distribution of $(-\beta_1, \beta_2)$, $\beta_1 < 0.15$

(2) Physical condition attribute

In addition to the disabled, the physical condition index H of the tourists is subject to the normal distribution $N(\mu, \sigma^2)$. And we take the physical condition index as h_1 . The proportion of tourists whose physical condition index is lower than h_1 is Mh_1 ,

$$Mh_1 = \Phi\left(\frac{h_1 - \mu}{\sigma}\right) \quad \#(4.18)$$

The physical condition index of the disabled person is set to a fixed value of 0 and the total proportion Mh_2 is set to 0.5%. Because the proportion of disabled people is very low, we can consider Mh as the proportion of the total number of tourists whose physical condition index is higher than h_1 and lower than h_2 . According to the above ratio, it can be assumed that the proportion of the people whose physical condition is lower than h_1 in the Louvre at a certain moment is mh_1 and the proportion of disabled persons is mh_2 .

$$\begin{cases} mh_1 = Mh_1 + z_1 \\ mh_2 = Mh_2 + z_2 \end{cases} \quad \#(4.19)$$

The value of z_1 is subject to a uniform distribution of $(-\beta_2, \beta_2)$, $\beta_2 < 0.15$

The value of z_2 is subject to a uniform distribution of $(-\beta_3, \beta_3)$, $\beta_3 < 0.05$

(3) Team attribute

Assuming that the number of groups whose population is i in the whole year is p_i ($0 \leq i \leq 10$), and the group ratio is:

$$N_{p_i} = \frac{ip_i}{M} \#(4.20)$$

According to the above ratio, we can assume that the number of tourists in the Louvre at a certain moment is np_i .

$$np_i = N_{p_i} + w \#(4.21)$$

The value of w is subject to a uniform distribution of $(-\beta_4, \beta_4)$, $\beta_4 < 0.1$

Under the above three models, consider the influence of these three attributes on the influence factor of the flow situation. The α value of tourists whose native language is French, English, and other languages increases in turn. The α value of tourists decreases with the body condition index increasing. The α value of tourists increases with the number of teams increasing. Besides, the lower the physical condition index, the greater the effect will be on the α value. The impact on the α value is small when the team size is large.

$$\alpha = 0.22\ln(np + 1) * (0.98a - 0.15b + 0.33c) * (mh^2 + 1.02) - 0.097 \#(4.22)$$

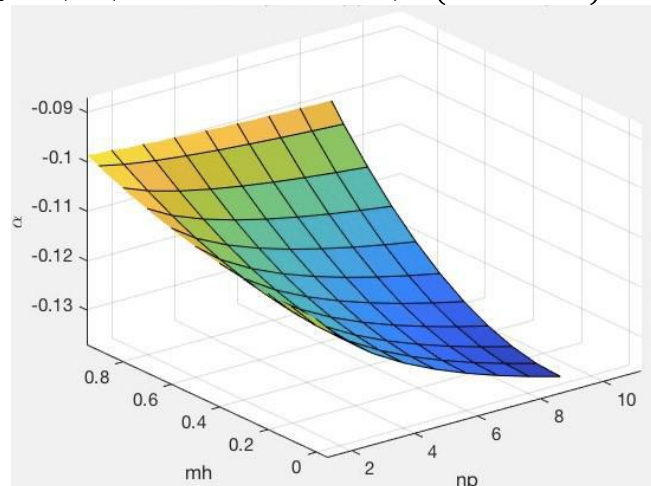


Figure 4. α with respect to np , mh at $a=0.25$, $b=0.16$.

3.2.3. Exclusion model

For the convenience of narrative and calculation, we assume that the coordinates of the cell at each position are $E_{ij}(i,j)$. When an unexpected situation requires evacuation, the pedestrian will choose the shortest path to leave the building. In the same floor, the location of the different exits is $E_{mn}(m,n)$.

At this time, if there is no obstacle, the minimum Euclidean distance from the pedestrian to the exit is recorded as

$$d_{\min} = \min_n \left\{ \min_n \sqrt{(m-i)^2 + (n-j)^2} \right\} \#(4.23)$$

If there is an obstacle, the minimum distance is calculated using the Dirichlet algorithm to allow the pedestrian to leave as soon as possible.

During the evacuation process, repulsive forces occur due to collisions between people and between people and the wall. In addition, when an accident such as a fire or a terrorist attack occurs, the tendency to reach a dangerous distance will cause the pedestrian to repel the source of the danger. According to the quantification of repulsive force by Weiguo Song [9], the Sigmoid function is used, and the neural network algorithm is used to define the rejection probability as

$$p = \frac{1 - e^{-kv}}{1 + e^{-kv}} = \frac{x_{ij} - x_{\min}}{x_{\max} - x_{\min}} \#(4.24)$$

In the above formula, k is the hardness coefficient. x_{ij} is the Euclidean distance of the cell $E_{ij}(i,j)$ to the dangerous source. x_{\max} is the distance farthest from the adjacent 8 cells from the danger source. And x_{\min} is the nearest to the 8 cells from the dangerous source distance. The closer the source of danger is, the greater the repulsive force generated. V is the relative movement speed of pedestrians. When the collision between pedestrians is mutually exclusive, $V = 2v$. When the pedestrian and the stationary object repel, $V = v$.

4. Experimental

4.1. Parameter determination

(1) Speed parameter

According to the data mentioned in 2.1.2, among the foreign tourists who come to the Louvre, the native English speakers account for about 15.61% of all tourists, and native speakers of other languages account for 21.07% of all visitors. The remaining tourists from non-mentioned countries accounted for 38.82%. According to the current number of people in the world, we estimate that A is about 25.138%, B is about 16.248%, and C is about 58.614%.

According to the above-mentioned total proportion of the whole year, it is assumed that the proportion of the native speakers of French, English and other languages in the Louvre at a certain moment respectively is $a = 0.25$, $b = 0.16$, $c = 0.59$.

Take $H \sim N(0.5, 153^2)$, the proportion of disabled tourists is 0.005,

Then $mh = E(h) = 0.005 * 0 + 0.95 * \mu = 0.475$;

$np = \sum_{i=0}^{10} np_i = 2.5$;

$U = 1.2$;

$\alpha = 0.22 \ln(np + 1) * (0.98a - 0.15b + 0.33c) * (mh^2 + 1.02) - 0.097 = -0.118$

(2) Road network topology

According to the Louvre plan and the Network Flow model in 4.1.1, the doorway of the main exhibition area and the main staircase are used as nodes. The network structure of the Louvre can be established as follows:

Since the evacuation exits are concentrated on the ground floor, the evacuation plan for the ground floor is more critical and representative than that for the other layers. Considering the complexity of the Louvre building structure, the evacuation of the road sections will only be carried out. Solving the evacuation scheme for other layers can also be obtained by applying the model.

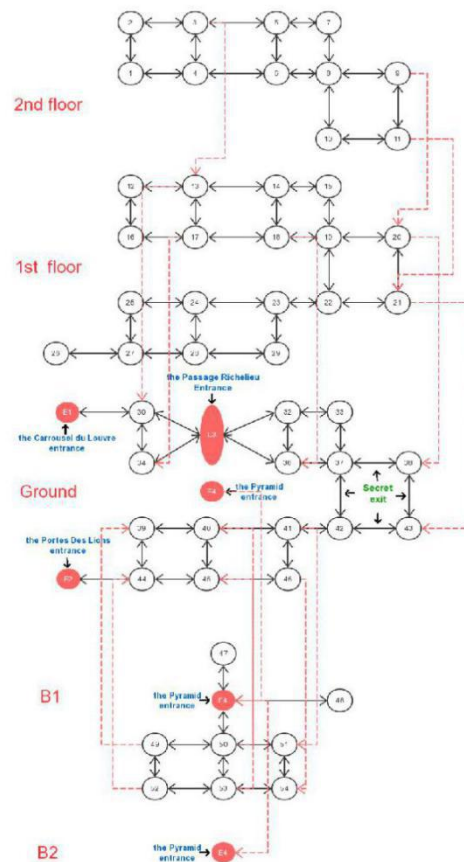


Figure 5. Path Network Diagram of the Louvre.

(3) Segment parameters

We assume that the capacity of the road section in the exhibition hall is 2.75 per/m². Then we divide the road section into main roads and branch roads and set the corresponding maximum road section capacity to 850 people and 390 people.

Combined with the analysis of the behavior of visitors to the Louvre Museum based on Yuji Yoshimura et al, the main visiting routes of the Louvre visitors and the visits can be known by using the data of Bluetooth data [10]. The popularity of the exhibition area determines the congestion of the path and stairs: the most congested route flow density ρ_1 was 0.8, and the congestion route ρ_1 was 0.6. Uncrowded route flow density ρ_1 has a value of 0.15. The route flow density ρ_2 of the stairs and the stairway has a value of 0.8. The congested route ρ_2 has a value of 0.6. And the uncongested route ρ_2 has a value of 0.2. According to the flow velocity model in 4.2.1, the average velocity of the flow of each direct pathway can be calculated. It can be seen from 1.1.2 that the total number of visitors to the Louvre in 2018 is about 10.2 million, so the total flow of people is assumed to be 27,945 per day. Of course, if you can monitor the flow of people in each section and perform dynamic input in real time, the accuracy of the output will be improved.

Finally, we can get the impedance value of each direct path.

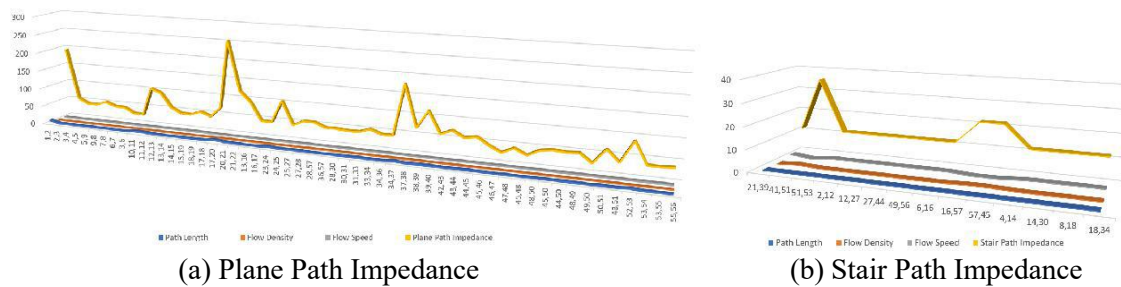


Figure 6. Path Impedance.

4.2. Solution Process and Analysis

4.2.1. Determination of the Louvre Bottleneck Position

(1) Preliminary judgment of bottleneck position

Bottleneck locations often occur in restricted areas during crowd evacuation. The bottleneck position is characterized by the narrow position of the bottleneck itself, and the relatively wide space connecting the two ends of the bottle. In the process of advancing toward the bottleneck position, the flow of people is often blocked due to the sudden contraction of the space, and the pedestrian movement drastically slow down even stop [11]. The actual bottleneck position usually exists in the restricted area of the crowd evacuation process, often near the doorway, underground passages, and so on. Therefore, when selecting nodes, the doorway of each pavilion shall prevail.

(2) Bottleneck position under simulation

Taking the ground layer as an example, the pedestrian simulation process is as shown in the following figure. In an emergency situation, the crowd usually speeds up and escapes from the building along the shortest path. After the evacuation begin, pedestrians gradually move to the exit. Initially, pedestrians left the doorway of each room according to the known escape routes. It can be observed that as some pedestrians become denser near the entrance, while the people lagging behind push those in ahead, resulting in collisions and fractions, and blockage at the door slows down the speed of moving sharply.

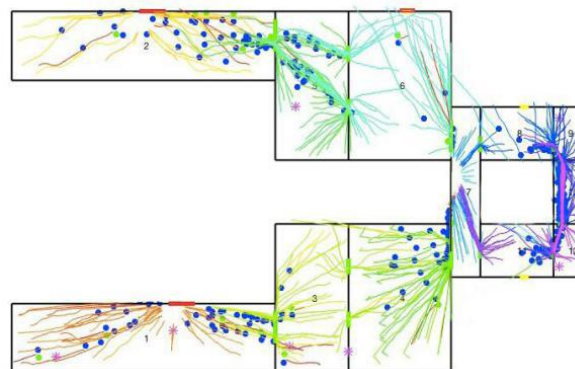


Figure 7. Bottleneck position under simulation.

From the solution of the speed model in 4.2.1 in the most ideal case, the speed of the crowd in the emergency state is 1.124m/s. The doorway of each room on the ground floor of the Louvre is divided into 12 locations as the following figure. When the blockage occurs, the speeds at 4, 4, 9, and 12 will drop to below 0.8m/s, in line with the above judgment on the bottleneck position

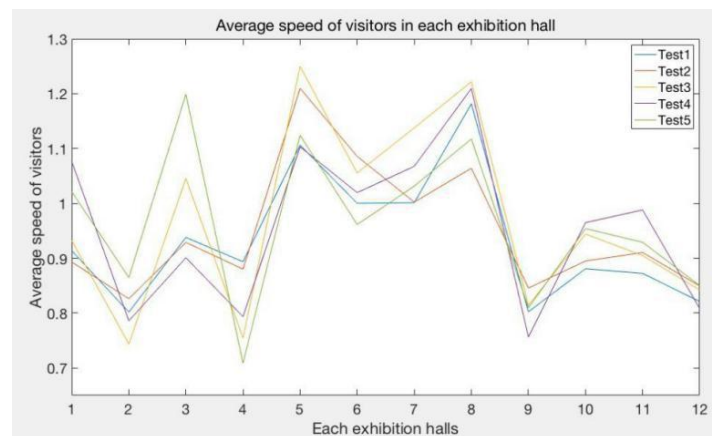


Figure 8. Average speed of visitor in each exhibition hall.

4.2.2. Determination of the Louvre Evacuation Plan

The following are the 12 routes with the largest expected traffic flow and the corresponding information of the road segment when the minimum evacuation time is reached.

Path type	Main road	Main road	Main road	Main road	Main road	Main road	Branch road	Main road	Main road	Main road	Branch road
Starting node	42	37	38	E3	37	43	41	41	40	40	36
Ending node	37	33	43	34	38	42	46	40	39	45	E3
Segment capacity	850	850	390	850	850	850	390	850	850	850	850
Flow density	0.6	0.15	0.15	0.15	0.15	0.15	0.15	0.6	0.6	0.15	0.15
Forward traffic flow	521.445	859.49	440.12	502.928	490.08	340.981	500.439	409.992	480.721	448.23	458.739
Reverse traffic flow	701.325	21.31	402.392	308.123	301.211	420.623	80.232	148.239	42.872	43.221	23.298
Total traffic flow	1222.77	880.8	842.512	811.051	791.291	761.604	580.671	558.231	523.593	491.451	482.037
Forward VC ratio	0.613	1.011	1.129	0.592	0.577	0.401	1.283	0.482	0.566	0.527	0.540
Reverse VC ratio	0.825	0.025	1.032	0.362	0.354	0.495	0.206	0.174	0.050	0.051	0.027
Average evacuation time/s	27	40	32	24	48	24	39	28	20	32	35

Figure 9. 12 Paths with the largest expected distribution of traffic.

VC ratio: The segment saturation (v/c) is the ratio of the segmented traffic to the maximum capacity of the segment, which reflects the congestion of the segment. From the above data we can formulate the following solutions:

- (1) Reasonably deploy emergency personnel to indicate evacuation locations.

It is estimated that the roads with heavy flows of people are $37 \rightarrow 33$, $42 \rightarrow 43$, $38 \rightarrow 37$, $37 \rightarrow 42$ and they are concentrated in adjacent areas. Due to the limited number of emergency personnel, museum officials and emergency personnel should be dispatched to guard the nodes with the highest visitors flow rate, which are the nodes 37, 38, 41, 42, 43, so as to maximize the effect of evacuation.

- (2) Guide the division of people in different routes.

There are 4 roads for people at node 37 to choose from. The flow of people allocated to the segment $37 \rightarrow 33$ is the heaviest, so the emergency personnel should guide the visitor to select this road (although it is not the shortest way for some visitors). At node 37, the visitor should be guided to select the road $37 \rightarrow 33$. At node 38, the visitor should be guided to select the link $38 \rightarrow 43$. At node 41, the visitor should be guided to select the link $41 \rightarrow 46$. At node 42, the visitor should be guided to select the link $42 \rightarrow 43$. At node 43, the visitor should be guided to select the link $43 \rightarrow 38$.

- (3) Rational use of secret exports.

Based on the literature [12], we can know the rating criteria of section load (VC): stable traffic (0.7-1), slow traffic (1-1.5), general congestion (1.5-2), and severe congestion (≥ 2). According to the degree of congestion in each section, the museum should determine the time to open the secret entrance. When 75% of the path is in slow transit, a secret exit should be opened. After a period of time, when the above limitation is reached again, other secret exits should be opened in order to reduce the load on the road section.

- (4) Solve the impact of fixed hazard sources on optimized road sections.

When there exists a fix hazard source, some evacuation route might be changed or closed. In such cases, the plan of the evacuated human traffic should be modified and the different evacuation scheme should be re-allocated.

(5) Guide the evacuation of visitors on other floors according to the traffic flow of ground.

For the 1st and 2nd floors, considering that the stairway capacity is usually smaller than the inner passage of the building, visitors should be guided to evacuate using the stairs which is near the path allocating traffic in the ground floor. Officials should direct visitors to leave the stairway near the ground floor. For example, guide the visitors in first floor to use stairs 11 → 21; 9 → 20.

For B1, considering that the traffic on the ground floor is already large, visitors should be diverted from the second floor.

For B2, visitors should leave directly from the exit in the second floor.

4.2.3. Solution Verification

Repeatedly applying of the improved Cellular Automaton simulation shows that the average evacuation time of the ground floor is around 333.84 seconds While in 5.2.1, the evacuation of pedestrians along their shortest path takes about 424.16 seconds. Evacuation efficiency was increased by 21.3% after applying the system's optimal evacuation scheme.

5. Conclusions

5.1. Policy and procedural recommendations for emergency management of the Louvre

In order to make the evacuation speed the fastest in the Louvre when an unexpected situation happen, it is necessary to consider the diversion of the visitors near the bottleneck and the path and time of emergency personnel entry.

(1) In order to reduce the congestion of the bottleneck position and decrease the overall evacuation time, we encourage the Louvre to develop the following measures:

- Take into account the impact of high-tech science and technology. We can set up Bluetooth monitors in various sections to monitor the traffic of each section in real time to help us determine the evacuation plan in case of an emergency.
- At the intersections where visitors leave the Louvre, a sign based on text or arrow content should be set to guide visitors in order to achieve the shortest evacuation time.
- After several simulations and actual rehearsals, the location of the bottleneck in the Louvre can be determined. The Louvre officials should be set up on the road leading to the main branch of the bottleneck to make a proportional diversion of the people in an emergency. According to the guidance of 5.2.2, all the people can move to the exit at the fastest speed to achieve the shortest total evacuation time.

(2) In order to minimize the time for emergency personnel to enter the Louvre and ease traffic pressure, we encourage the Louvre to develop the following measures:

- Take into account the low security level at the secret channel, we should try not to open the secret exits. Based on the relationship between real time traffic and optimal current capacity, we can determine the number of secret exits that should be open to allow emergency personnel to enter the Louvre.
- We should arrange emergency personnel to be in a position to the secret exit and other exits, and to inform the tourists the path leading to secret exits to ease the traffic pressure of other exits.

(3) In order to allow slower visitors to leave the Louvre as soon as possible, we encourage the Louvre to develop the following measures:

- Considering the different attributes of tourists, the elderly, the disabled and the children are slower. Therefore, when the emergency personnel are guiding, they do not divert such groups of people. Such groups of people should escape through the fastest path to minimize the overall evacuation time

5.2. Other large crowded structural adjustment and implementation model

Apart from museums,, we also consider two other types of large congestion structures for evacuation in the event of an emergency.

(1) Transportation hubs (subway interchanges, train interchanges, etc.)

The evacuation plan for the subway interchange is different from that of the Louvre. It is necessary to take into account that convection would not occur when people move to different exits, because they often walk in a single direction. Therefore, we made the following improvements to the evacuation model.

- In the improved Cellular Automaton model, the case in subway interchange does not need to consider the repulsion caused by factors such as collisions between pedestrians. However, it is necessary to consider the friction between people due to crowding.
 - In the process of abstracting the Louvre into a Network Flow model, the connection between nodes is considered to be two-way. While in the subway interchange, the connection between the nodes should be abstracted as one-way communication, which is more realistic.
- (2) High-rise buildings (high-rise residential buildings, high-rise office buildings, etc.)
- The high-rise building evacuation plans are different from the Louvre evacuation model. Pedestrians need to reach the lowest level of exit to escape. Therefore, in the evacuation process in high-rise buildings, the Network Flow model should be abstracted, and the connections between the floors should be connected in one direction to determine the shortest evacuation time.

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