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Summary Sheet

Emergency evacuation model：Time to leave the Louvre

summary

The Louvre is one of the largest and most visited art museums in the world. However, the growing number of terrorist attacks in France requires many popular destinations to have emergency evacuation plans. The diversity of visitors makes evacuation in an emergency more challenging. Therefore, the establishment of emergency evacuation model is of great significance.

First, we reduced the dimensionality of the three-dimensional map of the Louvre, abstracted it into a plane map, merged the adjacent exhibition halls into nodes, and renumbered them for subsequent evacuation plans.

Secondly, we use bellman algorithm to build the preliminary model, and then optimize the preliminary model by combining practical factors such as the capacity of stairs and the proportion of tourists, to work out the dynamic optimal evacuation route and identify the best entrance and exit.

Third, through the simulation of the Louvre actual condition, considering the potential threats posed by terrorism, such as stream of actual changes in actual situation, according to the model to calculate all the personnel in accordance with the optimal evacuation route to evacuate from the museum of evacuation time is 6 minutes and 48 seconds, and notify the evacuation and emergency personnel to 4 minutes to 5 minutes, finally the overall evacuation time of about 10 minutes. Besides, the "Affluences" application is combined to identify potential bottlenecks that may limit the evacuation, such as flow problems caused by busy days and opening hours, nationality and language issues of tourists, etc. In view of different evacuation difficulties, the Suggestions on adjusting emergency management policies and procedures are put forward to museum managers.

Finally, we discuss and generalize the model to be applied to the evacuation of other large crowded building structures.

Key words：Dimension reduction　Bellman algorithm　Dynamic evacuation

Contents

1. Introduction

1.1 Background

The Louvre is one of the world's largest and most visited art museum. In recent years, the number of tourists has been increasing year by year, with more than 8.1 million in 2017 [1]. However, from students being killed in Toulouse to a soldier attacked outside the Louvre museum in Paris, there have been at least 12 major terror-related incidents in France since 2012. The growing number of terrorist attacks in France[2] has required many hot spots to have emergency evacuation plans to ensure that all personnel leave buildings as quickly and safely as possible and empty them as quickly as possible.

The number of visitors to the museum varies throughout the day and year, and the diversity of visitors - multilingual, groups traveling together and disabled visitors - makes evacuation more challenging in an emergency. Therefore, the evacuation plan of the Louvre museum, the former royal palace of France and the world-famous art palace, is of great significance.

1.2 Restatement of the Problem

According to the requirements of the problem, we should develop an emergency evacuation model, including following aspects .

- Allow museum managers to try various methods to evacuate visitors from the museum as quickly and safely as possible, at the same time allows emergency personnel to enter the building as soon as possible.
- Consider the varies guests number in museum throughout the day and year and the diversity of visitor.
- Discuss how to use extra doors safely.
- Consider applying Louvre's online application "Affluences" to enhance our evacuation planning.
- Identify potential bottlenecks which may limit evacuation.
- Propose policy and procedural recommendations for emergency management of Louvre to ensure the safety of visitors, based on the results of our work.
- Discuss how to adjust and implement models for other large and crowded structures.

1.3 Overview Our Work

In order to establish the emergency evacuation model.

Firstly, we reduced the dimension of the map of Louvre, abstractly combined the -2 floor, -1 floor, 1 floor, 2 floor and 0 floor into a plan, and combined, classified and renumbered the adjacent exhibition halls for subsequent evacuation and allocation of stairs. Due to the limitations of computer speed and building size, when dividing the nodes of evacuation in the internal structure of the Louvre, we combined the nodes that can be combined to reduce the number of overall model nodes. The basis of node merging is to merge all nodes connected to the same node to form a new node.

Secondly, we use Bellman-ford algorithm in accordance with the shortest path principle to establish a preliminary model, and then combined with factors such as the maximum load and distance of the stairs, the nodes choose the next step of the stairs for weighted calculation of the final score, planning the evacuation route.

Thirdly, through the simulation of the actual situation of the Louvre, considering group travel and disabled visitors, the potential bottlenecks that may limit the evacuation can be found in conjunction with the application "Affluences", we can obtain the special waiting time for entering the museum, thus the possible human traffic can be estimated. Suggestions on the adjustment of emergency management policies and procedures to ensure the safety of visitors can be made to the museum administrators.

Finally, we discuss and generalize our model in order to apply evacuation realization for other large and crowded building structures.

2.Assumptions

- Because in an emergency, the shaft of the elevator is easy to be damaged, and the safety of the elevator is not easy to be guaranteed, we assume no elevator during emergency evacuation.
- We assume that in the process of evacuation, pedestrians are fully aware of the surrounding conditions, the location of safety exits, the layout of obstacles and other evacuation environments.
- There is no panic stampede in the evacuation process.
- We assume that all the evacuees to be evacuated fully follow the command and can complete the evacuation action according to the pre-established evacuation plan.

3.Notations

Notations	Definition
V	the number of vertices
E	the number of edges.
$dist^k[v]$	the length of the shortest path from the starting point u to the vertex v that can pass through at most k edges.
O	the distance of source vertex
W	the weight of the edge
D	distance matrix
P_i	the i th node

N_{P_i}	indicates the number of visitors at the beginning of the node P_i
γ	the coefficient of change in the number of nodes P_i
$h_{P_i}(t)$	the number of visitors who have passed or evacuated from the node P_i at the time t after the emergency.
$M_j(t)$	the number of tourists gathered at staircase S_i evacuated from a certain node at time t after an emergency
M_i	the maximum visitor capacity of staircase S_i
$\partial_i(t)$	actual situation of the staircase S_i at the time t after the emergency
$\varphi_{ij}(t)$	the road condition standardization score between the node P_i and the staircase S_j
d_{ij}	the distance between the node P_i and the staircase S_j
u_i	the distance between the node P_i and the staircase S_j
V_x	the average evacuation speed of tourists
T_{all}	the overall evacuation time

4.Model establishment and solution

4.1 Establish emergency evacuation model

4.1.1 Abstract the map of the Louvre for dimensionality reduction

The Louvre is built in a u-shaped structure. There are five floors in total, which include three floors above ground and two underground, with 198 pavilions large and small on all floors. The terrain is extremely complex. In order to establish the model of emergency evacuation, we reduced the dimension of the map of the Louvre.

According to the location of the exhibition hall, the distribution between the exhibition halls and the distance between the exhibition hall and each staircase, we combined the exhibition hall. In order to facilitate the calculation of the distance between nodes and stairs in the establishment of evacuation model, we abstracted the u-shaped map of each floor into a plan on the same horizontal line according to the type of the exhibition hall, as shown in figure 1. In figure1, the circle represents the staircase, the square represents the combined exhibition hall, the triangle represents the entrance and exit of the evacuated crowd, the color of the stairs on the same floor is the same, and the connecting line between each node represents the connection between each other.

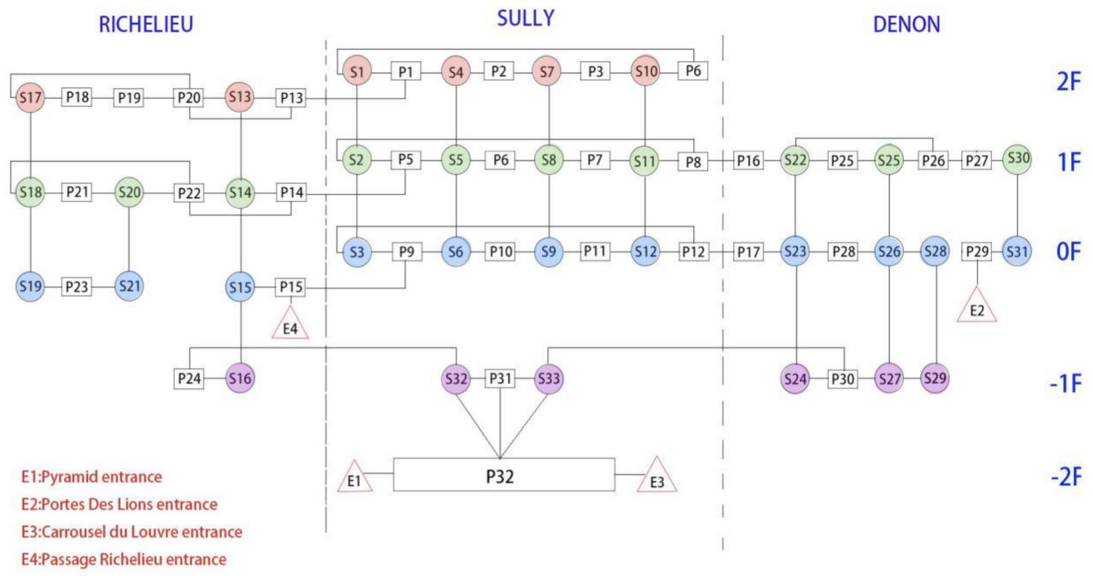

Figure 1: Plan map

As can be seen from the plan, there are four entrance and exit points for the evacuated crowd, namely Pyramid entrance(E1), Portes Des Lions entrance(E2), Carrousel du Louvre entrance(E3), Passage Richelieu entrance(E4). E1 and E3 are in the -2 layer and E2 and E4 are in the 0 layer.

4.1.2 Establish a preliminary model

Modeling background -- bellman-ford algorithm

Bellman-ford algorithm is an algorithm for computing the Single Source Shortest Path in weighted directed graph. This algorithm was published by Richard Bellman and Lester Ford in 1958 and 1956 respectively, while in fact Edward f. Moore also published the same algorithm in 1957. Therefore, this algorithm is often called bellman-ford-moore algorithm.

Bellman-ford algorithm is designed with Dynamic Programming, and the time complexity is $O(V*E)$, where V is the number of vertices and E is the number of edges.

The purpose of the Bellman-Ford is to construct an array of shortest path lengths

$$dist^1[v] \quad dist^2[v] \quad dist^3[v] \quad \ldots \quad dist^{n-1}[v]$$

$dist^1[v]$ represents the length from the starting point u to all the other vertices in the graph v that have only one edge.

$dist^k[v]$ is the length of the shortest path from the starting point u to the vertex v that can pass through at most k edges.

The whole point of the algorithm is to figure out $dist^{n-1}\left[v\right]$.

The formation of $dist^{1}\left[v\right]$: $dist^{1}\left[u\right]=0$

$$dist^{1}\left[v\right]=\begin{cases} W_{uv} & if\left\langle u,v\right\rangle is\, the\, directed\, edge\, of\, the\, graph \\ \infty & otherwise \end{cases}$$

The formation of $dist^{k}\left[v\right]$:

$$dist^{k}\left[v\right]=\min\left\{dist^{k-1}\left[v\right],\min\left\{dist^{k-1}\left[j\right]+w_{jv}\right\}\right\}$$

Specific steps of bellman-ford algorithm:

I. Create a set of distances from source vertex v to all vertices in the graph, and specify a distance value for all vertices in the graph. The initial value is Infinite, and the distance of source vertex is 0.

II. Calculate the shortest path and perform $v-1$ traversal (for each edge in the figure: if the distance d of the starting point u plus the weight w of the edge is less than the distance d of the end point V, then update the distance d of the end point V).

III. Test whether there are negative weight edges forming a ring in the graph, traverse all the edges in the graph, calculate the distance from u to v, if there is a smaller distance for v, it means that there is a ring.

Establish model -- emergency evacuation model

In order to establish the emergency evacuation model, we use Bellman-Ford algorithm to calculate the shortest distance between each node and all exits. After comparing the shortest distance between each node and all exits, we select the best exit of each node to form the evacuation route.

First of all, the figure 1 shows that there're a total of 32 nodes after the abstraction of planar maps with 33 stairs, specific nodes and stair distribution of each layer as shown in table 1, thus the 1 layer and 2 layer between the number of stairs, at least 2 layer and 0 each have two exports, so must to evacuate the crowd evacuation to - 2 layer or 0 layer.

Table 1 Node distribution

Floor	RICHELIEU Nodes Number	RICHELIEU Stairs Number	SULLY Nodes Number	SULLY Stairs Number	DENON Nodes Number	DENON Stairs Number	TOTAL Nodes Number	TOTAL Stairs Number
2F	4	2	4	4	0	0	8	6
1F	3	3	4	4	4	3	11	10
0F	2	3	4	4	3	4	9	11

-1F	1	1	1	2	1	3	3	6
-2F	0	0	1	0	0	0	1	0
total	10	9	14	14	8	10	32	33

First, we calculate the distance from each node to other nodes and all stairs according to the plane map in figure 4-1, and obtain the distance matrix is a symmetric sparse matrix,

$$D=\begin{bmatrix} d_{11} & \cdots & d_{1n} \\ \vdots & \ddots & \vdots \\ d_{1n} & \cdots & d_{nn} \end{bmatrix}$$

and part of the distance matrix is shown in figure 2. The distance between nodes without direct connection and stairs is INF, and the distance between nodes with direct connection and stairs is calculated in proportion.

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16
P1	0	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	1	Inf	Inf	Inf
P2	Inf	0	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
P3	Inf	Inf	0	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
P4	Inf	Inf	Inf	0	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
P5	Inf	Inf	Inf	Inf	0	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	1	Inf	Inf
P6	Inf	Inf	Inf	Inf	Inf	0	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
P7	Inf	Inf	Inf	Inf	Inf	Inf	0	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
P8	Inf	Inf	Inf	Inf	Inf	Inf	Inf	0	Inf	Inf	Inf	Inf	Inf	Inf	Inf	1
P9	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	0	Inf	Inf	Inf	Inf	Inf	1	Inf
P10	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	0	Inf	Inf	Inf	Inf	Inf	Inf
P11	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	0	Inf	Inf	Inf	Inf	Inf
P12	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	0	Inf	Inf	Inf	Inf
P13	1	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	0	Inf	Inf	Inf
P14	Inf	Inf	Inf	Inf	1	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	0	Inf	Inf
P15	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	1	Inf	Inf	Inf	Inf	Inf	0	Inf
P16	Inf	Inf	Inf	Inf	Inf	Inf	Inf	1	Inf	Inf	Inf	Inf	Inf	Inf	Inf	0

Figure 2: Partial distance matrix

To ensure the feasibility of the preliminary model, it is assumed that there is no crowding between the stairs and the entrance. We use Bellman - Ford algorithm for each node to calculate the shortest distance to the inward and outward $dist^k[v]$,

$$dist^k[v]=\min\left\{dist^{k-1}[v],\min\left\{dist^{k-1}[j]+w_{jv}\right\}\right\}$$

$$\text{and}\quad dist^1[u]=0$$

we use R language programming, combined with distance matrix to calculate the shortest distance of each node to the inward and outward, the end result, as shown in the table2.

Table 2: The closest distance matrix from 32 nodes to three exits

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32

P15	5	5	7	5	4	4	6	4	1	3	5	3	4	3	0	5	4	6	5	4	5	3	6	3	7	7	8	6	11	7	5	5
P29	10	12	10	10	9	11	9	7	10	12	10	8	11	10	11	6	7	14	13	12	13	11	14	12	6	4	3	7	0	8	10	10
P32	8	10	10	10	7	9	9	7	6	8	8	6	7	6	5	6	5	9	8	7	8	6	9	2	6	6	7	5	10	2	1	0

Because exit E1 is close to exit E3, when calculating the distance we combined E1 with E3, the shortest distance by the comparison of each node to the inward and outward, can select the best entrances and exits.

Table 4 The shortest distance from each node to the entrance

	X1	X2	S
1	1	5	1,33,34,35,9,15
2	1	5	2,36,37,38,9,15
3	1	7	3,42,43,44,12,35,9,15
4	1	5	4,33,34,35,9,15
5	1	4	5,34,35,9,15
6	1	4	6,37,38,9,15
7	1	6	7,43,44,12,35,9,15
8	1	4	8,34,35,9,15
9	1	1	9,15
10	1	3	10,38,9,15
11	1	5	11,44,12,35,9,15
12	1	3	12,35,9,15
13	1	4	13,45,46,47,15
14	1	3	14,46,47,15
15	1	0	15
16	1	5	16,8,34,35,9,15
17	1	4	17,12,35,9,15
18	1	6	18,19,20,45,46,47,15
19	1	5	19,20,45,46,47,15
20	1	4	20,45,46,47,15
21	1	5	21,50,22,46,47,15
22	1	3	22,46,47,15
23	1	6	23,51,50,22,46,47,15
24	3	2	24,64,32
25	2	6	25,54,26,27,62,63,29
26	2	4	26,27,62,63,29
27	2	3	27,62,63,29
28	3	5	28,55,56,30,65,32
29	2	0	29
30	3	2	30,65,32
31	3	1	31,32
32	3	0	32

X1 represents three exits corresponding to 1: P15; 2: P29; 3: P32;

X2 represents the distance;

S represents the path, and P less than 32 represents s is greater than 32;

4.1.3 Optimization model

Because we not consider traffic, the capacity of stair, group travel tourists and other practical factors, such as disabled visitors and in the primary model. At the same time, the unfamiliarity of visitors to the environment in the museum may lead to the crowding at one stairway entrance and the sparse flow of people at the adjacent stairway entrance, which may lead to the imbalance of the use of stairs or exits and slow down the evacuation speed, as shown in figure 3.

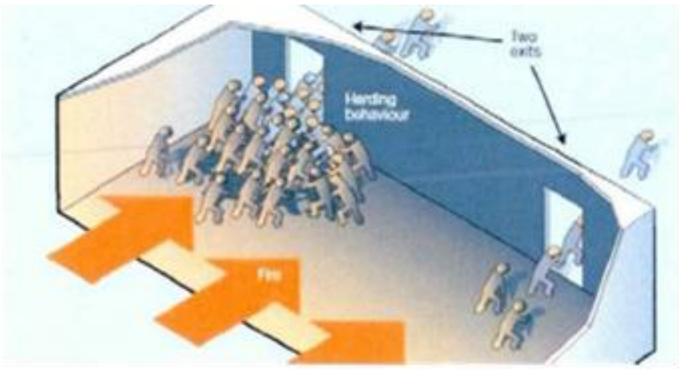

Figure 3: Uneven use of stairs or exits

In order to further optimize our evacuation model, we modified and improved the evacuation model in case of an emergency by combining the traffic flow data of the Louvre and the actual distribution of the building pattern.

We set the number of visitors of node P_i at time t as:

$$N_{P_i}(t) = N_{P_i} + \gamma * h_{P_i}(t)$$

Where N_{P_i} : indicates the number of visitors at the beginning of the node P_i ; γ: indicates the coefficient of change in the number of nodes P_i after an emergency, and the location of the node P_i is related to the floor space; $h_{P_i}(t)$: indicates the number of visitors who have passed or evacuated from the node P_i at the time t after the emergency.

We set the actual situation of the staircase S_i as $\alpha_i(t)$:

$$\alpha_i(t) = \frac{\sum_{j=k}^{l} M_j(t)}{M_i}$$

Where $M_j(t)$: indicates the number of tourists gathered at staircase S_i evacuated from a certain node at time t after an emergency; M_i: indicates the maximum visitor capacity of staircase S_i.

We will define $\alpha_i(t)$ according to the actual situation of the staircase S_i at the time t after the emergency, and define the road condition standardization score $\varphi_{ij}(t)$ between the node P_i and the staircase S_j,

$$\varphi_{ij}(t) = \begin{cases} k, & \text{if } \alpha_i(t) < \beta \\ \infty, & \text{if } \alpha_i(t) \geq \beta \end{cases}.$$

We redefine the distance $d_{ij}(t)$ between the node P_i and the staircase S_j at time t after the emergency:

$$d_{ij}(t) = d_{ij} + \varphi_{ij}(t)$$

Where d_{ij}: represents the distance between the node P_i and the staircase S_j, and $\varphi_{ij}(t)$ represents the road condition standardization score between the node P_i and the staircase S_j at the time t after the occurrence of the emergency event.

We redefine the distance $D_{ij}(t)$ between the node P_i and the exit E_j at time t after the emergency:

$$D_{ij}(t) = \sum_{1 \leq i \leq 32}^{1 \leq j \leq 4} d_{ij}(t)$$

Due to the different types of tourists, they can be divided into individual and group tourists as well as disabled tourists. According to the data, group tourists may slow down the normal evacuation speed by taking care of or looking for each other [with references], so the average evacuation of tourists Speed can be defined as:

$$\bar{v}_x = \sum_{i=1}^{3} \mu_i * v_i$$

In the formula, μ_i: represents the proportion of different tourists, where μ_1 represents the proportion of individual passengers, μ_2 represents the proportion of group tourists, μ_3 represents the proportion of disabled tourists, and satisfies $\sum_{i=1}^{3} \mu_i = 1$; v_i indicates the evacuation speed of different tourists, where v_1 indicates the speed of individual passenger evacuation, v_2 indicates the evacuation speed of group tourists, and v_3 indicates the evacuation speed of disabled tourists.

We set the time taken for someone to escape from all tourists at node P_i to exit E_j at speed v_x after an emergency as

$$T_{ij} = \frac{D_{ij}}{\bar{v}_x}.$$

We define the overall evacuation time as:

$$T_{all} = \max\{T_{ij}\}, \text{ for any } 1 \le i \le 32, 1 \le j \le 4.$$

In summary, we use our optimized model to redesign the emergency evacuation plan. According to the information, the opening time of the Louvre are shown in Table 4-6, and are open on Monday and Wednesday. The peak tourist season of the museum is from April to September, and the rest is off-season. According to Table 4-6, the average daily opening time is about 9.5 hours. Since the total number of visitors per day in the museum is about 30,000, combined with the museum opening hours, we can infer that the number of real-time visitors in the museum is about 18,000. Assuming that the average scattered distribution of tourists in the museum, N_{P_i} is related to the size of the node. First, calculate the distance matrix D(0) at t=0.

$$D(0) = \begin{bmatrix} d_{11}(0) & \cdots & d_{1n}(0) \\ \vdots & \ddots & \vdots \\ d_{n1}(0) & \cdots & d_{nn}(0) \end{bmatrix} = \begin{bmatrix} d_{11} & \cdots & d_{1n} \\ \vdots & \ddots & \vdots \\ d_{n1} & \cdots & d_{nn} \end{bmatrix}$$

Then, combining the actual situation of staircase S_i, $\partial_i(t)$, with the road condition standardization score $\varphi_{ij}(t)$ between node P_i and staircase S_j, the evacuation route was dynamically planned to find the best exit. After R language program calculation, the optimal exit and evacuation route of each node calculated by the optimized model are obtained, as shown in table 5.

Table 5 Optimal exit and optimal evacuation route results

Node	Pathway	Best Exit
1	1->13->45->46->47->15	E4
2	2->36->37->38->9->15	E4
3	3->42->4->33->34->35->29	E2
4	4->33->34->35->9->15	E4
5	5->14->46->47->15	E4
6	6->37->38->9->15	E4
7	7->43->8->34->35->9->15	E4
8	8->34->35->9->15	E4

9	9->15	E4
10	10->38->9->15	E4
11	11->44->12->35->9->15	E4
12	12->35->9->15	E4
13	13->45->46->47->15	E4
14	14->46->47->15	E4
15	15->0->15	E4
16	16->8->34->35->9->15	E4
17	17->12->35->9->15	E4
18	18->19->20->45->46->47->15	E4
19	19->20->45->46->47->15	E4
20	20->45->46->47->15	E4
21	21->50->22->46->47->15	E4
22	22->46->47->15	E4
23	23->51->50->22->46->47->15	E4
24	24->64->32	E3
25	25->54->55->56->30->65->32	E3
26	26->27->62->63->29	E2
27	27->62->63->29	E2
28	28->55->56->30->65->32	E1
29	29->0->29	E2
30	30->65->32	E3
31	31->32	E1
32	32->0->32	E1

In addition, we got that the evacuation time of all staff leaving the museum according to the optimal evacuation route was 6 minutes and 48 seconds, plus the notice of evacuation and the preparation time of emergency personnel was 4 minutes to 5 minutes, so the final overall evacuation time was about 10 minutes.

4.2 Identify potential bottlenecks that may limit evacuation

Combined with the evacuation routes of each node calculated by the above evacuation model, we will propose potential bottlenecks that may limit evacuation from the following aspects.

4.2.1 The bomb caused a problem with the closure of a staircase

As there are more and more terrorist attacks in France, there may be a terrorist who sets a bomb in the museum, which makes an area or stairs unusable. Therefore, combining with the evacuation model, we assume that the bomb is in the most crowded stairs or areas, and redesign the evacuation plan. According to the distribution of exhibition halls and tour routes, it can be inferred that the most crowded staircases in the museum are S15 and S18, so terrorists are most likely to set bombs in these locations, causing panic. Using our evacuation model, we plan the evacuation route according to the situation in figure 4, and evacuate tourists as soon as possible so as to empty the museum. According to the calculation, when there is a bomb in these stairs, the most likely crowded nodes for the stampede are P32、P31 and P30,as shown in figure 4.

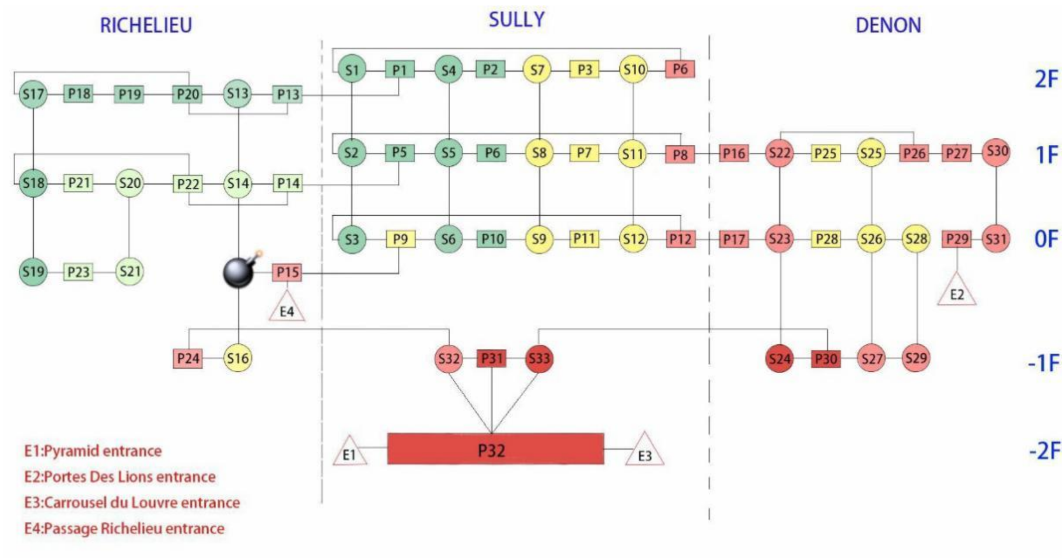

Figure 4: Nodal distribution map

Therefore, evacuation exit or VIP access can be added in these crowded areas for evacuation, and additional signs and emergency personnel to speed up the evacuation.

4.2.2 Top treasures of museum cause the problem of overcrowding

After reading information, The 3 top treasures of the Louvre museum are Mona Lisa,Vénus de Milo and Winged Victory. Its locations are room 711 on the first floor, room 703 on the first floor and room 345 on the first floor respectively. The corresponding plane map is the node.

Therefore, the number of tourists nearby will be large, as shown in figure5.

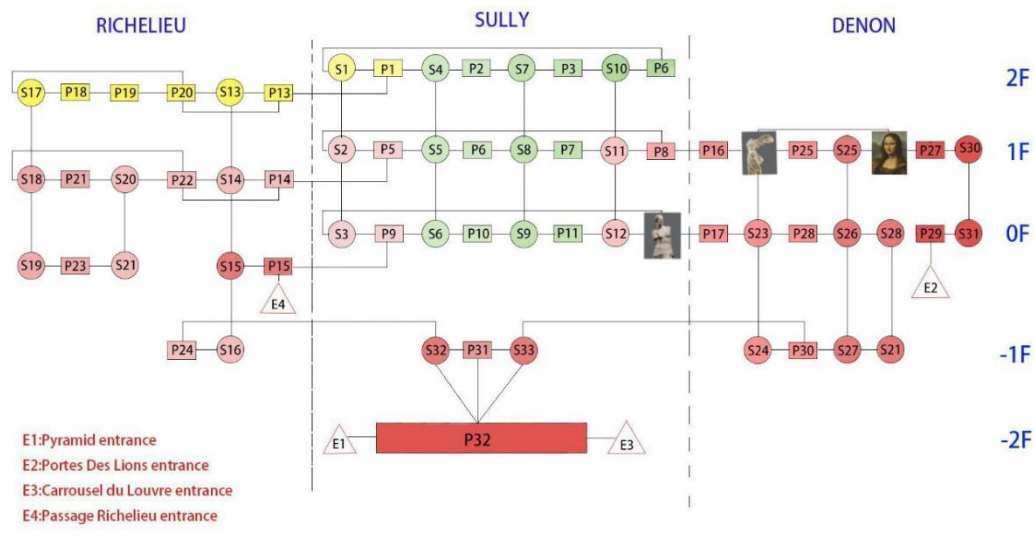

Figure 5: Nodal distribution map

The possible crowded area has been marked out, and the nearby stairs should be kept unblocked as far as possible to avoid the stampede event caused by the evacuation of tourists.

4.2.3 Key area signs, direction lights and emergency personnel arrangements

For the relatively crowded area in figure 5, insufficient indicator signs or lights and failure of emergency personnel to evacuate tourists in time may limit the evacuation speed and increase the difficulty of evacuation.

4.2.4 The nationality and language of the tourists

We get the visitor proportion of the Louvre museum, as shown in figure 6.

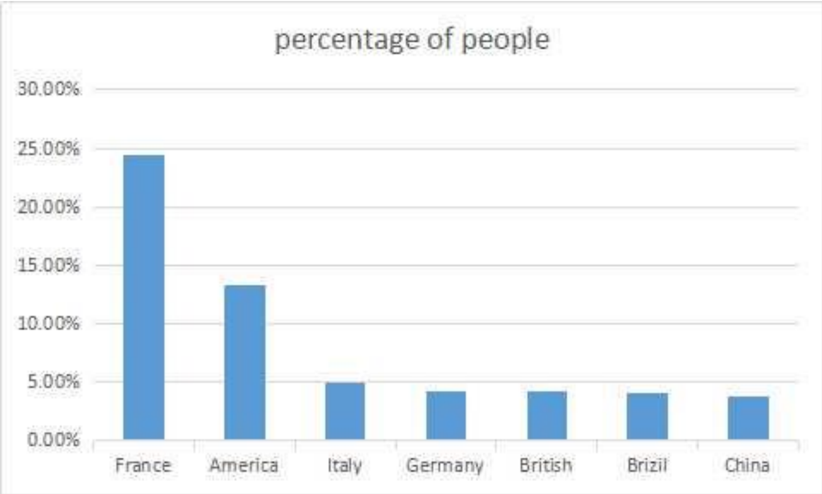

Figure 6: the percentage of tourists

Museum officials should consider the diversity of nationalities of visitors, and signs, emergency personnel and reminders should take into account the language of most visitors to avoid communication problems in evacuation caused by language problems.

4.2.5 Consider the different traffic in slack season, peak season and different opening hours

The Louvre's peak travel season is from April to September, and the rest is off season.The specific opening hours are shown in the table 5.

Table 5 Opening schedule

Data	Opening Time
Monday	9:00 a.m. ~6:00 p.m.
Tuesday	closed
Wednesday	9:00 a.m.~9:45 p.m.
Thursday	9:00 a.m. ~6:00 p.m.
Friday	9:00 a.m.~9:45 p.m.
Saturday	9:00 a.m. ~6:00 p.m.
Sunday	9:00 a.m. ~6:00 p.m.

Therefore, the number of tourists on Monday and Wednesday, the first Saturday of each month and the afternoon from 2 to 5 on the Open Day will be more, which will limit the evacuation speed and increase the difficulty of evacuation.

4.2.6 Emergency personnel access to the museum's entrance arrangements

According to the calculation results of the emergency evacuation model, we can get that the exits with relatively few personnel are: E2. Therefore, in order to accelerate the speed of emergency personnel entering the museum and reduce the convection phenomenon between emergency personnel and evacuated tourists, the exit of emergency personnel entering the museum should be set as the exit with few tourists.

4.3 Propose management policies

1. Add evacuation signs or lights near the nodes prone to emergencies, so that tourists can quickly leave the museum through the safe passage when evacuating.

2. For the exhibition halls with a large number of people in the museum, such as floor 711, floor 703, floor 345, etc., an appropriate emergency passage should be added in the vicinity, so as to facilitate the rapid evacuation after an emergency occurs.

3. As for the diversity of tourists' nationalities, attention should be paid to the language problem of most tourists and the language ability of emergency personnel to facilitate communication.

4. In view of the different traffic flow problems caused by the off-peak season and the opening time, attention should be paid to the on-site management and evacuation order when there is a large traffic flow, and appropriate emergency channels should be opened to prevent crowd congestion.

5. In the stairs or exits that are easy to be crowded, more emergency personnel should be added for timely and effective evacuation, so as to increase the evacuation speed

4.4 Discuss the adjustment and application of evacuation models for other large and crowded structures

In order to enhance the applicability of the model, we adjust the evacuation model. For large, crowd-prone building structures, each region is divided into blocks to replace nodes in the model, and the number of visitors is distributed in the region to replace nodes. For unknown personnel types, they are all normal people with normal evacuation speed, so as to calculate the required evacuation time according to the actual data

After the adjustment, our model can be applied to evacuation plans of large buildings such as shopping malls, office buildings and classrooms to plan the optimal evacuation route, find the best exit and empty the building as soon as possible to ensure personal safety and reduce necessary losses.

5. Evaluation and Improvement

5.1 Strength

- For the complex structure of large buildings in this problem, this paper USES the method of dimension reduction combination to obtain a simplified building plan, which simplifies the calculation process and reduces the difficulty of solution.
- The idealization of conditions has certain rationality
- We converted the road condition problem into the solution of the distance problem, which was simplified to solve the equation for the model
- Dynamically update the number of people to be evacuated at each node, so that the model is closer to the real situation and the required evacuation time is shorter

5.2 Weakness

- There are few quantitative data, which may be inconsistent with the real situation
- Strong dependence on specific data in the model.

Reference

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[4] “Pyramid” Project Launch – The Musée du Louvre is improving visitor reception (2014-2016).” Louvre Press Kit, 18 Sept. 2014
[5] “The ‘Pyramid’ Project - Improving Visitor Reception (2014-2016).” Louvre Press Release, 6 July 2016
[6] KongjinZhu,.”Study on evacuation characteristics and evacuation strategies of typical areas in buildings”,June,2013
[7] https://en.wikipedia.org/wiki/Bellman%E2%80%93Ford_algorithm#References

Appendix

###Bellman_Ford algorithm is used to calculate the shortest path problem of sparse graph###

```
Bellman_Ford <- function(a,b,c){
  #a：Number of nodes, b: source node, c: edge matrix
  p <- paste(b,sep = ",")
  #Create a list p store path
  dis <- rep(Inf,a)
  dis[b] <- 0
  #In the case of dis initialization, all are Inf except the source point is 0

  for(i in 1:(a-1)){
#Limit relaxation to avoid loops

    for (j in 1:dim(c)[1]){
      m <- c[j,1]
      n <- c[j,2]
      k <- dis[m] + c[j,3] #Calculate the distance from m node to n node
      if(k<dis[n])
      {
        dis[n] <- k
        #Put an edge in p when it can be relaxed
        l <- paste0(m,"$")
        n_p <- paste(grep(l,p,value = T),n,sep = ",")
        p <- c(p,n_p)
      }    #Update dis if you can shorten the distance
    }
  }
  return(list(dis,p))
}
```

###The congestion is converted into the extension of the distance between nodes, which is then solved by Bellman_Ford algorithm###
#Where c is the edge matrix,
#r is the matrix storing the shortest distance. The row represents 32 nodes, and the column from left to right is the distance to P15, P29 and P32
#p1 is the shortest path to store 32 nodes to P15
#p2 is the shortest path to store 32 nodes to P15
#p3 is the shortest path to store 32 nodes to P15

#Find the shortest path from each node to all exits and its path

```
shusanmoxing <- function(c){

r <- matrix(1,65,3)
p1 <- list()
p2 <- list()
p3 <- list()
for(i in 1:65)
{
   dis <- Bellman_Ford(65,i,c)
   p <- dis[[2]]
   dis <- dis[[1]]
   r[i,] <- dis[c(15,29,32)]

#Filter out paths that do not match the shortest distance
s <- grep("15$",p,value = T)
for(j in s)
{
   t <- 0
   split_p <- strsplit(j,split = ",")
   split_p <- as.numeric(split_p[[1]])
   while (length(split_p) > 1) {
   t <- t+c[which(c[,1] == split_p[1]&c[,2] == split_p[2]),3]
   split_p <- split_p[-1]
   }

   if(t == r[i,1])
   p1[[i]] <- j
}

s <- grep("29$",p,value = T)
for(j in s)
{
   t <- 0
   split_p <- strsplit(j,split = ",")
   split_p <- as.numeric(split_p[[1]])
   while (length(split_p) > 1) {
      t <- t+c[which(c[,1] == split_p[1]&c[,2] == split_p[2]),3]
      split_p <- split_p[-1]
   }

   if(t == r[i,2])
      p2[[i]] <- j
}
s <- grep("32$",p,value = T)
```

```
for(j in s)
{
  t <- 0
  split_p <- strsplit(j,split = ",")
  split_p <- as.numeric(split_p[[1]])
  while (length(split_p) > 1) {
    t <- t+c[which(c[,1] == split_p[1]&c[,2] == split_p[2]),3]
    split_p <- split_p[-1]
  }

  if(t == r[i,3])
    p3[[i]] <- j
}
}
return(list(r,p1,p2,p3))
}


###Pick one way to the nearest exit###
shusanmoxing_step2 <- function(r,p1,p2,p3)
{
r_1 <- matrix(0,65,2)
for(i in 1:65){
  s <- which(r[i,] == min(r[i,]))
  s <- s[1]
  r_1[i,] <- c(s,r[i,s])
}
r_1 <- data.frame(r_1)
s <- NULL
for(i in 1:65){
  if(r_1[i,1] == 1)
  {
    s <- c(s,p1[[i]])
  }else if(r_1[i,1] == 2)
  {
    s <- c(s,p2[[i]])
  }else if(r_1[i,1] == 3)
  {
    s <- c(s,p3[[i]])
  }
}
r_1 <- cbind(r_1,s)
return(r_1)
}
```

###According to the shortest path from each node to the exit at each time, the distribution of personnel in each node can be dynamically adjusted###

```
#Convert the distance matrix a to the edge matrix c
s <- NULL                    #S is the distance
c <- which(a>=0,arr.ind = T)
for(i in 1:4225)
{s[i] <- a[c[i,1],c[i,2]]}
c<- cbind(c,s)

ori_c <- c
##################################
  c <- ori_c
  t <- 0
  h <- ori_h
  k <- ori_k
  v <- 1000
  book <- matrix(0,65,66)
  book[,1] <- 1:65
  p <- matrix(0,65,2)
  d <- c()
  z <- c()
while (F %in% (h==0)) {
   t <- t+1
   #Calculate the nearest exit and path of the node in the initial state
   s <- h/k
   s <- s+1
   z <- c(z,which(s>1))
   n_c <- c
   for(i in 1:65){

      m <- c(which(c[,1] == i),which(c[,2]==i))

      n_c[m,3] <- c[m,3] * s[i]

   }
   c <- n_c
   n_r <- shusanmoxing(n_c)
   n_r_1 <- shusanmoxing_step2(n_r[[1]],n_r[[2]],n_r[[3]],n_r[[4]])
   n_r_1$s <- as.character(n_r_1$s)
   h[c(15,29,32)] <- h[c(15,29,32)] - v
   #Clear at the exit
   h[which(h < 0)] <- 0
```

```
for(i in 1:65){
    q <- strsplit(n_r_1[i,3],",")[[1]]
    q <- as.numeric(q)
    p[i,1] <- q[1]
    p[i,2] <- q[2]
    w <- which(book[,t] == p[i,1])
    book[w,t+1] <- p[i,2]

}
p[is.na(p[,2]),2] <- p[is.na(p[,2]),1]

for(i in 1:65){
d[i] <- min(v,h[p[i,1]])
h[p[i,2]] <- h[p[i,2]] + d[i]
}
for(i in 1:65){
h[p[i,1]] <- h[p[i,1]] - d[i]
}
h[c(15,29,32)] <- h[c(15,29,32)] - v
#Clear at the exit
h[which(h < 0)] <- 0
}
```

Result1:The path and distance of the node from the nearest exit

Node	Recent export	Distance	Pathway
1	1	5.8	1,33,34,35,9,15
2	1	5.8	2,36,37,38,9,15
3	1	8.2	3,42,43,44,12,35,9,15
4	1	5.8	4,33,34,35,9,15
5	1	4.6	5,34,35,9,15
6	1	4.6	6,37,38,9,15
7	1	7	7,43,44,12,35,9,15
8	1	4.6	8,34,35,9,15
9	1	1	9,15
10	1	3.4	10,38,9,15
11	1	5.8	11,44,12,35,9,15
12	1	3.4	12,35,9,15
13	1	5.055555556	13,45,46,47,15
14	1	3.888888889	14,46,47,15
15	1	0	15
16	1	5.6	16,8,34,35,9,15
17	1	4.4	17,12,35,9,15

18	1	7.055555556	18,19,20,45,46,47,15
19	1	6.055555556	19,20,45,46,47,15
20	1	5.055555556	20,45,46,47,15
21	1	7.013888889	21,52,22,46,47,15
22	1	3.888888889	22,46,47,15
23	1	7.951388889	23,53,52,22,46,47,15
24	3	2.133333333	24,64,32
25	3	6.933333333	25,54,55,56,30,65,32
26	2	4.75	26,27,62,63,29
27	2	3.75	27,62,63,29
28	3	5.733333333	28,55,56,30,65,32
29	2	0	29
30	3	2.133333333	30,65,32
31	3	1	31,32
32	3	0	32
33	1	4.6	33,34,35,9,15
34	1	3.4	34,35,9,15
35	1	2.2	35,9,15
36	1	4.6	36,37,38,9,15
37	1	3.4	37,38,9,15
38	1	2.2	38,9,15
39	1	7	39,2,36,37,38,9,15
40	1	5.8	40,6,37,38,9,15
41	1	4.6	41,10,38,9,15
42	1	7	42,4,33,34,35,9,15
43	1	5.8	43,8,34,35,9,15
44	1	4.6	44,12,35,9,15
45	1	3.888888889	45,46,47,15
46	1	2.722222222	46,47,15
47	1	1.361111111	47,15
48	1	2.527777778	48,47,15
49	1	6.255555556	49,20,45,46,47,15
50	1	7.728888889	50,22,46,47,15
51	1	8.928888889	51,50,22,46,47,15
52	1	5.451388889	52,22,46,47,15
53	1	6.701388889	53,52,22,46,47,15
54	3	5.733333333	54,55,56,30,65,32
55	3	4.533333333	55,56,30,65,32
56	3	3.333333333	56,30,65,32
57	2	5.95	57,26,27,62,63,29

58	3	5.013333333	58,59,30,65,32
59	3	3.573333333	59,30,65,32
60	3	6.073333333	60,61,59,30,65,32
61	3	4.823333333	61,59,30,65,32
62	2	2.5	62,63,29
63	2	1.25	63,29
64	3	1.066666667	64,32
65	3	1.066666667	65,32

Result2:The evacuation path obtained after dynamic model calculation

Node	Pathway
1	1->13->45->46->47->15
2	2->36->37->38->9->15
3	3->42->4->33->34->35->9
4	4->33->34->35->9->15
5	5->14->46->47->15
6	6->37->38->9->15
7	7->43->8->34->35->9->15
8	8->34->35->9->15
9	9->15
10	10->38->9->15
11	11->44->12->35->9->15
12	12->35->9->15
13	13->45->46->47->15
14	14->46->47->15
15	15->0->15
16	16->8->34->35->9->15
17	17->12->35->9->15
18	18->19->20->45->46->47->15
19	19->20->45->46->47->15
20	20->45->46->47->15
21	21->50->22->46->47->15
22	22->46->47->15
23	23->51->50->22->46->47->15
24	24->64->32
25	25->54->55->56->30->65->32
26	26->27->62->63->29
27	27->62->63->29
28	28->55->56->30->65->32
29	29->0->29

30	30->65->32
31	31->32
32	32->0->32
33	33->34->35->9->15
34	34->35->9->15
35	35->9->15
36	36->37->38->9->15
37	37->38->9->15
38	38->9->15
39	39->2->36->37->38->9->15
40	40->6->37->38->9->15
41	41->10->38->9->15
42	42->4->33->34->35->9->15
43	43->8->34->35->9->15
44	44->12->35->9->15
45	45->46->47->15
46	46->47->15
47	47->15
48	48->47->15
49	49->20->45->46->47->15
50	50->22->46->47->15
51	51->50->22->46->47->15
52	52->22->46->47->15
53	53->52->22->46->47->15
54	54->55->56->30->65->32
55	55->56->30->65->32
56	56->30->65->32
57	57->58->59->30->65->32
58	58->59->30->65->32
59	59->30->65->32
60	60->58->59->30->65->32
61	61->59->30->65->32
62	62->63->29
63	63->29
64	64->32
65	65->32