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T2 ________________		F2 ________________
T3 ________________	Problem Chosen	F3 ________________
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A Smart Adaptable Model of Evacuation for Structure

Summary Sheet

Abstract

There have been over 10 terror attacks occurred in France in the past five years. The increasing number of terror attacks requires a review of emergency **evacuation plans** at many popular destinations. Aimed to design the best evacuation plan at the Louvre in Paris, we build up **evacuation model based on probability distribution** to make the evacuation plan. With the help of our model, we calculate the evacuation time accurately and the model is practical and adaptable to other structure.

According to the requirements, we must take various factors into account while making the plan. The process of our model building is executed step by step. First, we create a model based on cell automata. This model is quite simple and only suitable in some small occasions. It cannot be applied to large structure. Then we set up a model based on uniform distribution of personnel. Compared with the previous one, this model is more accurate, but still too ideal to be applied. Thus we create the model based on probability distribution and this time we make it works. This model considers the floor layout of a structure and the evacuation speed of personnel so no matter how the structure changes, the proper evacuation plan can always be found. When applying it to Louvre, we find out that the distribution of visitors is quite complex and the diversity of visitors is a tough rock. Additionally, the floor layout of Louvre and various exits in the museum making it difficult for us to make a proper evacuation plan.

In order to make the model **more adaptable,** we combine brand-new technology with our model. The technology, which is developed by Louvre itself, can locate the visitor and send them message when necessary. The combination makes it convenient to evacuation and successfully solve the problems above.

While making the evacuation plan, we are also required to propose on how to utilize the extra exits properly. Since it is an adaptable model, there may be some potential threats such as bottlenecks and security risks during the evacuation. It's important to analyze the benefits and weaknesses of our plan.

The sensitivity analysis of our model has pointed out that the width of exits and corridors is the most important factor that affects the efficiency of evacuation. When making an evacuation plan, it's necessary to consider the width of exits and corridor in a structure.

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1 Introduction

1.1 Background

Since the beginning of the 21st century, there have been 5,878 terror attacks in the Europe in 15 years.

In recent years, with the rise of the Islamic state, united front against international terrorism has been gradually formed, the Western powers and the United States joined force to implement a strong blow against the increasingly rampant terrorism. However, the combats brought crazy revenge led by Islamic state and other terrorist forces, which suffered badly the France in series of terrorist attacks. From the blow up of “The Charlie weekly event” in January 7, 2015, the haze of terrorism in France was not scattered but occurred again in Paris which caused 129 deaths, 300 injured. Later in 2016 during the National Day in France, broke out“The Nice terrorist attack”.

Terror attacks not only cause panic in public, but also affect the development of society. In order to prevent terror attack, the authorities have made various policies. After the horrific terrorist attack in Paris on November 13, 2015, Hollande showed unprecedented anger and anti-terrorism determination, and attempted to establish a wide-ranging international anti-terrorism alliance with the world.

1.2 Restatement of the Problem

Design evacuation model(s) to support the evacuation plan in Louvre.

Propose policy and procedural recommendations for emergency management of the Louvre.

Adapt and implement our model(s) for other large, crowded structures.

1.3 Our work

We are asked to make a proper evacuation plan to have all occupants leave the building as quickly and safely as possible.

First, our team should develop an emergency evacuation model to explore a range of options to evacuate visitors from the museum while allow the emergency personnel to enter the building as quickly as possible. It’s essential for us to create an adaptable model to address a broad set of considerations and potential threats that might alter or remove segments of possible routes to safety.

Second, when creating the model, it's a must for us to take various kinds of factors such as the current number of guests in the museum, the diversity of visitors, the structure of Louvre, the environment outside the exits and so on into account. Louvre itself has an app called Affluences that provides real-time updates on the estimated waiting time at each of these entrances. We can use this technology to facilitate our evacuation plan. There are some exit points which only emergency personnel and museum officials know. While visitors can use these exits to leave, their use would simultaneously cause security problems. So it's necessary for us to make a balance between the speed of evacuation and the safety of visitors.

Third, we should apply our model(s) to the Louvre to calculate the evacuation time when incidents occur. The model may give various evacuation plans for us to select, so choosing the plan that having the shortest evacuation time is necessary for us. Meanwhile, the safety of the occupants cannot be ignored.

Last but not least, our team should adapt and implement our model(s) for other structure.

2 General Assumptions

To simplify our model(s), we list several assumptions below in order to get the best solution of evacuation plan:

- Each floor of the Louvre has the same structure.
- The evacuation speed of every visitor is same and won't change during evacuation.
- No collisions and trampling between visitors.

3 Notation

Abbreviation	Description
P_{ij}	The revenue of cell(i,j)
D_{ij}	Direction parameter
E_{ij}	Selection parameter

N_i	The number of visitors in area i
ρ_i	Density of visitors
S_i	The area of the zone under investigation
m_n	The number of staircase on the nth floor
P_n	The number of visitors on the nth floor
δ	Distribution of visitors on the nth floor
$\frac{P_n}{m_n}$	Capacity of each stairs
$\{f_n\}$	**Floor set**
$R_m^{f_n}$	**The path set of the** f_n floor
T^{f_i}	the longest evacuation time costed by the f_i floor
T_{f_i}	the shortest evacuation time costed by the f_i floor
$\mathrm{P} = \{P_m^f\}$	the personnel flow

4 Establishment of Model

4.1 Evacuation Model based on Cellular Automata

4.1.1 Model Introduction

For the scheme of how to evacuate visitors on the same floor and calculate the evacuation time, we adopt an evacuation model based on cellular automata. At present, the simulation technology based on cellular automata has been widely used in intersection pedestrian flow, simulation of pedestrian flow and evacuation pedestrian flow. The cellular automaton realizes the simulation and research of the overall macroscopic behavior characteristics of the system by simulating the microscopic behavior characteristics of simple individuals in the system. After investigation, we find that the theory of cellular automata can well get the movement rules of visitors during the evacuation process to better formulate the evacuation plan.

5.1.2 Model Assumptions

There are many uncontrollable factors in the actual evacuation process, such as the panic of the visitors, the collision between visitors and so on. These factors can cause great difficulties in modeling, so we have idealized some factors to facilitate the establishment of the model.

- ✧ The moving speed of the visitors remains the same during evacuation.
- ✧ Visitors will choose the nearest exit to leave Louvre during evacuation.

5.1.3 Description and implement

The evacuation model is built in N two-dimensional discrete cell grids, that is, the moving area of each floor of the Louvre is divided into N equal-sized discrete cell spaces. The obstacles are used to occupy the boundary cells of the system to form a wall, and the exit is represented by a cell space on the wall. Each space location can only accommodate one visitor. The movement of the visitors is discretized into equal time steps. Within each time step, the visitors can only move the position of one cell. The visitors can choose to stay in the same place or move to one of the eight positions around them during each step. The moving area is shown in Figure 1. Visitors cannot cross the wall directly and can only leave the floor through a safe exit. When moving, the visitor will judge the moving revenue of each location in the mobile area and select the location with the largest moving revenue as his target location. The moving revenue is shown in figure 2.

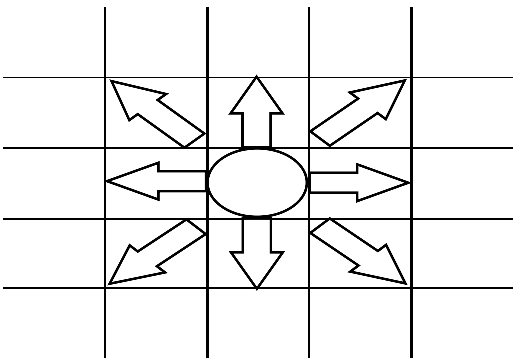


Figure1 visitor's moving

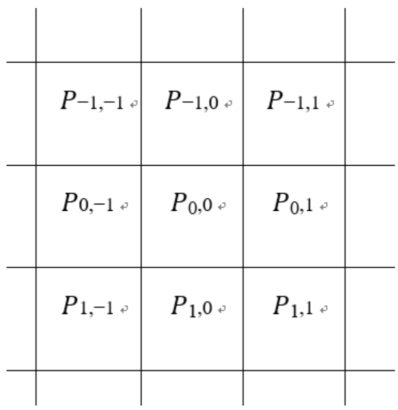


Figure2 Moving revenue

Evacuation time refers to the time it takes from the start of evacuation to the last visitor to a safe exit. Visitors have the ability to think as a social person. Visitors will adjust their movement speed and direction according to the situation around them. Since an assumption that the speed of visitors won't change, we only consider the direction change. To simplify the analysis, we constrain the movement of the visitors by introducing two parameters—direction parameters and selection parameters.

The direction parameter describes the proximity of the visitor's current location and exit. Visitors are purposeful and directional when evacuated. The purpose is to refer to the destination of the passenger's movement as a safe exit. The directionality means that the visitor will move as far as possible to the safe exit nearest to him during the evacuation process. When calculating the direction parameter, first calculate the shortest distance between the cell position and the safety exit. When there are multiple safety exits on the floor, the distance from the nearest safety exit is the shortest distance; when the width of the safety exit is larger than one cell space, the distance between the cell where the visitor is located and the nearest cell in the safety exit is the shortest distance. The distance from the position to the safety exit is shown in equation (1).

$$L_{xy} = \begin{cases} \min\limits_{m}\left(\min\limits_{n}\left(\sqrt{(x-x_n^m)^2+(y-y_n^m)^2}\right)\right) & cell(x,y)\ represents\ space \\ 1000 & cell\ (x,y)\ represents\ wall \end{cases} \tag{1}$$

In equation (1), L_{xy} represents the shortest distance between the cell(x,y) and the safety exit; (x,y) is cell's coordinate in the floor system; $(x_n^m,\ y_n^m)$ is the coordinate of the nth cell belonging to the mth gate in the system. L_{xy} equals 1000 when the cell is on the wall, which means the wall has little attraction to the visitors and the visitors are less likely to head towards wall. In the moving area where the visitor occupies the center position, the value of the corresponding direction parameter is equal to D_{ij},

$$D_{ij} = \begin{cases} \dfrac{L_{00}-L_{ij}}{1}, & Moving\ straightly,\ i+j=1,\ -1 \\ \dfrac{L_{00}-L_{ij}}{\sqrt{2}}, & Moving\ diagonally,\ i+j=0,\ 2,\ -2 \end{cases} \tag{2}$$

In equation (2), L_{00} is the shortest distance between the center cell of the area and the safety exit; L_{ij} represents the shortest distance between the cell(i,j) in the moving area and safety exit.

The selection parameters describe the likelihood that the visitor will move in all directions in the moving area. Visitors can choose to move to the empty cell , or move to the cell occupied by other visitor, or choose to stay. The value of the selection parameters E_{ij} is presented in equation (3).

$$E_{ij} = \begin{cases} 1\ empty\ cell \\ 0\ center\ cell \\ -1\ occupied\ cell \end{cases} \tag{3}$$

According to the data provided on the website the area of each floor of Louvre is about 48000 ㎡. Assuming all visitors will choose the nearest exit around them to leave, we simulate that the evacuation time and the density of visitors are in a positive linear relationship. ρ is defined as the density whose unit is number of visitors per square meter; T is defined as evacuation time whose unit is second.

The line is shown in figure 3.

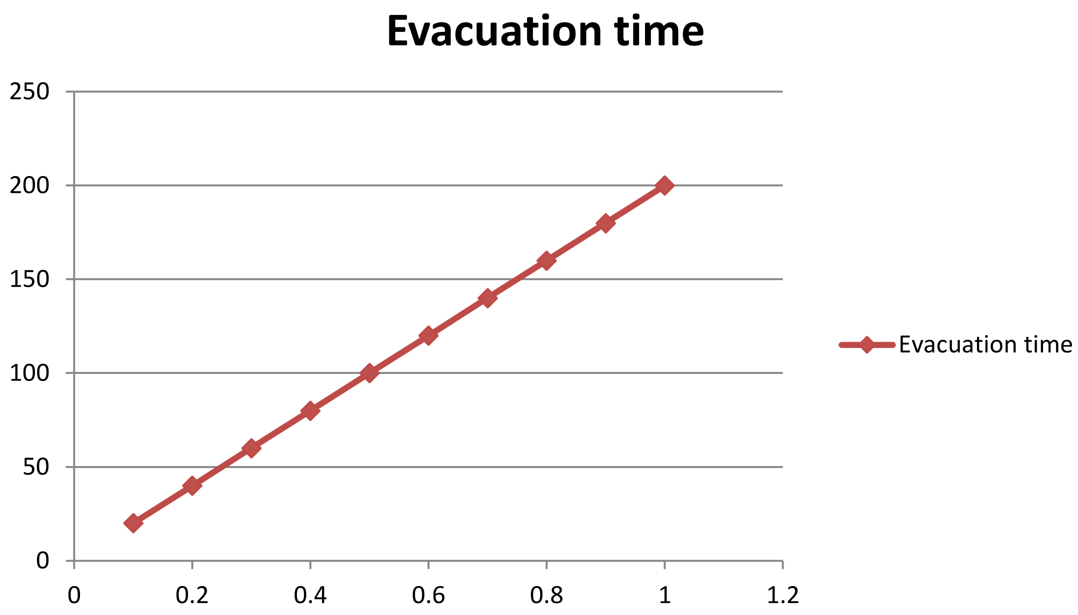


Figure3 relationship between density and evacuation time

5.1.4 Strength and Weakness

Strength

- The model is quite simple and easy to understand.
- This model is suitable in some small places.

Weakness

- When applied to large structures, the distributions of exits and there are many floors in a building, the evacuation time simulated by this model may not be accurate or even invalid.

5.2 Evacuation Model Based on Uniform distribution of Personnel

5.2.1 Model Introduction

Considering the weaknesses of evacuation model based on cell automata, we are going to replace it with uniform distribution model.

5.2.2 Model Assumption

- ✧ Visitors are evenly distributed.
- ✧ Every visitor moves at the same speed.
- ✧ Every floor in Louvre has the same area.

5.2.3 Description and implement

In emergency evacuation state, the optimal path is not the shortest path. Taking the congestion situation into account, choosing the longer but smoother path may help evacuating faster. Therefore, the visitor density becomes the decisive factor of the evacuation time. The number of visitors in a certain area is $N_i = \rho_i \cdot s_i$ where s_i represents the area of the zone under investigation, and ρ_i represents the density of visitors in the zone under examination. Since the visitors are evenly distributed in this model, ρ_i is a constant and is recorded as ρ, and the number of visitors in a certain area is $N_i = \rho \cdot s_i$.

Since the stairs leading to the exit of the Louvre are only on the -2 floor, visitors who are not on the -2 floor should move to the downward staircases of the floor. Assuming that the number of staircases on nth floor is m which is recorded as m_n, then for the nth floor, the optimal solution for evacuation should be "having the total evacuation time of each staircase be the same". Under the circumstances that the evacuation speed of every visitor is equal, the optimal scheme above can be expressed as "making maximum people capacity of each staircase the same as others'. " for a certain floor (such as the nth floor), there are m_n available staircases, and the evacuation plan needs to satisfy the following equation:

$$N_1 = N_2 = \cdots = N_m$$

Since $N_i = \rho_i \cdot s_i$, then the formula above can be converted into

$$\rho_1 \cdot s_1 = \rho_2 \cdot s_2 = \cdots = \rho_m \cdot s_m$$

Since it is assumed that each floor of visitors is evenly distributed, the formula above can be converted into

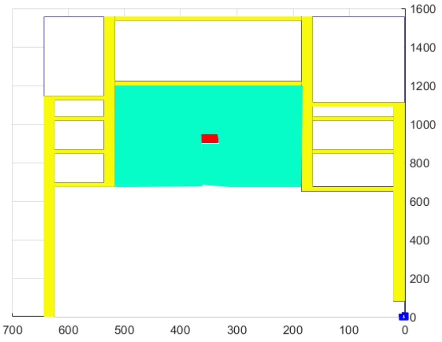
$$s_1 = s_2 = \cdots = s_m = s$$

The above formula indicates that the optimal solution requires that the assigned area of each staircase on the nth floor should be equal. If there are m_n available staircases on the nth floor, the assigned area of each staircase is $\frac{A}{m_n}$, where A is the total area of the corridor on each floor of the Louvre. The Louvre building covers an area of 48000 ㎡, so A=48000 ㎡.

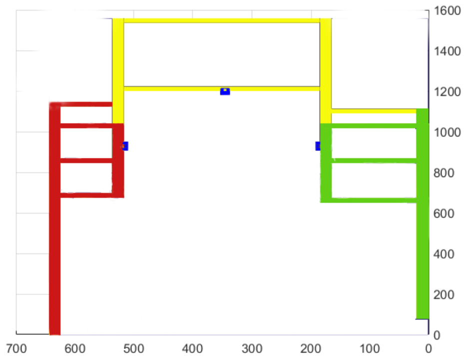
n	m	s(㎡)
2	2	24000
1	6	8000
0	2	24000
-1	3	16000

-2	1	48000

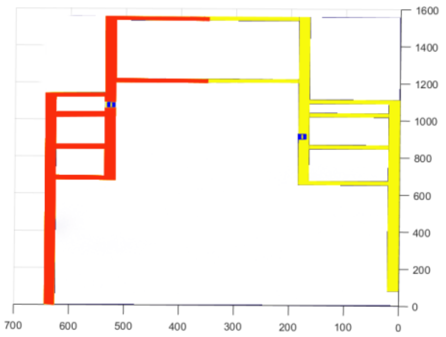
According to the area of each stairway calculated by the above table, draw an aliquot of each floor area to obtain the evacuation distribution scheme as shown in the following figure:



-2



-1



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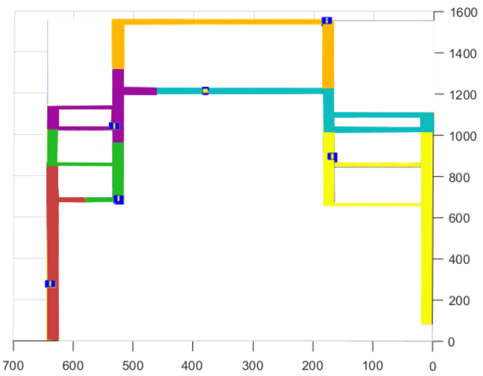
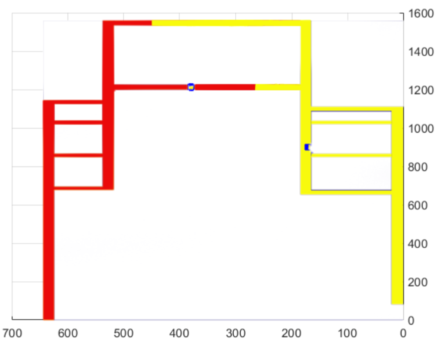


1



2

In the above results, the different colors represent the evacuation area assigned to each stairway (exit), that is, the staff in the same color area should guide the visitors to the staircase in the certain area.

Strength and Weakness

- We consider the congestion of each staircase, the marginal congestion is equal.

However, the model is too ideal because "The personnel are evenly distributed" often does not exist in real life. So this model is not quite practical.

5.3 Evacuation Model based on Probability Distribution

5.3.1 Model Introduction

To overcome the disadvantages of the model based on uniform distribution, we develop a model based on probability distribution of people.

5.3.2 Model Assumption

✧ Every visitor has the same evacuation speed

5.3.3 Description and Implement

Based on the analysis of the above model (the evacuation model under the uniform distribution of visitors), we break the hypothesis that "assuming visitors are evenly distributed" in the above model, which is inconsistent with reality, that is to say, in this model, visitors can be randomly distributed on the floor. We define that the distribution of visitors on the nth floor is δ, then for a given zone, the number of visitors in this area is a function of the area of the particular zone, which is expressed as $N_i = \delta(s_i)$, where s_i represents the area of the zone under investigation.
For the plan maker, there is a must to solve a problem: "How staff in different zones the visitors to different directions." So for plan maker, they need to allocate the pavilion area so that the staff knows how to guide the visitors correctly, which means we need to calculate s_i and the corresponding area for each staircase.

In the previous model, we pointed out that for the nth floor, the optimal solution for evacuation should be "Making evacuation time of each staircase the same as others'". This conclusion is still applicable in this model since we have assumed that each visitor has the same evacuation speed, this optimal solution can be converted into "for the m_n staircases on this floor, making the number of people at each stairway equal". Assuming that there are a total of P_n people on the nth floor, the number of people that every staircase on this floor need to hold is $\frac{P_n}{m_n}$.

From the above we conclude that for a given area, the number of visitors in this area is a function of the area of the particular zone, which is expressed as $N_i = \delta(s_i)$, where s_i represents the area of the zone under investigation. If the inverse function of δ is ϕ, then we have $s_i = \phi(N_i)$, where N_i represents the number of visitors in the area investigated. **The inverse function ϕ changes with the change of the original function δ, and the original function varies with the distribution of visitors. Therefore, in the real application, the original function δ and inverse function ϕ are determined and adjusted according to the distribution of the visitors.**

Based on the above model, we conclude that the Louvre's evacuation allocation scheme is as follows:

Floor n	Number of staircase m_n	Capacity $\frac{P_n}{m_n}$	$staircase\ area\ s_m = \phi(N_m)$(㎡)
2	2	$\frac{P_1}{2}$	$\phi(\frac{P_1}{2})$
1	6	$\frac{P_2}{6}$	$\phi(\frac{P_2}{6})$
0	2	$\frac{P_3}{2}$	$\phi(\frac{P_3}{2})$
-1	3	$\frac{P_4}{3}$	$\phi(\frac{P_4}{3})$
-2	1	$\frac{P_5}{1}$	$\phi(\frac{P_5}{1})$

P_n represents the number of visitors on the nth floor. The requirement of this model is to determine the number of visitors and the distribution of visitors on each floor in real time. In order to achieve this goal, some technical support is needed. For example, we can use APP to locate the location information of the visitors to adjust the visitor distribution function timely.

5.3.4 Strength and Weakness

Strength

In general, this model is extremely adaptable and is manifested in the following aspects:

- Applicable to the status of any visitor distribution, more suitable for the real situation.
- It can be adapted at any time of day or year.
- It can adapt to a structure with different floors.

Weakness

- We need some complex technology to locate the position of every visitor in order to update the distribution of visitors timely.

5.4 Positioning Technology based on APP to guide Evacuation

5.4.1 Model Introduction

According to the problem listed, we can combine APP with our model to help executing our evacuation plan.

5.4.2 Model Assumption

- ✧ Most of the visitors use relating APP in their smart phone.

5.4.3 Description and Implement

Based on the analysis of the above model, we can apply the model to any structures and any time period, but we need to know the current distribution of visitors. In order to meet the requirements of this data collection, we can locate the visitors and get the t detailed distribution of visitors in the structure.

We use a computer to simulate the distribution of visitors represented by the positioning information of the visitors when the visitors use the APP. The distribution is shown in figure 5.4.1 below:

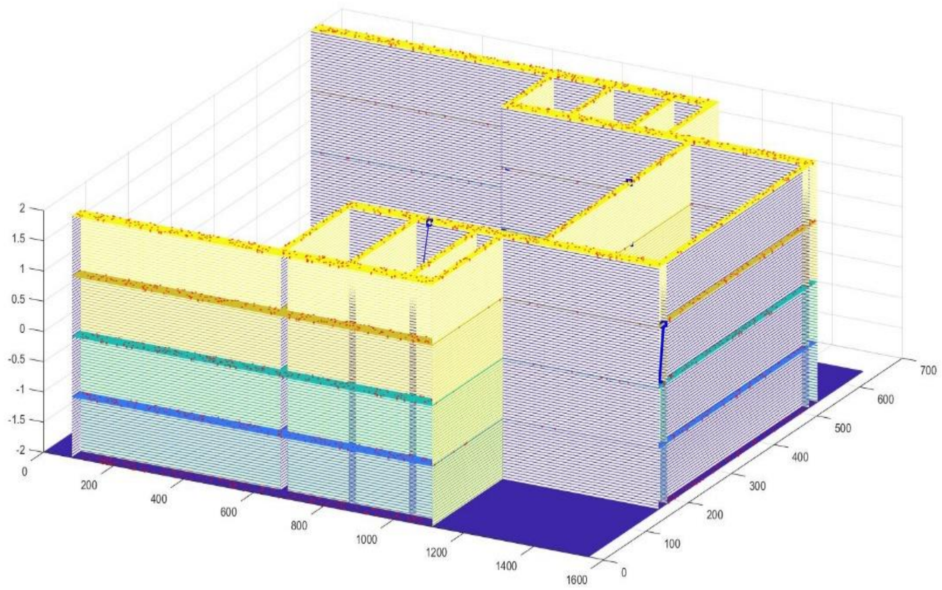


Figure 5.4.1 Distribution of Visitors

In the model above, the dense red dots represent the visitors. From this three-dimensional model, the location information of the visitors can be clearly seen. Meanwhile, the distribution of the visitors is also obtained, and the previous model can be used to calculate the evacuation area and evacuation method.

At the same time, the use of APP helps the planner to make their evacuation plan. In realistic evacuation process, the planner can also convey the visitors distribution information and make evacuation guidance to the visitors through the APP, reducing the information asymmetry between the visitors and the planner, effectively avoiding the game dilemma such as the prisoner's dilemma, so that the evacuation of the museum is coordinated with the visitors' self-escape, and the overall evacuation efficiency is improved.

5.4.4 strength and Weakness

Strength

- ➢ The positioning technology is used to provide planners with large data support for determining the distribution of visitors and provides the distribution parameters for the planners to use the previous model to solve the evacuation allocation problem.
- ➢ APP provides a platform for information communication between visitors and planners, reducing information asymmetry between visitors and planners.

5.5 Evacuation through extra exits

5.5.1 Model Introduction

The pyramid entrance is the main and most used public entrance to the museum. However, there are also three other entrances usually reserved for groups and individuals with museum memberships. When making evacuation plan. Additionally, there are some exits which only museum officials and emergency personnel know exist. we should utilize these three channels properly.

5.5.2 Model Assumption

- ✧ Visitors cannot find these exits without the guidance of the staff.
- ✧ Each floor has a special exit (or special staircase).
- ✧ Assuming that there are special exits around each stairway.

5.5.3 Description and Implement

According to all the above models, the optimal visitor escape guidance allocation scheme is solved, and the distribution plan is adjusted timely according to the visitor positioning, and the escape direction of the visitors can be achieved in a balanced state for a period of time. However, if the population density of a certain stairway in the short-term is significantly higher than the average population density of the floor, block will occur. In order to alleviate the evacuation pressure of the stairway visitors in a short period of time and improve the overall evacuation efficiency, we consider opening the stairway with significant congestion. The nearby dedicated passage provides a diversion function to relieve the evacuation pressure of visitors in a short period of time.

When a new exit is opened, the distribution plan for the evacuation route will be redistributed. Assuming that a dedicated channel is opened at Layer 2, the original allocation scheme will be broken, forming a new allocation scheme:

State	Floor n	Downward stairs m_n	Capacity of stair $\frac{P_n}{m_n}$	Assigned area of stair $s_m = \phi(N_m)$(㎡)
Closed special channel	2	2	$\frac{P_1}{2}$	$\phi(\frac{P_1}{2})$
Opened special channel	2	3	$\frac{P_2}{3}$	$\phi(\frac{P_2}{3})$

It is worth noting that although the opening of special channels can alleviate the pressure of more congested stairways in the short term, it also leads to the redistribution of visitor flows. In this redistribution process, more uncertain factors will appear on the one hand, leading to safety. On the other hand, if the visitors' redistribution process is affected by irrational factors, it will lead to the emergence of new congested staircases. In other words, "to solve a problem and bring new problems." Therefore, opening up new exits requires careful consideration.

5.5.4Strength and Weakness

Strength

- Reducing the evacuation burden.

Weakness

- Once new exits are opened, the balance of existing visitor distribution will broken, the distribution of visitors will be redistributed, and the process of redistribution will create new uncontrollable factors.

5.6 Evacuation model of different floors

5.6.1 Model Introduction

Louvre has five floors in all, in the previous part we have discussed the evacuation model on the same floor. So it's time for us to design the model of different floors to make our evacuation plan more practical.

5.6.2 Model Assumption

- ✧ Assuming that the corridors in the pavilion are of equal width, the length are all 10 meters.
- ✧ The structure of each floor is the same

5.6.3 Description and Implement

Personnel flow distribution

At the place where people meet, priority is given to evacuating the evacuated personnel on the higher floors (which take longer).

At the place where people meet, on the basis of "successful saturation of higher floors (longer time-consuming evacuation personnel and shortest path in the same floor), it is also necessary to ensure uninterrupted flow of personnel at each level (personnel flow is not less than 1).

The upper floors on the public roads (longer evacuation time) are preferred, and the floors with short evacuation time are waiting for the evacuation of the high floors to evacuate. Set F to the floor set, F=$\{f_n\}$; $R_m^{f_n}$ is the path set of the f_n floor, where m is the path note; the longest evacuation time costed by the f_i floor is T^{f_i}, The longest evacuation time costed by f_j floor is T^{f_j}, the shortest evacuation time costed by the f_i floor is T_{f_i}, and the shortest evacuation time costed by the f_j floor isT_{f_j}. Then the flow distribution of people is as follows:

$$\begin{cases} p_m^{f_i} > p_m^{f_j}, & T^{f_i} > T^{f_j} \\ p_m^{f_i} < p_m^{f_j}, & T^{f_i} < T^{f_j} \end{cases}$$

When priority is given to the same level of shorter path evacuation:

$$\begin{cases} \sum_{t=1}^{\infty} p_i^{f_n}(t) > \sum_{t=1}^{\infty} p_j^{f_n}(k), & T_i^{f_n} > T_j^{f_n} \\ \sum_{t=1}^{\infty} p_i^{f_n}(t) < \sum_{t=1}^{\infty} p_j^{f_n}(k), & else \end{cases}$$

Personnel flow at any path is not zero at any time:

$$p_m^f(t) \neq 0$$

T represents the instantaneous moment during the evacuation.

Step of model algorithm

1. When Initializing, the floor set is F, F = $\{f_n\}$, the group of people to be evacuated is P, the passage time of each arc is t_{ij}, and the staff capacity at any time is c_{ij}.

2. First find all feasible pathsR_m^f for each floor, where m is the path number of the fth floor and sort according to the length of the evacuation time, $T_m^f = \sum t_{ij}, T_1^f \leq T_2^f \leq \cdots \leq T_m^f$.

3. The input parameter starts with ϕ, m=1.

4. Using the idea of a single source point model to determine the set of paths that can actually participate in the evacuation R = $\{R_m^f\}$, the evacuation time T = $\{T_m^f\}$, the personnel flow P = $\{P_m^f\}$.

5. When reaching the highest level f_n, the longest evacuation time of the building is recorded as: T^{f_n}, $T^{f_n} = \max\{T^{f_n} \mid f_n \in F\}$, otherwise move to Step 4.

6. Update the path personnel flow, $p_m^f(t) = \begin{cases} p_m^f, & T_{f_n} \leq t \leq T^{f_n} \\ 0, & else \end{cases}$, T = T − $\{T^{f_n}\}$、P = P − $\{P_m^f\}$.

7. The shortest path of the f_n floor is $R_m^{f_n}$ and the other arbitrary floor path is $R_m^{f_i}$. If there is no common road between the two paths, that is, the set $\{e_{ij} \mid e_{ij} \in R_m^{f_n} \cap R_m^{f_i}\} = \emptyset$, the personnel flow is independent, and can be handled according to the

evacuation model of single source point, $p_m^f(t) = \min\{c_{ij} | e_{ij} \in R_m^f\}$; otherwise, move to step 8 for common road segment Personnel flow distribution.

8. Assuming that the evacuation starts from the paths $R_m^{f_i}$ and $R_m^{f_j}$, both paths belong to the feasible path set. The escape times of the two paths are $T_m^{f_i}$ and $T_m^{f_j}$, respectively. For these two paths, if $T_m^{f_i} \geq T_m^{f_j}$, the f_i floor personnel should be evacuated first. Then we discuss the specific situations of evacuation personnel flow $p_m^{f_i}$ and $p_m^{f_j}$: When $t < \min(T_m^{f_i}, T_m^{f_j})$, , $p_m^{f_i} = 0$ and $p_m^{f_j} = 0$, both paths are unmanned, and evacuation ends; when $T_m^{f_j} \leq t \leq T_m^{f_i}$, $p_m^{f_i}(t) = 0$, only the path starting from the f_j floor is evacuated, $p_m^{f_j}(t) = \min\{c_{ij} | e_{ij} \in R_m^{f_j}\}$; Similarly, when $T_m^{f_i} \leq t \leq T_m^{f_j}$、$p_m^{f_j}(t) = 0$、$p_m^{f_i}(t) = \min\{c_{ij} | e_{ij} \in R_m^{f_i}\}$; When $\max\{T_m^{f_i}, T_m^{f_j}\} \leq t \leq T_m^{f_i}$, both paths are evacuated, and the flow of personnel is their respective flows, $p_m^{f_j}(t) = \min\{c_{ij} | e_{ij} \in R_m^{f_j}\}$、$p_m^{f_i}(t) = \min\{c_{ij} | e_{ij} \in R_m^{f_i}\}$; If the f_i floor and the f_i floor appear the road section personnel congestion, the congestion path$c_{ij} = \left\{p_m^{f_i}(t) + p_m^{f_j}(t) \middle| p_m^{f_i}(t) \geq p_m^{f_j}(t) \& p_m^{f_j}(t) \geq 1\right\}$.
9. The algorithm ends, and finally the path set, the human flow set F, and the evacuation time set T are respectively output.

The Louvre has 5 floors and only has an exit to the pyramid on the -2 floor. Therefore, during the evacuation process, people on all floors must first reach the -2 floor and then leave the Louvre through the -2 floor. Its stair distribution modeling diagram is shown in figure 5.6.1below:

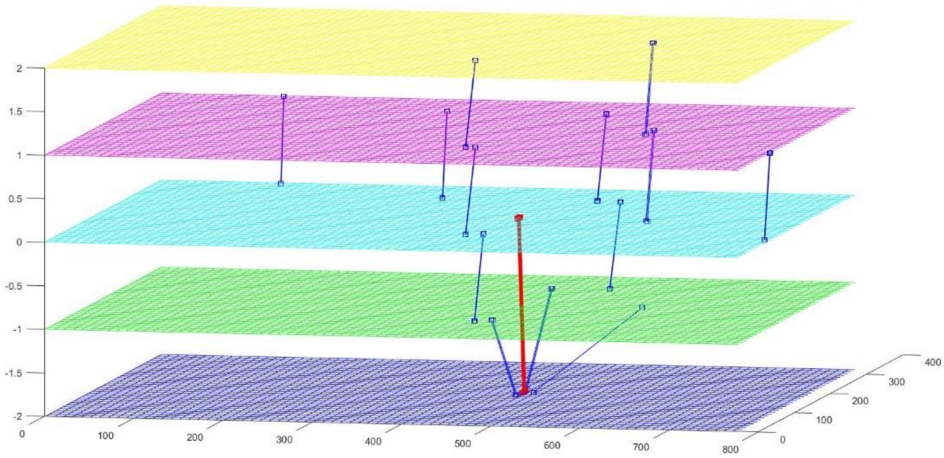


Figure 5.6.1 stair distribution

In each floor, since all visitors are concentrated on the stairs of this floor, and the intersection between different floors can only rely on stairs, we regard each stairway as the starting point of evacuation, denoted as ST, and Each node is numbered, and each arc segment is numbered in the form of (arc capacity, transit time), and the transit time here is the time without considering the common road segment. The network diagram is shown in figure 5.6.2

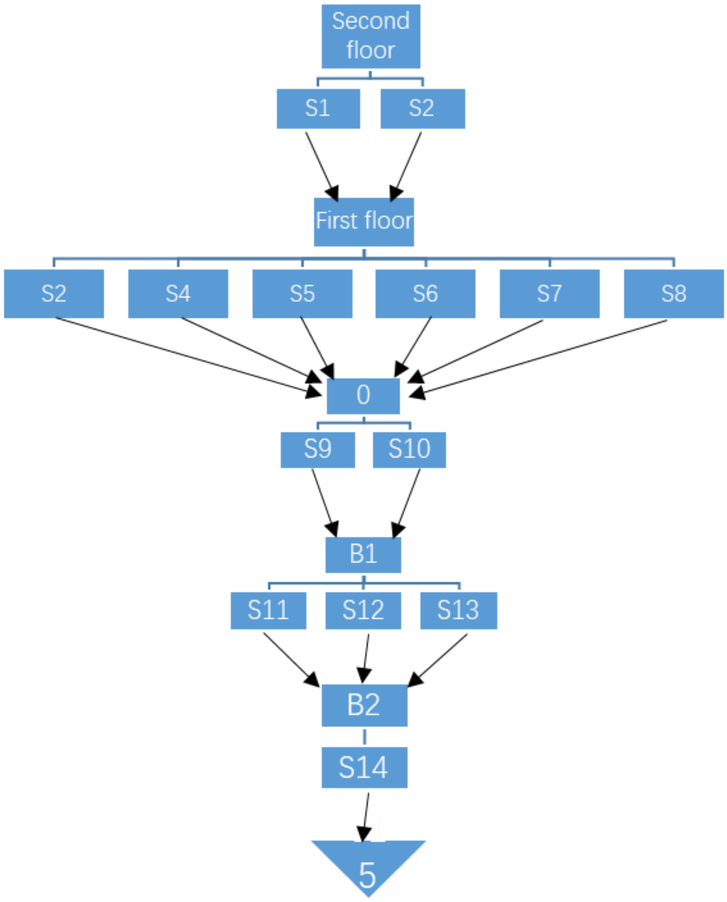


Figure 5.6.2 Net diagram

When calculating the intersection of tourists between floors in a certain floor according to the “Evacuation Model Based on Tourist Distribution”, we start our analysis with the above network map, using the algorithm flow calculation of this model and combining it with the evacuation model of the interior of the floor, to conclude The shortest evacuation time.

5.7 Evacuation of special people

5.7.1 foreigners

Under the current trend of globalization, the diversity of language becomes a critical factor affecting guide staff to guide visitors. Ensuring smooth communication with visitors can make the evacuation process more coordinated and improve evacuation efficiency. In order to achieve this goal, the conventional practice is as follows: First, the staff can be equipped with multi-language translation tools, and second, multi-language support can be provided in the APP.

For some foreigners who speak small languages, because this group of people is a minority among all visitors, and they are not easy to get timely and effective communication, they can be guided to evacuate them on the temporary open channels at each level.

5.7.2 Disable People

Due to the slow speed of the disabled in the evacuation process, the disabled in the crowd will not only result in a slower evacuation of the visitors, but also lead to safety events such as pedaling. Since the number of disabled people is not large, people with disabilities should be guided to enter the special exits and they should not be allowed to escape with ordinary visitors.

5 Strength and Weakness of model

5.1 Strength

- The evacuation model described in this paper is not limited to a specific building structure. It can be changed with the distribution of people in the building, so it is highly adaptable.
- The model considers the help of technology in evacuation. Using APP can not only help planners understand the real-time distribution of tourists, but also facilitate the planners to correctly guide the evacuation of tourists. It also helps tourists to understand their own situation and independently find

the best solution for their escape. , reducing information asymmetry, making the evacuation between tourists and planners more coordinated, and improving the efficiency of evacuation.

- The model reveals that although the opening of new exports can improve the efficiency of escape in a short period of time, it also breaks the original law of distribution balance, causing the re-flowing of people in the building and increasing the uncertainty of the system. Therefore, the administrator is advised to cautiously open special exports when evacuating personnel.
- This model considers the evacuation of special groups such as disabled people. Because the mobility of disabled people is weak, it will affect the overall evacuation efficiency of the system. Therefore, managers should provide special exports to groups with weak mobility such as disabled people during evacuation.

5.2 Weakness

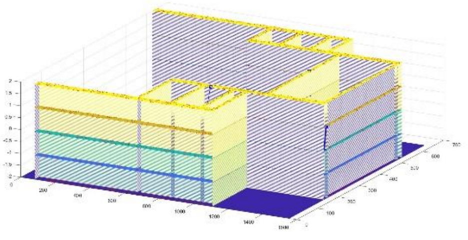
- The model requires managers to know the distribution status of the people in the building timely, so the requirements for actual data collection are harder, and the management cost is increased.
- In the model of evacuation at different levels, the situation that the evacuation speed of the upper-level personnel is slowed down due to the congestion of the public road section is not considered, so there is a certain gap with the reality.

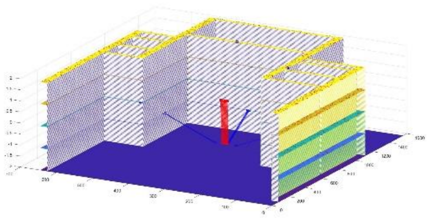
7 Implementation and Results

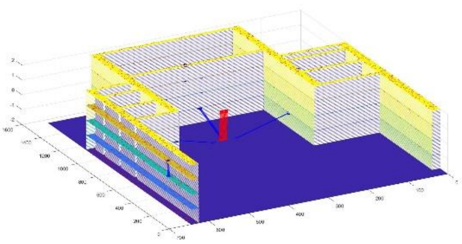
Based on the analysis above, we use the evacuation model of the known visitors distribution when solving the Louvre visitor evacuation plan, and assume that most visitors use the APP to provide his location information, while considering special visitors (such as disabled people and foreigners, etc.)), and the planners who organize the evacuation will temporarily open the secret channel as needed. For the intersection between different floors, we use the above-mentioned "evacuation model between different floors" to solve. All of the above models are combined to solve the best escape time of the Louvre.

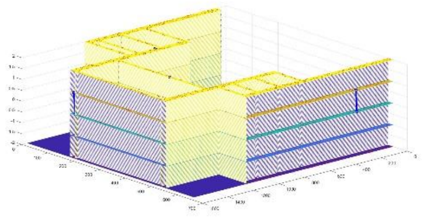
The Louvre's overall building is "U" shaped and covers an area of 24 hectares. The building covers an area of 4.8 hectares. According to statistics, the Louvre Museum covers an area of 19 hectares including the courtyard. It lie on the right bank of the Seine from east to west. The length of both sides is 690 meters. The east facade is about 172m long and 28m high.

By looking up the information, it is necessary to go to the second floor of the building to escape to the pyramid exit. The stairs are 3m wide and the corridor is 10m wide. Create a 3D model through matlab, as shown below:









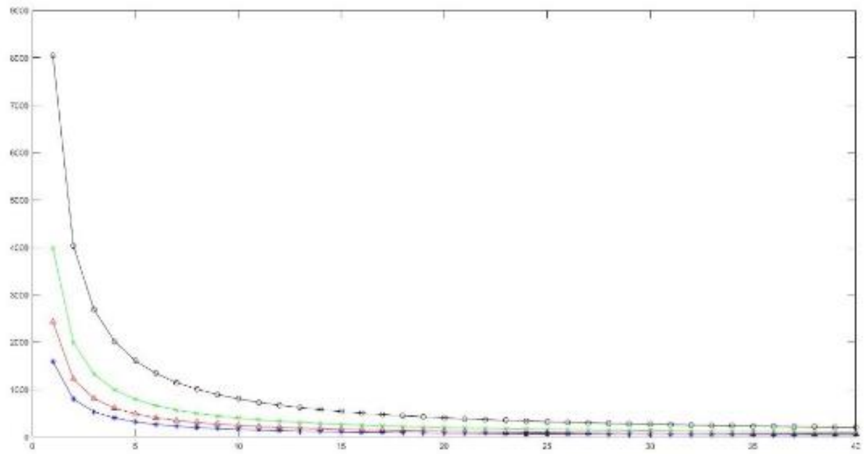
The dense red dots in the red indicate the use of computers to simulate the distribution of visitors.

We set the total visitor speed of the corridor to v_i. The corridor width and the visitor speed can estimate the maximum flow capacity of the corridor. The passage time of the visitors is introduced for the length of the stairs and the corridor. It is assumed that there are 12,000 visitors in the Louvre. Bringing the above information and parameters into the above model, the total escape time of the Louvre is 243 seconds based on the above optimal evacuation scheme.

8 Sensitivity Analysis and Promotion

.8.1 Width of Safety Exit and corridor

Regardless of the distribution plan, the width of the safety exit plays a decisive role in the evacuation time, because the width of the safety exit directly determines the evacuation speed of the visitor. For our model, the width of the safety exit has a direct impact on the model's results. Secondly, the width of the corridor is also decisive for the results of our model. Therefore, we perform sensitivity analysis on the width of the safety exits an corridors.



8.2 Promotion

For any building, the above model can be used, and tools such as APP can be used to locate the visitors in the building and track their location information to adjust the distribution of people in the building in real time.
At the same time, it should be clarified that although the opening of special exports can alleviate the pressure of an export in the short term, it also breaks the original distribution balance and leads to more uncertainty because of the newly opened exports, which makes the redistribution of the evacuated population. Increased system security risks, so special exits should be opened cautiously.
For groups with weak mobility, such as special people, especially disabled people, their involvement in evacuation of buildings will seriously affect the evacuation speed of personnel, and may even lead to safety accidents such as stepping on. In order to avoid such risks, planners evacuated within buildings should try to provide additional special exits for people with weaker mobility, not only to ensure the safety of special populations, but also to make evacuation of most people more efficient.
For the evacuation between different levels of people, our “evacuation model between different layers” has certain universality, so for any building, the algorithm of this model can be used to plan the optimal allocation scheme between floors.
Since the safety exit and corridor width have a direct decisive effect on the evacuation time, these two quantities should be adjusted as the parameters vary with the building. Under other conditions, they have a certain functional relationship with the evacuation time. Therefore, all of the above models are still applicable in different building parameters.

9 Reference

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10 Appendix

```
clear;
tic;

Louvre = zeros(322*2,778*2,5)-2;
for f = 2:5
    Louvre(1:10*2,41*2:555*2,f) = f-3;
    Louvre(7*2:92*2,327*2:336*2,f) = f-3;
    Louvre(83*2:92*2,333*2:778*2,f) = f-3;
    Louvre(7*2:86*2,546*2:555*2,f) = f-3;
    Louvre(93*2:258*2,601*2:610*2,f) = f-3;
    Louvre(265*2:322*2,563*2:572*2,f) = f-3;
    Louvre(313*2:322*2,1:566*2,f) = f-3;
    Louvre(259*2:268*2,338*2:778*2,f) = f-3;
    Louvre(93*2:258*2,769*2:778*2,f) = f-3;
    Louvre(265*2:316*2,510*2:519*2,f) = f-3;
    Louvre(265*2:316*2,424*2:433*2,f) = f-3;
    Louvre(265*2:316*2,338*2:347*2,f) = f-3;
    Louvre(11*2:82*2,510*2:519*2,f) = f-3;
    Louvre(11*2:82*2,424*2:433*2,f) = f-3;
end

% stair
% ----
% r0, c0, f0
% r1, c1, f1
```

```
% ----
% [-2 -1]
stair(:,:,1) = [159*2 463*2 -2; 93*2 463*2 -1];
stair(:,:,2) = [187*2 463*2 -2; 258*2 463*2 -1];
stair(:,:,3) = [172*2 478*2 -2; 172*2 600*2 -1];
% [-1 0]
stair(:,:,4) = [262*2 527*2 -1; 262*2 539*2 0];
stair(:,:,5) = [88*2 446*2 -1; 88*2 456*2 0];
% [0 1]
stair(:,:,6) = [83*2 438*2 0; 83*2 449*2 1];
stair(:,:,7) = [88*2 771*2 0; 88*2 777*2 1];
stair(:,:,8) = [170*2 605*2 0; 190*2 605*2 1];
stair(:,:,9) = [265*2 512*2 0; 265*2 522*2 1];
stair(:,:,10) = [261*2 340*2 0; 261*2 345*2 1];
stair(:,:,11) = [318*2 136*2 0; 318*2 139*2 1];
% [1 2]
stair(:,:,12) = [83*2 438*2 1; 83*2 449*2 2];
stair(:,:,13) = [170*2 604*2 1; 190*2 604*2 2];
% [0 -2]
stair(:,:,14) = [170*2 461*2 0; 170*2 467*2 -2];

figure('Name', '卢浮宫-3D 图')
for k = 1:5
    mesh(Louvre(:,:,k),'LineStyle',':')
    hold on
end
f = 1;
for k = 1:10000
    yi = randi(322*2);
    xi = randi(778*2);
    if Louvre(yi,xi,f+1) == f-2
        plot3(xi,yi,f-3,'.r')
        hold on
    end
end
for f = 2:5
    for k = 1:10000
        yi = randi(322*2);
        xi = randi(778*2);
        if Louvre(yi,xi,f) == f-3
            plot3(xi,yi,f-3,'.r')
            hold on
        end
    end
```

```
end
for k = 1:size(stair,3)-1
	plot3(stair(:,2,k),stair(:,1,k),stair(:,3,k),'-sb')
	if stair(1,2,k)==stair(2,2,k)
		for n = 1:5
			plot3(stair(:,2,k)+n,stair(:,1,k),stair(:,3,k),'-sb')
		end
	end
	if stair(1,1,k)==stair(2,1,k)
		for n = 1:5
			plot3(stair(:,2,k),stair(:,1,k)+n,stair(:,3,k),'-sb')
		end
	end
end
plot3(stair(:,2,k+1),stair(:,1,k+1),stair(:,3,k+1),'-sr')
for n = 1:19
	plot3(stair(:,2,k+1),stair(:,1,k+1)+n,stair(:,3,k+1),'-sr')
end
hold off
toc;
```