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2020
MCM/ICM
Summary Sheet

Louvre Emergency Evacuation Optimization Plan

Summary

Since the 21st century, terrorist attacks have intensified. As a famous attraction in France and the world, the research on Louvre's emergency evacuation program has far-reaching guiding significance for the establishment of emergency evacuation programs for large public facilities in the world.

In order to establish an emergency evacuation model, we analyze the psychological and behavioral characteristics of tourists, the impact of different disasters, and the impact of different population characteristics and density. For the emergency evacuation problem of multi-floor complex buildings, our model is divided into intra-floor models and inter-floor models.

Our intra-floor model consists of the security response zone division model and real-time path planning model based on network.

In the Security Response Zone Division Model, the size of the security response zone(SRZ) is related to the number of visitors in the area and the properties of the passage. We use the goal planning method to calculate the total evacuation time as our objective function to determine the size of the SRZ corresponding to different exits or stairways. Meanwhile, calculating the objective function, we could get the minimum total time for evacuation in a floor.

In the Real-time Path Planning Model Based on Network, the doors are regarded as the nodes. We define the congestion factor, the risk factor, and the corridor length as three factors that influence the evacuation of tourists. The equivalent length, which is based on the three factors, can more accurately reflect the time and the safety of the evacuation of tourists. Therefore, the optimal path with the minimum equivalent length is chosen as the target.

For the establishment of the inter-floor model, the structure of the network is used to calculate the flow distribution of the human flow after passing through different nodes and edges. According to the real-time traffic time image, we can effectively avoid the occurrence of over-aggregated during the evacuation process.

Finally, we offer a range of solutions that can be combined with our emergency evacuation program to deal with difficult situations, such as how to effectively evacuate small language visitors, how to arrange rescue workers to enter the venue as soon as possible, and so on.

Key Words: Security response zone, Equivalent length, Network, Emergency evacuation program

Contents

1 Introduction

1.1 Background

With the increase in terrorist attacks in recent years, the world is committed to preventing terrorist attacks. However, god's way is higher than man's. The number of deaths due to terrorist attacks is still increasing in the worldwide. As a result, reviews of many popular attractions should be put on the agenda.The Louvre is the world's largest and most visited art museum , any exhibit in it can be said to be the treasure of the world. Its fame also makes it easier to be the target of attack, so it becomes a hot discussion topic to provide a reasonable emergency evacuation plan for Louvre.

1.2 Restatement

When we consider the evacuation of the Louvre, we need to consider the time and route of evacuation of different tourists. In order to evacuate visitors from the museum, while also allowing emergency personnel to enter the building as quickly as possible, we are required to answer the following questions.

- Develop an emergency evacuation model which should evacuate the visitors from the museum, while also allowing emergency personnel to enter the building quickly.
- The model should be an adaptable model.
- Consider the number of visitors and the diversity of visitors when implement our model in Louvre
- Consider carefully when and how any additional exits might be utilized.
- Propose some policy and procedural recommendations for emergency management of Louvre and implement our model for other large,crowd structures.
- Think how technology, such as apps like *Affluences*, or others could be used to facilitate our evacuation plan.

1.3 Literature Review

At present, the terrorist attacks in France are increasing and the security situation is becoming increasingly serious. The Louvre is the most visited museum in the world. Therefore, it is necessary to pay great attention to the evacuation of personnel. At present, there is much literature on the issue of evacuation of people, and the method is relatively mature. There are even professional software that can simulate the evacuation of personnel, such as $Pathfinder$ and $Anylogic$.

For the evacuation of personnel, the widely used method is to use a cellular automaton. Such as [8]and[7]. In fact, the model built by the cellular automaton has many shortcomings. For example, the grid division makes it impossible to slant, so that the moving distance increases a lot. There are also some models that use BIM and dynamic planning to provide a more reasonable idea of the problem, such as [2]and [6]. Some people have taken a different approach and analyzed the behavior and psychology of people in the fire. They can also propose effective and valuable measures to help us solve the problem of evacuation, such as [1]. There are also some literature that directly simulate human behavior. They have made some common models that can be used for people and solved the problem of crowd evacuation, such as [4] and [5].

1.4 Our Work

The overall objectives of our model is listed as follows:

1. Design a pragmatic function for the movement of people.Meanwhile,set a reasonable objective function to accurately calculate the total minimum time for people on each floor to complete the evacuation and thereby divide the area to several safety response zone that each exit can radiate
2. By abstracting the topographic map of each floor into an undirected network, we plan the best way for people on this floor to get to the designated exit.
3. Inter-floor Sorting Model is established to visually describe the PF after superimposed on two floors
4. In order to make our model more convincing and adaptable, we have also made a number of recommendations for managers of the place where emergency occurs, which involve all aspects of an evacuation.
5. We validate our models and discuss how the Louvre would implement it.

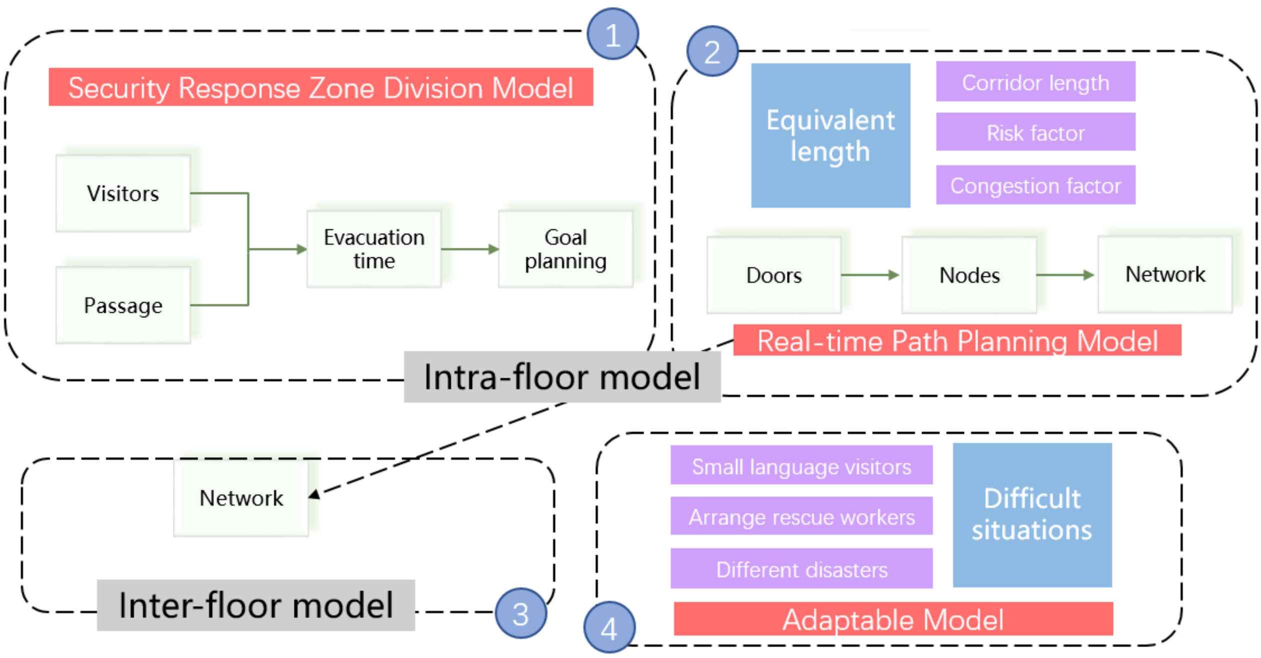

Figure 1: Our Work

2 Preparation of the Models

2.1 Assumptions

- **We assume that the official evacuation instructions have a strong guiding effect on tourists.**

Justification: from a psychological point of view, when a security incident occurs, people are affected by panic and fear, and at this time, authoritative guidance is extremely needed.

- **We assume that the elevator is not used by normal people during emergency evacuation.**

  Justification: based on case studies of security incidents and inquiries from professionals, the use of elevators increases safety hazards when security incidents occur

- **We assume that everyone on the same floor knows an emergency at the same time.**

- **We assume that staircase can be used as escape routes in any case .**

2.2 Terminology

PF: It is defined as the people flow, which is the number of people who pass the effective section per unit time.

SRZ: It is defined as the safety response zone, which divides a floor into different evacuation areas.

2.3 Notations

The primary notations used in this paper are listed in **Table 1**.

Table 1: Notations

Symbol	Definition
F	The export capacity
T_e	The time for evacuation
ω_{ij}	The equivalent coefficient in the node
k	The hazard index to evaluate the danger degree
Δ	The acceptable group number

3 Security Response Zone Division Model

3.1 Model Overview and Analysis

When security incidents occur in large public places such as museums, it is highly prone to tourists' conflicts, trampling, and casualties due to intensive tourists and disordered orders. Therefore, when we establish an emergency evacuation plan for the Louvre, we must first divide the Security response zone (SRZ)for each of its floors. The division of the SRZ is set according to the exit location and the regional tourist density. When a security incident occurs, the visitor security personnel and staff guide the tourists to evacuate as soon as possible in the SRZ, and avoid cross-regional evacuation activities to reduce the occurrence of tourist conflicts, improve the efficiency of evacuation, and ensure the safety of tourists.

3.2 Model Construction

3.2.1 Security Response Zone Model

In order to avoid the occurrence of tourist conflicts as much as possible, we establish our zoning model according to the two principles of safety and efficiency. The number of the SRZs is equivalent to the number of exports. We use the shortest evacuation time as the objective function to build a programming model.

Considering the actual situation, we use a combination of experience zoning and real-time adjustment when zoning. Because it is difficult and inefficient to quickly and accurately divide the security response zone model(SRZ) when a security incident occurs. It is necessary to divide the reasonable standing SRZ according to the previous data of passenger flow and tourist density heat map. When the crisis occurs, we will make real-time adjustments in areas where the amount of tourists and historical experience are clearly inconsistent or the evacuation efficiency is particularly low.

In the standing SRZ, we define its area as a function of tourist density and export capacity in the area. The function can be expressed as

$$F = a^3 b_1 \iiint (a) \sqrt{\frac{a}{b}} \tag{1}$$

where F represents the export capacity, which is the number of people in the area served within the specified time; R represents the area radius; ρ represents the density distribution function within the area. When F and R are given, we can calculate the radius of the area by the above formula.

When the calculation is finished, it is easy to notice that the value of these R_j will lead to overlapping areas, but there will always be some inconsistencies in the case of the permanent area and the actual situation. We propose a standard criterion, that is, by which we re-divide the coincident area according to the calculated arc-shaped area, to ensure that the integrity of the exhibition room is not separated into two parts, and to divide the visitors as evenly as possible.

3.2.2 F Evaluation Model

When we are considering the evacuation problem, the individual is not regarded as a particle in the PF, because the individual's shape will affect the use of the evacuation channel. For example, if Tom is particularly strong, it is possible to occupy two people's space,which will affect the passage of others. Therefore, we first deal with the population density and represent the individual through the horizontal projection area of the person to the ground.

$$\begin{gathered} f_0 = \sum_i \theta_i A_i \\ \rho = \rho_{initial} f_0 \end{gathered} \tag{2}$$

where f_0 represents the average single-person horizontal projection area, and its value is obtained by weighted average of the horizontal projected area of the three types of people who are thin, normal, and strong; ρ is the result of projection processing on people density.

Based on the daily traffic flow of the Louvre in one year, we can simulate the PF density function $D(t)$ when the passenger arrives at the ideal exit. The ideal exit means that the exit cross-sectional area is large, so it will not interfere with people's access.

However, the actual situation is that when more tourists pass the exit, the tourists have to queue up, and the export flow is constant, which is limited by the exit's cross-sectional area. Therefore, after passing through the exit, the contour of the PF density function changes, and we regard this change as a queuing transformation (hereinafter referred to as Q-transform). $D(t)$ is converted to $D^*(t)$ by Q-transform. It is expressed as

$$D^*(t) = Q - transformD(t) \tag{3}$$

We have done the assumptions and defined new transformations. Calculating the evacuation time for an export is the next step.

$$Y_{in} = \int_0^T N(t)B\mathrm{d}t$$

$$Y_{out} = \int_0^{T_0} N(t)B\mathrm{d}t + (T - T_0)N'B'$$

$$\delta Y = Y_{out} - Y_{in} = \int_{T_0}^{T} N(t)B\mathrm{d}t + (T_0 - T)N'B'$$

where Y_{in} is the number of tourists entering the exit;Y_{out} is the number of tourists leaving the exit; is the number of tourists staying the exit channel;B is the width of the exit; $N(t)$ is the specific PF density, which is defined as $N(t) = Dv(D)$. According to Predtechenski and Milinskii's research [3], the PF velocity in the horizontal channel under normal conditions is:

$$v = 112D^4 - 389D^3 + 434D^2 - 217D + 57$$

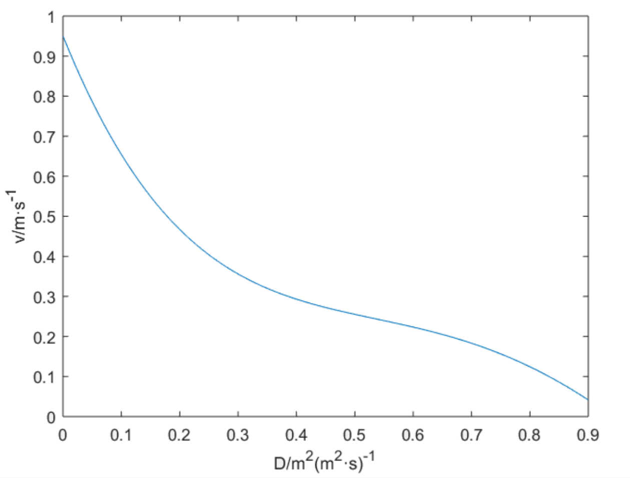

Figure 2: PF velocity-D diagram

Assuming that the real-time visitor density is Q_j in the jth area and the ending time is T_j, we get that

$$T_j = T_0 + \frac{Q_j - \int_0^{T_0} N(t)B\mathrm{d}t}{N'B'} \tag{4}$$

where Q represents the number of visitors in the area.

If there are n exports in the floor, we can get a set of functions $T_j(Q_j), j = 1, 2, 3, ..., n$. In order to minimize the total evacuation time, the evacuation time of the exit with the longest evacuation time should be as short as possible. The goal planning function can be expressed as

$$min\{max\{\{T_j\}\}\}, j = 1, 2, 3, ... \tag{5}$$
$$s.t \begin{cases} \sum Q_j = Q \\ 0 < Q_j < Q \end{cases}$$

Through the goal programming we can find an optimal solution, and substitute this solution back to (4), we can reverse out a set of Q_j. By definition, the number of visitors Q in the region is numerically equal to the export capacity F.

3.2.3 Available Exit Point Option

Considering the poor security of other available exits, it is easy to cause security risks. We set a indicator to evaluate whether to use them and the impact of the utilization. We will improve the standard evacuation time calculation formula for public places as a threshold for us to determine whether to use other available exits for evacuation.

$$t_0 = \gamma\{1 + \frac{\sum\sum Q_{i,j}}{0.9[A_1(N-1) + A_2 Z]} + T_{pass}\} \tag{6}$$
$$\gamma = Ce^{-k}$$

where $\sum\sum Q_{i,j}$ indicates the number of people in the facility; A_1 indicates the capacity of the escalator (unit: $(mmin)^{-1}$); A_2 indicates the capacity of the stairs (unit: $(mmin)^{-1}$); N indicates the number of escalators; Z indicates the total width of the stairs; 0.9 indicates that the escalator and stairs are converted by a 10% discount; T_{pass} represents the time required to reach the exit from the farthest exit of the facility; and γ time-risk factor.

We assume that T represents the actual time required for evacuation. If T > t_0, it means that the four main doors are no longer sufficient for emergency evacuation, and we need to use other available exits. If not, it means that the four main doors have been able to meet the needs of emergency evacuation, and we do not need to use other available outlets.

When other available exits are used, we recommend that the museum take the following measures to ensure that visitors are safely evacuated.

1. Add security forces to guide the tourists to evacuate in an orderly manner for the available exits used.

2. Deliver the information of other available outlets to specific SRZs or several exhibition rooms to prevent widespread dissemination of information, resulting in excessive visitors flocking to the exit

3. Select other available outlets based on real-time visitor density distribution and regional evacuation efficiency

4 Real-time Path Planning Model Based on Network

4.1 Model Overview and Analysis

In the above model, we successfully partition the whole floor into several zones and people in the corresponding zones could only walk through the dedicated doors in this zone. Therefore, it is important to consider how to get people from different rooms in this zone to the exit. In this paper, The staircase for this floor is equivalent to the exit for the building. Meanwhile, people on the same floor are notified of emergencies at the same time. When an emergency occurs, people's first reaction is to run to the door of their room or to the narrow corridor connecting the room and the room, where bottlenecks are easily created. In addition, unexpected events such as sudden roof collapsing can increase the risk of roads or create bottlenecks.What we need to do now is to arrange reasonable routes for people, keeping them from bottlenecks and risks.

4.2 Model Construction

4.2.1 The Details about Model

Any emergency evacuation space can be modeled as $G(v, E)$ network. To illustrate our model, we take a room with three doors for an example.

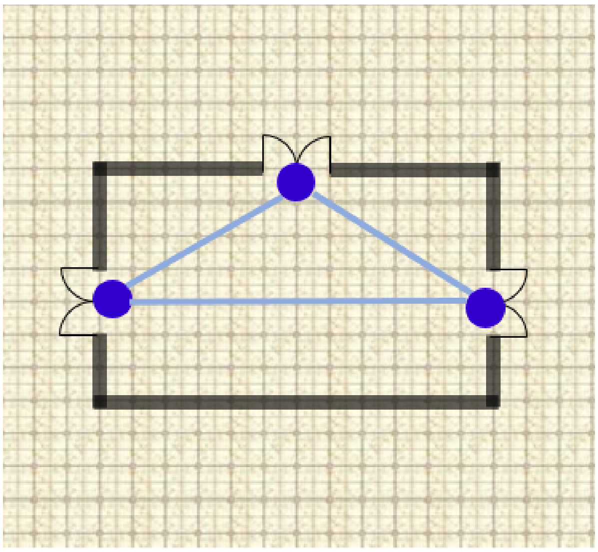

Figure 3: Network

In the graph, there are three nodes u_1,u_2,u_3, which make up the node set $\{u = u_1, u_2, u_3\}$ of the space. In the graph, there are three sides, they are $(u_1, u_2), (u_1, u_3), (u_2, u_3)$. They make up the edge set $e_{ij} = \{(u_i, u_j)\}$ of the space.

We regard the door of each room or the narrow corridor connecting two rooms as nodes. The connection between the two nodes through the exhibition hall is regarded as the edge, so we abstract a concrete terrain into a network.In many emergency response strategies in the past. Visitors always regard the shortest distance to the door as the best escape path,but we think that the shortest distance to reach the exit does not mean the shortest time to reach the exit, since there are many bottlenecks slowing down the speed. Even the path which cost the shortest time to reach the exit can not prove that this is the best path, because the danger coefficient of this road may be very high. People pay the price of damaging their health in order to pass in a shorter time.

Because danger usually occurs when running from room to room, congestion mainly occurs when queuing at the door.To solve this problem,We set the equivalent length w_{ij} of each edge as

$$w_{ij} = q_{ij}\beta_{ij}l_{ij} \tag{7}$$

where q_{ij} is crowding coefficient of two nodes connected to the edge; β_{ij} is the danger coefficient of each edge; and l_{ij} is the actual length of this edge.

We define the congestion coefficient as

$$q_{ij} = \frac{v_{max}^2}{v_i v_j}$$

$$v = 112D^4 - 389D^3 + 434D^2 - 217D + 57$$

where v is a function of the people flow density. v_{max} is the speed at which people pass through the door when the people flow density is zero.

According to the types of emergencies that occur and the degree of danger that emergencies bring to people in different locations, we give the danger coefficient tto measure the danger degree as

$$\beta_{ij} = 10^k \quad k = 0, 1, 2, 3, 4$$

When a disaster occurs, people's first reaction is to run to the nearest door or follow a familiar person to a random door or look for the door farthest from the disaster., so we use cellular automate (CA) to simulate the initial congestion coefficient of each node in this room and calculate the the equivalent length of each edge. Each node can choose many routes to reach the final exit. We believe that the path with the shortest sum of the equivalent lengths is the optimal path in this moment.

However, as the crowd starts to flow, the congestion coefficient of nodes and the danger coefficient of edges may change. Therefore, we redesign the route every Δt for all those who have not yet arrived at the exit. At this time, many people may not have reached the next node or have left the next node. The number of visitors in an edge is counted into the next node in the network.

4.2.2 Adaptability of Risk Index k

According to statistics and information in Knoema and Google, earthquakes, fires, gunpowder terrorist attacks, and biochemical terrorist attacks are the most threatening and frequent disasters or crimes in large venues such as museums.

Earthquake grading M: Earthquakes are classified into 1-10 levels according to the Ricker series. We assume that people on the same floor have the same risk index and the risk index increases with the floor increases

Classification of fire disaster F : By considering the area of combustion , the speed of expansion of the fire and the distance from the person to the fire point comprehensively,we can give the risk index.

Classification of gunpowder terrorist attacks T: This mainly includes gun-type attacks, bomb attacks, and suicide attacks.Calculate the risk index by combining the degree of damage of the attack with the distance of the visitors from the threat

Classification of biochemical terrorist attacks w: This mainly includes poisonous gas bombs, chemical and biological weapons and other attacks. Based on the data we have investigated, we measure the degree of risk by the concentration of biochemical substances and the speed of transmission.

$$w = a\gamma^m v^n$$

among them, a is determined by chemical weapons and properties; γ is the ratio of the concentration of biomass to mass; v is the propagation speed of the biochemical liquid-gas substance at the place of use.

Risk Index(k)	Earthquake (M)	Fire Disaster(F)	Gunpowder terrorist attack(T)	Biochemical terrorist attack(w)	Others
1	0-4	F1	T1	w1	(3, 100)
2	4-5.5	F2	T2	w2	(10, 300)
3	5.5-7	F3	T3	w3	(17, 500)
4	>7	F4	T4	w4	(x>17|y>500)

Figure 4: Risk index

Here, (x, y) in the column "$Others$" means, the number of casualties is less than x and the area of the damaged zone is less than y m^2.Choose the highest level that can be achieved when defining.

In the event of an emergency security incident, it is difficult for staff to accurately classify disasters. Therefore, we propose a standardized risk grading scheme as Figure 2 to guide staff to respond quickly to threats and select appropriate emergency evacuation plans.

4.2.3 Calculation of PF in Network Nodes

If we count the PF of the visitor to the exit, we can know that he obeys a certain distribution. The PF waveform undergoes a series of waveform transformations as it passes through nodes and edges in the network.

- Time-delaying transform:

The waveform of the PF needs to pass through the nodes and the edge process for a certain period of time, which corresponds to the time required for the flow of people through the exhibition hall and the corridor. This results in the time delaying transform.

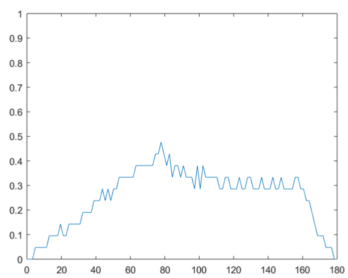

Figure 6:
Initial waveform

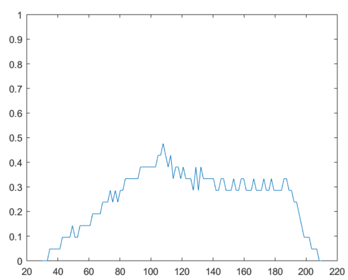

Figure 7:
Time-delaying transform

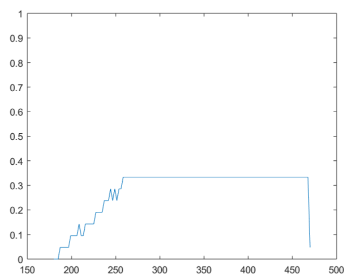

Figure 8:
Q-transform

- Q-transform:

When the PF from a wide area to a narrow area, there is a queuing phenomenon here due to the limitation of the channel size. The resulting waveform transform becomes a Queue transform

According to the definition of nodes and edges, we know that nodes are narrow corridors, which are generally prone to Q-transform, while edges are not easy to occur. But the Time-delaying transform is the transformation that takes place on both the nodes and the edges.

5 Inter-floor Sorting Model

When people on the higher floor flow to the lower floor, the PF from the upper floor will be pooled with the PF queued here on the lower floor. At this time, the density of tourists will increase rapidly. When the density of tourists exceeds a certain range, it will restrict the movement of individuals and people, and it will easily lead to accidents such as conflicts and trampling. Therefore, we need to analyze the superimposed PF waveform and guide the staff to guide the way and time of the two PFs to be collected.

Here, we introduce the relationship between population density and population behavior in previous studies to guide us in solving this problem.

Crowd density	Group condition
5	People can contact with each other's clothing
6	People can pick up items and turn around
7	People's shoulders and elbows will have a sense of squeeze
8	A person can barely pass between two people
9	People's behavior is limited, their hands can't move up and down, creating a sense of anxiety
10	People feel a lot of pressure from the surroundings, the body can't move, there is a cry for help, and it is easy to have a stampede accident.

Table 2: The relationship between population density and population behavior

We can see that when the density exceeds $7m^{-2}$, the crowd is prone to accidents. Therefore, the staff should prevent the density of visitors at the stairway and at any queue point from exceeding $7m^{-2}$.

The following examples are used to demonstrate the guiding significance of our previous PF calculations for the convergence of people between floors. Through the Time-delaying transform and Q-transform mentioned above, we can calculate the waveform of any node in the network that flows to the exit or stairway. When any two streams meet, they will be superimposed to form a new waveform.

From the example, the result of the superposition is less than 0.7, and the corresponding tourist density is less than $7m^{-2}$. Therefore, at this gathering point, there is no need for staff to drain visitors. But we must be vigilant and guide people to maintain order. When the situation turns into a PF upstairs and a PF pool that is being queued downstairs, the waveform is superimposed as

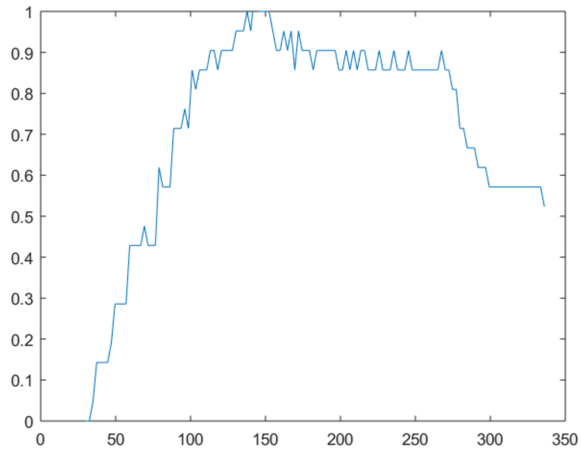

Figure 8: Superimposed inter-floor PF waveform

From the example, the result of the superposition is more than the corresponding tourist density is greater than $10m^{-2}$. Therefore, at this stairway, the staff upstairs should guide some tourists to evacuate to other stairways in advance or ask the upstairs tourists to wait for a while, keep order, and inform the staff downstairs to evacuate the tourists as soon as possible.

6 Model Solution and Analysis

6.1 Forecast of the Number of Tourists

We assume that the evacuation of the Louvre occurred in 2019, when we need to forecast the number of visitors. Based on the number of visitors to the Louvre in 2007-2018, the Fourier curve fitting is utilized to predict that the number of visitors to the Louvre in 2019 will be $10,658,792$.

In order to calculate the evacuation of the Louvre more accurately, we need to get data of the specific number of visitors to the Louvre. We calculated the number of visitors to the Louvre by computer simulation based on some rules.

The rules are as follows:

- The number of visitors per day is positively related to the opening hours. The opening hours of the Louvre in a week will cause periodic changes in the number of visitors per day.
- There will be disabled visitors on Tuesday, which are not counting the model considerations. There are 2100 of disabled visitors throughout the year, which is too small compared to millions of regular visitors.
- The number of visitors increased during the exhibition. It is understood that the Louvre has a spring exhibition and autumn exhibition, and will also host a free night market. The number of visitors increased during these time periods.
- The number of tourists increased during the holiday period.

The Louvre opened 3215.2 hours a year. Combined with our forecast of the number of visitors in 2019 and the above rules, we calculate that the minimum number of visitors per day in the Louvre is $21,345$ in 2019, with a maximum of $526,60$ and an average of $526,60$ per day.

6.2 Calculation of Emergency Evacuation Time

Based on the daily visiting data for the Louvre's annual statistics, we select data for visitors to a certain day in July 2019. A random simulation of the distribution of visitor density on the Louvre day at each floor.The reason why we randomly simulate the distribution of tourists is because we cannot get specific data. But we know that the daily data of the Louvre every day varies greatly and does not have regularity, while the Louvre generally has a large flow of people in the pyramid gate, Mona Li Sasha and Broken Arm Venus. We meet these conditions during our simulation. Therefore, the simulation we have made is also realistic to some extent. We first select the situation of the day and briefly explain the operation process.It is assumed that there was a fire on the first floor of the venue at 13:14 pm this day and there are 927 visitors here. Through computer simulation, we get the distribution image after the flow of people go through the stairs.

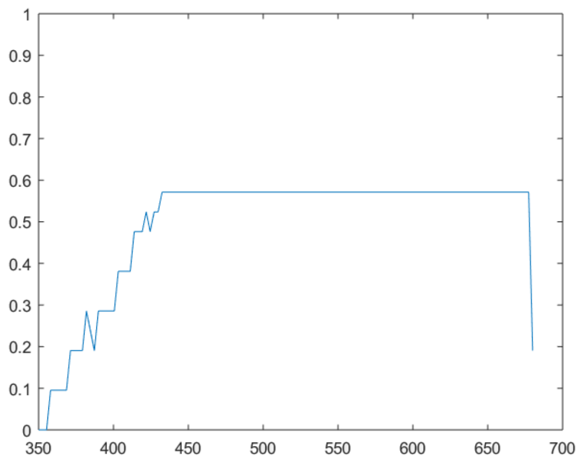

Figure 9: Superimposed PF waveform at a stairway

We can get an approximate expression for this image.

$$D(t)\begin{cases} 4.59\times 10^{-3}t-1.6065, 350<t<480 \\ 0.597, 480<t<678 \end{cases}$$

Through the measurement we calculated that the average width of the six stairs or escalators on this floor is 2.8m. At the same time, the average width of our visitors is 0.5m. The projected channel flow density threshold can be calculated as $\eta = 0.367$.

When the visitor passes through the stairway, $D(t)$ is Q-transformed.

$$D^*(t)\begin{cases} 4.59\times 10^{-3}t-1.6065, 350<t<429.96 \\ 0.597, 429.96<t<631.11 \end{cases}$$

When we substitute this function $D^*(t)$ and parameters into equation 4 and 5, we can use MATLAB to solve the target function $min\{max\{\{T_j\}\}\}, j = 1, 2, 3, ...$

$$T_1 = T_2 = T_3 = T_4 = T_5 = T_6 = 459s$$

$$\{Q_j\} = \{100.8016, 173.4728, 156.6091, 155.4747, 198.4536, 141, 4097\}$$

It indicates the optimal time for evacuation in the 1st floor is 8min7s. We substitute the calculated data into (1) to calculate a set of regional radius values.

$$\{R_j\} = \{198.12, 101.73, 167.84, 123.76, 134.60, 179.22\}$$

We give the partition mode of this floor according to the partition radius as shown in the figure below.

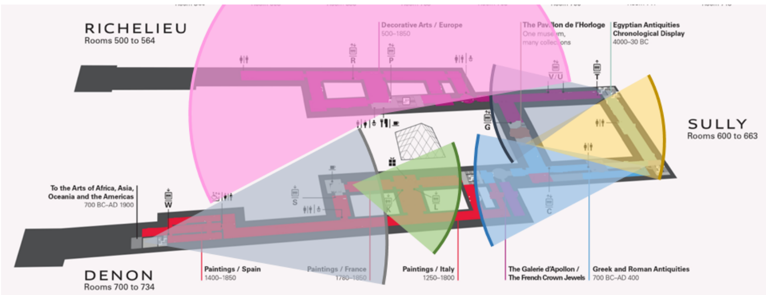

Figure 10: SRZ Division Diagram

Based on the time-shifted results of the simulated PF waveform, we learned that the group of people reached the lower floor through the stairs for 187 seconds in the 1st SRZ. Using the intra-floor planning method above, we can calculate the time to exit from the stairway to the doorway is 207s.

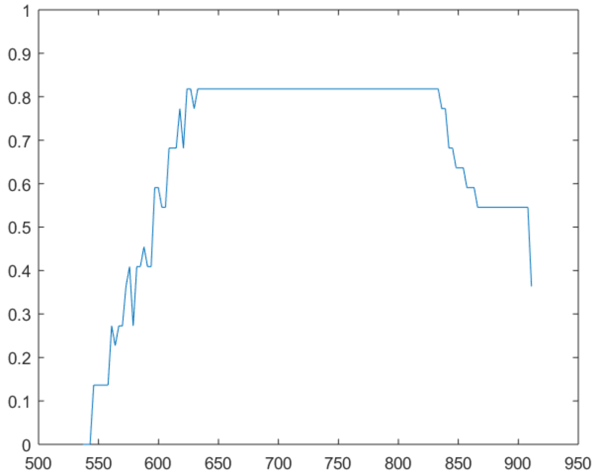

Figure 11: PF Waveform after the Stairway

Therefore, we can calculate the total evacuation time of all partitions of the five floors as $t_{i,j}$, which indicates the evacuation time of the ith floor jth SRZ. We know that the final evacuation time can be expressed as $max\{t_{i,j}\}$. In this example, we calculated the total evacuation time $t = 16min46s$.In this example, we calculated the total evacuation time $t = 16min46s$.

6.3 Optimal Path Selection

We assume that the fire occurred on the edge between node and node 2, but the disaster is not very serious. Therefore, we set the hazard index here to be $k = 2$. According to the initial parameters we set for each of our floors, we can calculate by formula (7) that the equivalent coefficients of different nodes and edges are

$$\{[\omega_j]; [\epsilon_j]\} = \{[5.4, 689.71, 7.8, 6.6, 4.3, 7.8, 6.8, 9.1]; [78.34, 24.31, 27, 88, 87.91, 88.34, 54.66, 54.36]\}$$

The figure above is a demonstration of our optimal path for an SRZ calculation. In the same way, our model can guide different SRZ staff to guide visitors on different nodes to choose the optimal path for their escape.

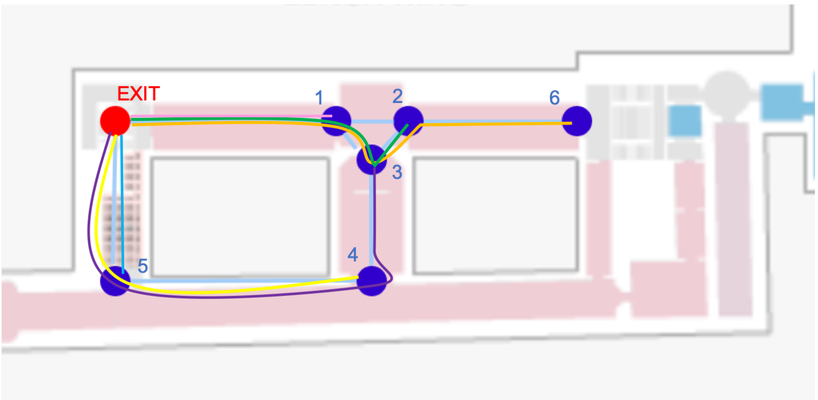

Figure 12: Optimal Path Selection in a SRZ

7 Priorization Scheme

7.1 Overview and Analysis

In the previous paper, we have established a general emergency evacuation model, but we still have many problems to consider, such as the appropriate time that the emergency personnel should enter the building, the best route for disabled people to escape and the way for people from different countries to know the emergencies more effectively . To solve these problems, we give reasonable suggestions through our analysis.

7.2 Emergency Personnel Entry Plan

It is vital that emergency personnel should enter the building at first. By consulting the literature, we know that the highest turntable ladder is 101 meters. Therefore, when an emergency occurs in the high building , emergency personnel can first take the ladder to enter or take helicopter to reach the floor where disaster occur. Although some emergency personnel can arrive quickly, most of them still have to enter the building through the door. we designed adaptable entry schemes according to the total number of people in the building.

Taking the Louvre as an example, we design an entry plan fore mergency personnel .

When the density of visitors in the building is less than $5m^{-2}$. At this time, we can use the Richelieu entrance for the evacuation of tourists on the first and the second floors. Personnel can evacuate some tourists on the the floor who is far away from the Richelieu entrance and those on the negative floor from the exit on the two negative floor. The Portes Des Lions entrance without the evacuation of tourists is used as the entrance for emergency personnel.

When the density of tourists is greater than $5m^{-2}$ but less than $8m^{-2}$, we think that all the main doors should be used to evacuate tourists. Emergency personnel can enter the special access by the main door for them.

When the density of tourists is greater than $8m^{-2}$, we think that the density of tourists is beyond the load range of the main door. At this time, we will open available exit for emergency personnel to enter and other available doors for visitors to evacuate.

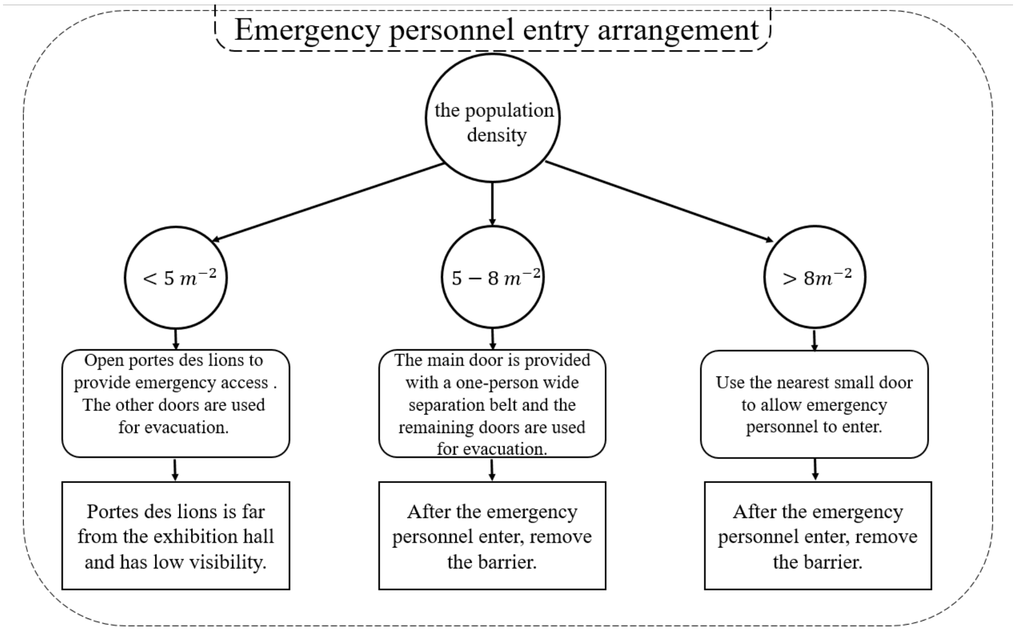

Figure 13: Emergency Personnel Entry Plan

7.3 Visitor Characteristics Analysis and Solutions

- **Tourists' linguistic diversity**

By reading the information, we can learn that the main languages used by visitors to the Louvre include: French, English, German, Italian and Chinese. The multilingual nature of visitors can hinder the delivery of evacuation orders during emergency evacuation. In response to this problem, let us give some measures to optimize our evacuation plan.

1. During the emergency evacuation, the staff use the broadcasting equipment in the venue to conduct French-British bilingual command evacuation.
2. The museum should strengthen foreign language training for staff in densely populated areas and important venues, where staff and security personnel with foreign language skills are resident.
3. In the case of emergency evacuation, evacuate instructions in multiple languages are sent on the application.
4. The Louvre will provide simultaneous interpretation on the app.

- **Tourist group problem**

According to statistics, more than 60% of tourists visited the Louvre in units of two or more. In the case of emergency evacuation, visitors tend to act together emotionally and behaviorally, which can cause some problems for our evacuation, especially when the group is very large. But if the museum chooses not to allow all groups that violate the evacuation order to act together, it is also very unfriendly. In fact, it is a reasonable emergency evacuation plan to allow a group to be dismantled within an acceptable range. Here we have the following standards.

$$\Delta = \chi \frac{nt}{N}$$

where Δ denotes the acceptable group number; N denotes the number of booths; χ denotes the convergence coefficient; t denotes the difference between the evacuation threshold and the actual theoretical evacuation time.

- **Evacuation of disabled tourists**

The disabled are required to take special care of the staff during emergency evacuation. At the same time, if the disabled and the normal person are evacuated together, they are both vulnerable and hinder the actions of the crowd. Therefore, when our staff finds disabled people, we need to arrange someone to lead them to transfer from the staff passage or the elevator.

7.4 Crowd Management and Control Procedure

In the event of a public safety incident, visitors will exhibit the following behavioral characteristics due to fear, panic and herd mentality:

- **Preemptive behavior for passing** visitors will show up in the various passages and push and push, so that they can leave as soon as possible.
- **Inertial behavior** The evacuating staff often fall into the inertia trap when evacuating, and the visitors are impressed by the familiar entrances and exits, which leads to crowds.
- **Dodge behavior** people have the nature of being profitable and avoiding harm. When a hazard occurs, people prefer to travel around the road rather than passing through the danger.

Therefore, it is very important to strengthen the emergency evacuation training for staff and to convey correct and timely instructions. This requires us to reasonably arrange the location of the staff and the number of staff in different locations during evacuation. It can be proved that important venues, access intersections and stairways as well as exits are locations where accidents are likely to occur. We set $\omega_1(\rho, n)$, $\omega_2(d, B, p)$,$\omega_3(\rho, n)$, measuring the importance of a location by three weighting indicators. We calculate the number of staff in this SRZ by calculating the sum of the weight values within an SRZ. At the same time, we have to arrange more staff in the large location of ω in SRZ, especially those with foreign language ability and security personnel.

8 Sensitivity Analysis

We have conducted a sensitivity analysis of the Safety Response Zone Division Model.

Considering that the model is large and complex, a cellular automaton with low accuracy is used to take simulation. Therefore, we use a cellular automaton with low accuracy to simulate the second floor. The length and width parameters of an exhibition hall is changed in the model, and then we observe the effect on the results.

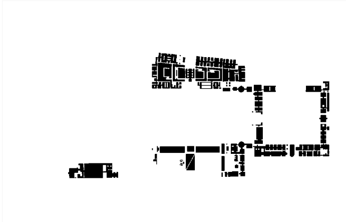

Figure 15:
Background

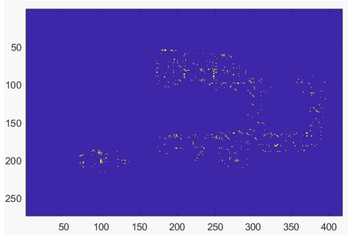

Figure 16:
Cellular automaton

One Exhibition Hall		
Length	Width	Average Evacuation Time
15	10	459s
10	10	463s

Table 3: Evacuation time change

We notice that the evacuation time increased after the distance between one exhibition hall is shortened. We reckon there are two reasons:

- The randomness of cellular automata behavior. Its randomness comes from our randomness in setting the initial position of the visitor.
- After the length of the exhibition hall became shorter, the number of evacuated visitors increased. This results in a total evacuation time.

Overall, the time between the two simulations is not much different, which indicates that the results of our model do not change much after a small change in parameters. Our model is reliable.

9 Strengths and Weaknesses

9.1 Strengths

Quantified and rational goals We set quantified goals strictly based on optimal path planning theory

Robustness and flexibility The fundamental strength of our model comes from its enormous flexibility,where most of the parameters in our model is not fixed. Furthermore, our model has the notion of time,which is omitted in most mathematical model.

Easy to understand adopting a hierarchical structure, our model can be easily understood with single graph and several pictures of explanation.

9.2 Weaknesses

Potential invalid assumptions Another obstacles that may hold back our model's performance is that the assumptions made to simplify the model may be invalid,therefore leading to a less useful model.

Potential vulnerability due to the lack of data The fundamental weakness of our model also comes from data. Since we can't obtain the accurate data of the Louvre, there is a lot of uncertainty in the validation of our model.

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A Appendix: Data

Year	2013	2014	2015	2016	2017	2018
Number of tourists	9.3million	9.3million	8.6million	7.4million	8.1million	10.2million

Table 4: Number of yearly visitors to the Louvre.

B Appendix: Code

B.1 Picture Conversion

```
close all;
clear;clc;
%%
%Image reading and conversion (reading, grayscale, filtering effectiv
%Image reading
floor0 = imread('floor0.png');
%subplot(3,2,1),imshow(floor0);
%grayscale
gfloor0 = rgb2gray(floor0);
figure(1),imshow(gfloor0);%Effective color center value:221 226 178 2
gfloor0(gfloor0(:,:)>=217&gfloor0(:,:)<=225) = 0;
gfloor0(gfloor0(:,:)>=222&gfloor0(:,:)<=230) = 0;
gfloor0(gfloor0(:,:)>=174&gfloor0(:,:)<=182) = 0;
gfloor0(gfloor0(:,:)>=211&gfloor0(:,:)<=219) = 0;
gfloor0(gfloor0(:,:)>=233&gfloor0(:,:)<=241) = 0;
gfloor0(gfloor0(:,:)~=0) = 255;
len = size(gfloor0,1);
wid = size(gfloor0,2);
%figure(1),imshow(gfloor0);
for j = 1:20
    for i = 1:len
        for j = 1:wid
            if gfloor0(i,j)<=5
                mat = gfloor0(i-2:i+2,j-2:j+2);
                num = sum(mat(:)==0);
                if num <= 9
                    gfloor0(i,j) = 255;
                end
            end
        end
    end
end
%figure(1),imshow(gfloor0);
len = size(gfloor0,1);
wid = size(gfloor0,2);
for i = 1:len/4
```

```
        nfloor0(i,:) = gfloor0(4*i-1,:);
    end
    for i = 1:wid/4
        mfloor0(:,i) = nfloor0(:,4*i-1);
    end
    %imshow(mfloor0);
    pfloor0 = double(mfloor0);
    figure(2),imagesc(pfloor0);
```

B.2 Estimated Number of Visitors Per Day

```
%Estimated number of visitors per day.
mon = normrnd(28088,2000,52,1);
tue = normrnd(40,10,52,1);
wed = normrnd(43712,2000,52,1);
thu = normrnd(28088,2000,52,1);
fri = normrnd(43712,2000,52,1);
sat = normrnd(28088,2000,52,1);
sun = normrnd(28088,2000,52,1);
years = [mon,tue,wed,thu,fri,sat,sun];
yearr = [reshape(years',1,364),normrnd(28088,3000,1,1)];
%china
yearr(181:240) = yearr(181:240)+300;
yearr(1:60) = yearr(1:60)+300;
%us
yearr(151:240) = yearr(151:240)+700;
yearr(335:365) = yearr(335:365)+700;
%show
yearr(1:210) = yearr(1:210)+500;
yearr(300:365) = yearr(300:365)+500;
plot([1:365],yearr)
%with Tuesday
big = max(max(yearr))
smalltue = min(min(yearr))
%without
sm = min(years);
sm(:,2) = [];
small = min(min(sm))
```