Analysis and Optimization of Emergency evacuation in the Louvre

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Abstract

With the escalation of the threat of terrorism, the government pays more and more attention to the emergency evacuation plans in the tourist attractions. A reasonable and effective evacuation plan should attach importance to the evacuate speed and the personal safety of tourists. Tourists will encounter various potential threats in evacuation, such as casualty evacuation and route damage. Besides, language barriers, the group travel and other factors will also affect the evacuation. Therefore, we need to figure out the impact of these potential issues and make some modifications to evacuate quickly and safely. Based on the evacuation velocity model, we develop the basic evacuation model to simulate the general situation and analyze the properties of tourists in emergency evacuation. By using the software, we find that the total evacuation time fail to meet the basic escape requirements under no guidance. In order to improve the evacuation efficiency, we establish three effective models and use Simulated Annealing Algorithm to optimize the solution. The first one is the "tourist evacuation management model" (TEM). It considers the role of emergency personnel. The results show the importance of emergency personnel in evacuation. Therefore, in the event of an emergency, emergency personnel should enter the museum quickly from the emergency exits. The second model is the "route damage evacuation model" (RDE). It considers the impact of the unavailable routes. By analyzing the results, we find that route damage will make the evacuation time fail to meet the escape requirements. Therefore, it is necessary to open the emergency exits for tourists when the route damaged. The third model is the "multi-type tourist evacuation model" (MTTE). It is used to analyze the impact of different tourist types in evacuation. From the results, we know that the more the injured, the elderly and the disabled in tourists, the more total evacuation time will be cost. We also study the influence of group travel, and we find that the increasing number of group visitors will also increase the total evacuation time. Meanwhile, we study the effect when the model variables change. The result shows that our models can still keep their high effectiveness. In other words, our models have extensive applicability and high stability.

Keywords

Emergency evacuation; the evacuation velocity model; Simulated Annealing Algorithm; emergency personnel; Goal Programming.

1. Introduction

1.1 Background

1.1.1 An Overview of the Problem

In recent years, French government requires a review of the emergency evacuation plans at many popular sites for the increasing number of terrorist attacks. An appropriate emergency evacuation plan shoule not only have all people leave the building as quickly as possible, but also ensure the safety of tourists to the greatest extent. If tourists need a lot of time to evacuate, the secure system of tourists might be imperfect. This has an adverse impact on the scenic spot.

Take the Louvre for example, the annual flow of tourists to the Louvre fell sharply since the terrorist attacks in 2016(Net1,2018). However, with the construction of the emergency evacuation plan, the annual number of tourists to the Louvre has increased year by year(Net2,2014) and reached 10.2 million in 2018(Net3). The more tourists there are, the larger impact of terrorist attacks on casualties and panic among people. This makes evacuation very important in an emergency.

Besides, the number of the tourists varies every day and the diversity of tourists ---speaking different languages, group tourist and disabled visitors make evacuation in an emergency even more challenging. Therefore, it makes sense to solve the evacuation problem.

1.1.2 The Process of Emergency Evacuation

The Louvre has five floors and four main exits. Among them, Passage Richelieu entrance, Portes Des Lions entrance and Pyramid entrance are on the ground floor, Carrousel du Louvre entrance is on the negative 2 floor(Net4).

Because the Pyramid entrance is mainly designed to divert tourists to help more tourists enter the Louvre. And it is also convenient for tourists to buy tickets from the ground floor to the negative 2 floor, so it is not very useful in an emergency.

We can get the evacuate routes for each layer as follows:

Floor 2: tourists go downstairs or escalators to floor 1.

Floor 1: tourists go downstairs or escalators to floor 0.

Floor 0 (ground): tourists can evacuate from the Passage Richelieu entrance, Portes Des Lions entrance, or go downstairs to the negative 1 floor.

Negative 1 floor: tourists go downstairs or escalators to negative 2 floor.

Negative 2 floors: tourists leave from the Carrousel du Louvre entrance or the subway station.

1.2 Literature review

In order to simplify the problem and facilitate the computer language to simulate the evacuation in an emergency, the researchers analyzed the psychology and behavior of the crowd in evacuation. The researchers found that in emergencies, people would follow the "neighbor effect" and tends to move with the people around(Max Kinateder, Brittany Comunale, William H. Warren,2018). In the process of evacuation, there is also a "pressure effect". People will suffer psychological pressure because a large amount of people gathered together. It will lead tourists to fall or push when the pressure reached a certain value(Bode, N.W.F., Codling, E.A., 2013). Moreover, other researchers found a "collective effect". People would evacuate with friends they know or their family(Drury, J., Cocking, C., Reicher, S., 2009).

Based on the previous research and the necessary mathematical knowledge(Net5), we hope to find some convenient evacuate plan.

1.3 Our Work

Construct a mathematical model to simulate the emergency evacuation of the Louvre to find out the bottlenecks.

Make some modifications on museum emergency management.

Make some modifications on the basic model, and discuss the potential threat during the evacuation process and its impact on the evacuation time. The potential threats are the destruction of the evacuation route and the increase number of the injured.

On the basis of optimization model, make sensitivity analysis from three aspects: language barrier, proportion of different types of tourists and group tourist.

Propose policies and procedures suggestions for the emergency management of the Louvre.

Propose crowd management methods that are necessary for visitor security.

Analyze the advantages and disadvantages of the model.

2. Model Assumptions and Notations

2.1 Assumptions and Justifications

In order to simplify the course of modeling and draw some reasonable conclusions from our model, we make assumptions as follows:

The data we found are true and reliable.

The power supply of the lifts will be cut off in an emergency, so people evacuate mainly through stairs and escalators. The risk of taking lifts is extremely high in terrorist attacks.

449 showrooms are open from 9:00 a.m. to 17:00 p.m.(Net4). The Louvre has a total of 403 rooms and a 14.5 kilometers' gallery. So we convert the gallery area into the room area to calculate the number of the people. This could mitigate the impact of the varying number of the showrooms every day.

Every period of time, there are 60% of all the visitors in a day inside the museum, so there are 16000 visitors in the museum. The Louvre is closed on Tuesdays, so the average number of visitors per day is about 26000, compared with 340,000 visitors during the peak season (for example, free Sundays). When an emergency occurs, not all the visitors in a day are in the museum, so we use an estimate value to simulate the situation.

Ignore the effects of the size variations in different types of stairs and galleries. In our model, the aisle area and exit width are calculated according to the relative scale of the navigation map of the Louvre(Net4). According to the calculation results, the average stair width, aisle width, ground exit width and underground exit width in the Louvre are 2.5m, 10m, 2m, 4m respectively.

There is no emergency during the evacuation. We make the analysis based on the situation after terrorist attacks. If there is a terrorist or explosion in a certain place, it is possible to disrupt the evacuation order.

Emergency exits and secret exits are primarily used for emergency personnel to access. These exits are small and not safe enough. Since they cannot guarantee the security of the tourists, they should be considered when the main exits cannot meet the requirements.

About 2.4% of visitors choose to appreciate the Louvre's three treasures, and about 1.2% in the classic galleries mentioned in the roadmap. Tourists always give priority to classic works. About 75.5% of the visitors are from other countries.

We don't consider the Pyramid entrance in emergency evacuation. The Pyramid entrance is designed to divert the tourists and use revolving doors, so it is useless in the emergency evacuation.

In case of emergency, tourists will follow the crowd. Even without the guidance of emergency personnel, tourists will choose a closer stair and form a diversion automatically. People converge to the stairs, and it is a regional downward movement of visitors in different showrooms.

We don't consider the minuscule deceleration of the velocity of the people at the turning of the terrain.

2.2 Notations

Here we list the symbols and notations used in this paper, as shown in Table 1.

Some of them will be defined later in the following sections.

Table 1: Notations

Symbol	Description
R	the original number of tourists on the floor
Q	the total aisle area of the floor
ρ_{aisle}	the flow density of the tourists in the aisle
ρ_{stair}	the flow density of the tourists in the stair
ρ_{door}	the flow density of the tourists in the door
V_{aisle}	the speed of the flow of people in the aisle
V_{aisle}^{*}	the initial flow speed of the showroom aisle
V_{stair}	the speed of the flow of people in a stair
V_{door}	the speed of the flow of people in a door
t_0	the time tourists move to the stair from the aisle
L	he length of the aisle
D_{door}	the width of the exit
d_0	the width of the stair
D_{aisle}	the width of the aisle
T_e^{fimal}	the total evacuation time
S	the number of stairs taken in unit time
top	the data of the upstairs
α、β、γ	the transfer rate of the visitors
$change$	the corresponding data after change
N	the stairs number in the region of the current floor
$N_{\text{stair}}^{\text{damage}}$	the number of stairs that cannot be used
$N_{\text{door}}^{\text{damage}}$	the number of exits that cannot be used
η_{people}	the proportion of tourists injured
$\eta_{injured}$	the proportion of tourists injured
F	a unit horizontal projection area
W	the cover area of the people

3. Analysis of problem

3.1 Basic Ideas of The Basic Model

We first consider the location of the exits and divide the people into two parts: evacuate from the ground and from the negative 2 floor. Then we assume tourists only flow with the crowd in the simulation of evacuation and use the degree of population density to explain the congestion. Then, we distribute the number of the people according to the regional congestion situation to reduce evacuation time.

3.2 Basic Ideas of Modification Model

We analyze the potential threats and divide it into two cases --- certain exits or stairs are unavailable and the number of injuries increased. Then we redistribute the people and change the proportion of tourists in different showrooms in order to have a best solution to solve or mitigate the impact of potential hazards.

3.3 Basic Ideas of Sensitivity Analysis

The basic model simulates an ideal evacuation situation. It assumes that most of the tourists are young people and the tourists follow the guidance of the emergency personnel. However, some factors such as language barrier, the proportion of the disabled and the elderly, and group travel, will affect the results of the model to a certain extent. Therefore, we need to analyze the impact of these three factors on the evacuation model.

4. The Basic Model of Emergency Evacuation

In the event of a sudden emergency, tourists follow the crowd from the showroom to the staircase. If there are too many tourists near the stairs, people move slowly and become congested. When tourists leave the exits, they can evacuate safely. The time all tourists leave the museum is the total evacuation time. We can find that the congestion will increase the overall evacuation time, so we need to find the bottleneck and its reasons to adjust the model.

4.1 The Design of the Model

In order to demonstrate our basic model clearly, we divide it into the two following sub models.

Movement model: this model is designed to simulate the movement of people between floors in order to find out where and why congestion occurs during the evacuation process.

Time model: this model is designed to simulate the entire evacuation process and calculate the total time.

4.2 Sub Models

4.2.1 Moving Model

Moving model(Net5,Net6) simulates the flow of people between floors. In the process of evacuation, people will experience two situations: movement and congestion. At the beginning of evacuation, people move freely. When the density of people reaches a certain value, congestion occurs. The flow chart is shown in figure 1.

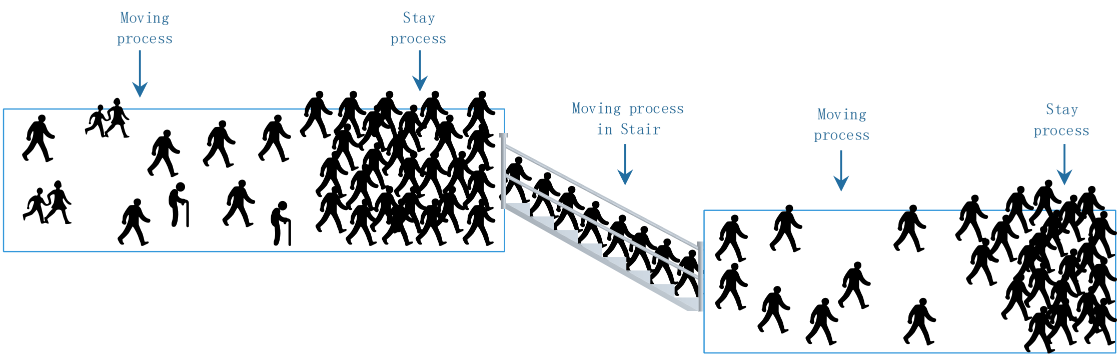

Figure 1: Flow chart of floor evacuation

R is the original number of tourists on this floor, Q is the total aisle area of this floor, ρ_{aisle} is the flow density of the tourists in the aisle of showrooms, ρ_{stair} is the flow density of people in stairs, ρ_{door} is the flow density of people in the doorway, V is the horizontal speed of a normal walk, V_{aisle} is the speed of the flow of people in the showroom aisles, V^*_{aisle} is the initial flow speed of the showroom aisle, V_{stair} is the speed of the flow of people in a stair, V_{door} is the speed of the flow of people at the door, t_0 is the time tourists move to the stair from the aisle, L is the length of the aisle. We can get the model as follows:

$$\begin{cases} V_{aisle} = 112\cdot\rho_{aisle}^{4}\text{-}380\cdot\rho_{aisle}^{3}+434\cdot\rho_{aisle}^{2}\text{-}217\cdot\rho_{aisle}+57(m/min) \\ V_{stair} = 1.21\cdot V\cdot[0.775+0.44e\text{-}0.39\cdot\rho_{aisle}\cdot sin(5.16\cdot\rho_{aisle}\text{-}0.224)](m/min) \\ V_{door} = 1.21\cdot V\cdot[1.17+0.13\cdot sin(6.03\cdot\rho_{aisle}\text{-}0.12)](m/min) \\ V_{aisle} = 1.34\rho_{stair}^{-0.8} \\ V_{\mathrm{stair}} = 1.34\rho_{\mathrm{door}}^{-0.8} \\ t_0 = L/V_{aisle}^{*} \end{cases}$$

The flow density of tourists in each floor is different, and it always varies with time, but it has a common method to calculate. S is the number of stairs taken in unit time, d_0 is the width of the stairs, t represents the time, N is the number of stairs in the region of the current floor, and top is the data of the upstairs.

We can use this equation to calculate the flow density of the top-level layer aisle:

$$\rho_{aisle} = (R\text{-}V_{stair}Sd_0tN\rho_{stair})/(Q\text{-}V_{stair}Sd_0tN)$$

We can use this equation to calculate the flow density of the median layer aisle:

$$\rho_{aisle} = (R\text{-}V_{stair}Sd_0tN\rho_{stair}+V_{stair}^{top}S_{top}d_0^{top}t_{stair}^{top}N_{top}\rho_{stair}^{top})/(Q\text{-}V_{stair}d_0StN+V_{stair}^{top}d_0^{top}S_{top}tN_{top})$$

We can use this equation to calculate the flow density of the lowest layer aisle:

$$\rho_{aisle} = (R+V_{stair}^{top}S_{top}d_0^{top}t_{stair}^{top}N_{top}\rho_{stair}^{top})/(Q+V_{stair}^{top}d_0^{top}S_{top}tN_{top})$$

4.2.2 Time Model

Time model(Net7) simulates the whole evacuation process to calculate the total time. The floors are relatively independent and connected by stairs. We calculate the number of tourists at the exits in emergency evacuation. And the total time T_e^{fimal} is the time when the total number through the exits is equal to the number of people in the museum before the evacuation. The flow chart of the evacuation at the door is shown in figure 2.

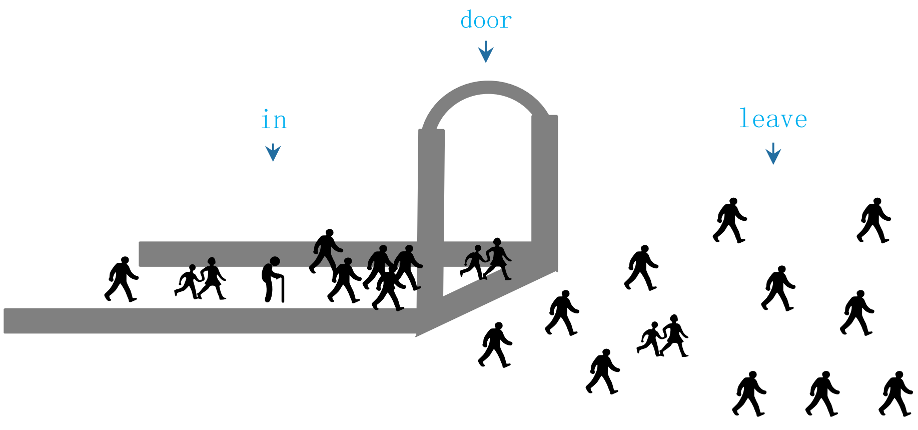

Figure 2: Flow chart of the evacuation at the door

T_e is the total evacuation time, t^* is the time at which a steady flow occurs, V_{aisle} is the speed of the flow of people in the aisle, V_{door} is the speed of the flow of people at the door, ρ_{door} is the flow density of people at the door, D_{door} is the width of the exits, n is the number of exits. We can use this equation to calculate the time:

$$T_e = t^* + \left[R_e - \sum_{i=1}^{n} \int_0^t V_{aisle}(i) D_{door} \rho_{door} dt \right] / \left[\sum_{i=1}^{n} V_{door}(i) D_{door} \rho_{door} \right]$$

We divide the flow of people into two parts according to the psychological analysis of people in emergency evacuation:

Tourists on floor 2 and floor 1 evacuate with the ground tourists from the ground exits, the evacuation time is T_{e0}.

Tourists underground evacuate with the tourists on the Napoleon Hall from the exit at the negative second floor, the evacuation time is $T_{e\text{-}2}$.

The two parts are relatively independent, so the total evacuation time is:

$$T_e^{fimal} = max\left(T_{e0}, T_{e\text{-}2}\right)$$

4.3 The Result of the Basic Model

We use Matlab software to implement the model, and use Simulated Annealing Algorithm to optimize the solution. We calculate the basic data according to the scale of the navigation map of the Louvre(Net4), and then process the data to study the causes of congestion.

4.3.1 Related data

We separate different exhibition halls in the model, and calculate the area according to the scale of the navigation map of the Louvre(Net4). And we allocate the number of tourists according to the distribution of the room and the location of the popular showrooms. Suppose there were 16024 tourists in the Louvre when the terrorist attack occurred. The results are shown in table 2.

Table 2: Relevant data for each floor and region

Floor	Exhibition hall	People Number	Stairs Number	Area/m2
2nd floor	Richelien	1620	2	400*5.053*2
	Sully	1460	2	290*5.053*2
1st floor	Richelien	2153	4	500*5.053*2
	Sully	1905	5	503*5.053*2
	Denon	1761	3	390*5.053*2
Ground floor	Richelien	1719	4	540*5.053*2
	Sully	2119	6	504*5.053*2
	Denon	1130	6	230*5.053*2
Lower Ground floor	Richelien	820	1	185*5.053*2
	Sully	243	2	120*5.053*2
	Denon	890	5	350*5.053*2
Napoleon Hall	All	228	0	420*5.053*2

4.3.2 Congested location

We consider the evacuation situation in different areas and draw figure 3-9. From figure 3, we can see the change in the flow density of the people. According to the maximum value, we can know whether congestion will occur or not.

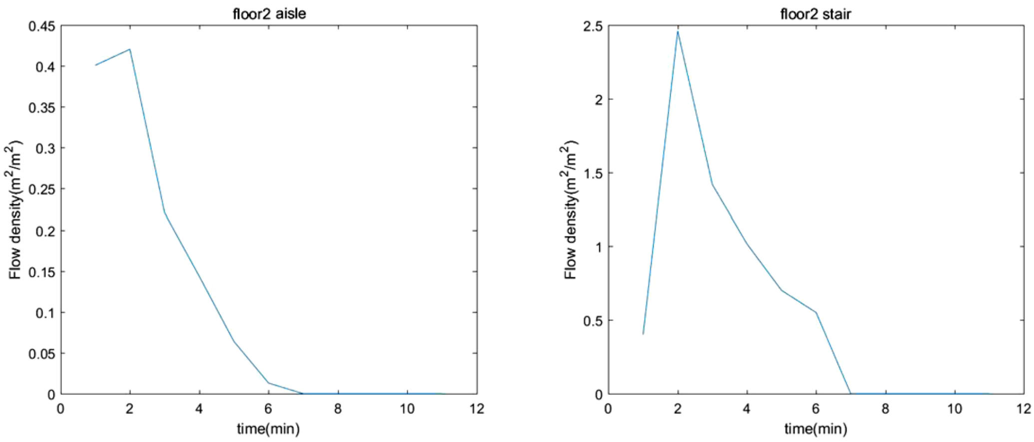

Figure 3: The flow density at the aisle and the stair on the second floor of Richelien

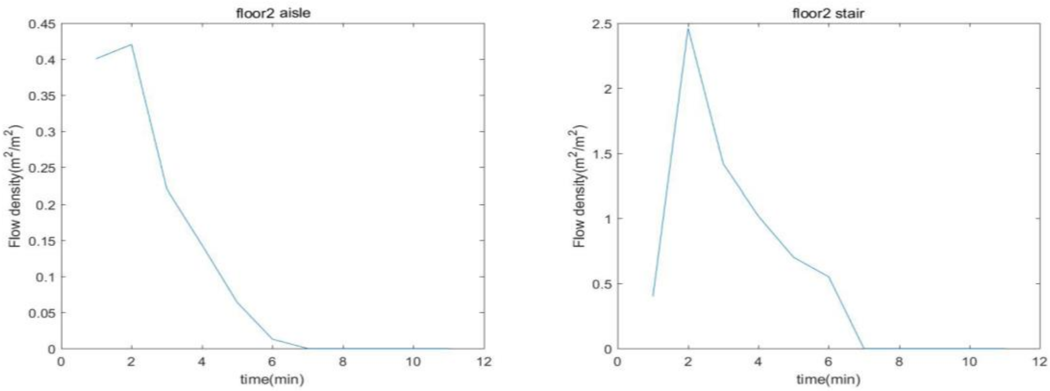

Figure 4: The flow density at the aisle (left) and the stair (right) on the first floor of Richelien

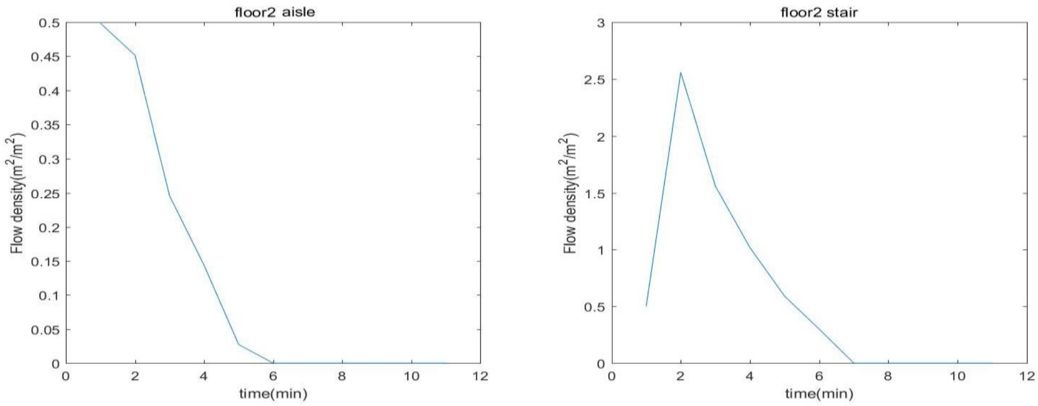

Figure 5: The flow density at the aisle (left) and the stair (right) on the second floor of Richelien

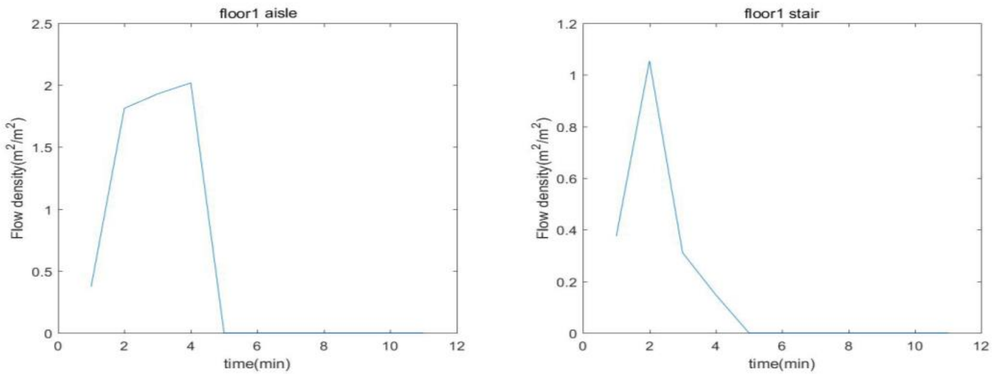

Figure 6: The flow density at the aisle (left) and the stair (right) on the first floor of Sully

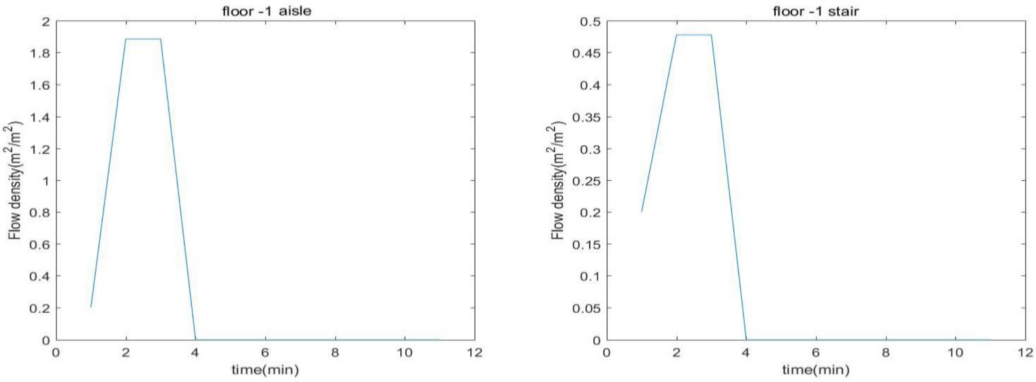

Figure 7: The flow density at the aisle (left) and the stair (right) on the lower ground floor of Sully

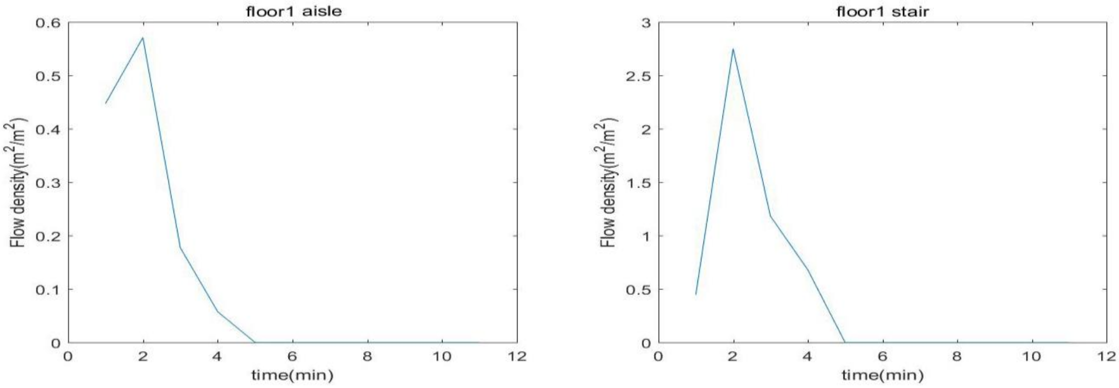

Figure 8: The flow density at the aisle (left) and the stair (right) on the first floor of Denon

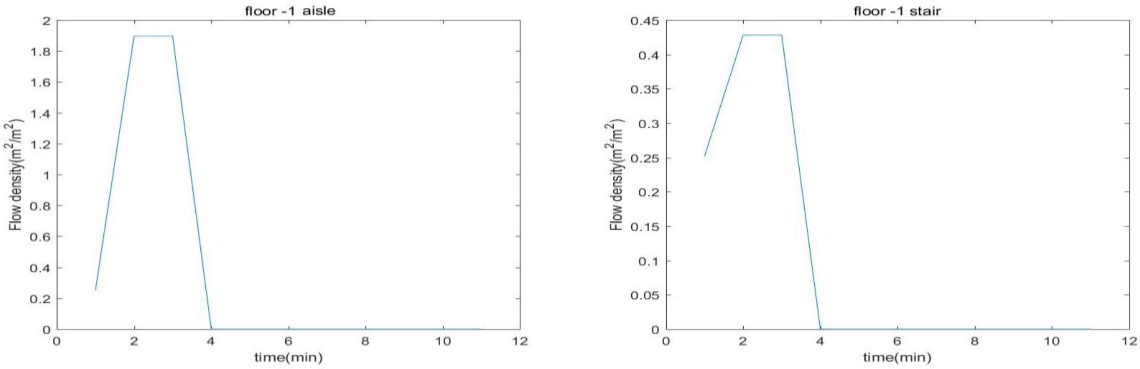

Figure 9: The flow density at the aisle (left) and the stair (right) on the lower ground floor of Denon

According to the literature(Net5), when the flow density of the people is 2.0 people/m^2, people would move slowly. And a congestion would occur. We simulate the evacuation process and collate the maximum flow density in each region then draw Table 3:

Table 3: The maximum flow density for each floor and region in evacuation

Floor	Richelien		Sully		Denon	
	Aisle	Stair	Aisle	Stair	Aisle	Stair
2nd floor	0.42	2.48(*)	0.5	2.55(*)		
1st floor	0.59	2.75(*)	2.0(*)	1.05	0.58	2.75(*)
Lower Ground floor	0.44	2.40(*)	1.9	0.48	1.90	0.43
	Aisle			Door		
Ground floor	0.390			3.1(*)		
Napoleon Hall	0.175			1.58		

The symbol (*) in Table 3 indicates the congestion at this location and reveals the risk of stampede event. The bigger the value is, the more likely a stampede event happens. After comparison, we know that in emergency evacuation, tourists are prone to congest when they go downstairs and leave the exits, but it is hard to be congested in the aisle. This is because most of the exhibits in the Louvre are hung on the wall or on the aisle, so there is a lot of room for tourists to move around and it is not easy to have congestion in

the aisle in evacuation.

However, because the width of the stairs is smaller than the aisle, it will form a congestion when tourists go downstairs. And it is the same for the exits. Besides, there will be congestion at the ground exits while no congestion at the underground exits in the simulation. This is because the number of the people evacuate from the ground exits is more than underground.

4.3.3 Total evacuation time

After simulating through the software, we can get the results as shown in figure 10:

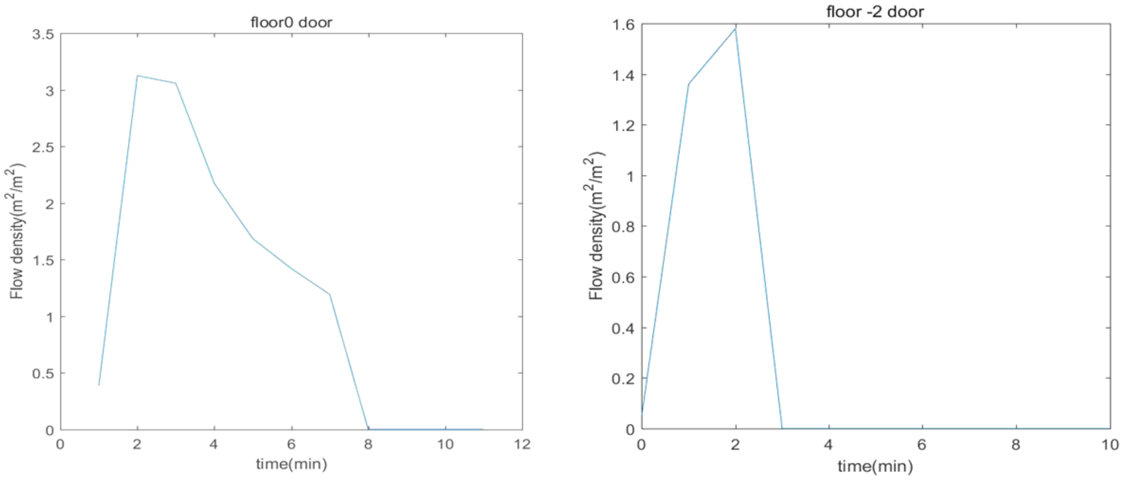

Figure 10: Evacuation time at ground exits (left) and negative layer 2 (right)

According to the safety evacuation requirement(Net8), the escape time of high-rise buildings is recommended as 5-7 min. From figure 10, we know that the evacuation time on the ground T_{e0} is 8min and the evacuation time on the negative second floor $T_{e\text{-}2}$ is 3 min. The main reason for the large difference between the two is the excessive number of tourists above the ground. The total evacuation time T_e^{fimal} is 8 min. This means the evacuation time of the Louvre does not meet the basic requirements of safe evacuation under no guidance.

5. Modifications to the Emergency Evacuation

As is mentioned in Section 4, the basic evacuation model does not meet the requirements. So we need to make some modifications. In this section, we modify the model based on the following three aspects.

Tourist evacuation management Model(TEM Model) --- Consider the guidance of emergency personnel.

Route damage evacuation Model(RDE Model) --- Consider the damage of stairs and doors.

Multi-type Tourist evacuation Model(MTTE Model) --- Consider the number of the injured.

We use Matlab software to implement the model, and use Simulated Annealing algorithm and linear equation to optimize the solution.

5.1 Tourist evacuation management Model

5.1.1 The Design of TEM Model

Under no guidance, the excessive flow density will affect the overall evacuation time. In the previous model, there were too many tourists above the ground. So, it is obviously that we can manage the distribution of personnel. Emergency personnel should guide some tourists on the ground to underground, and they need to control an appropriate flow density during the evacuation.Amend to read as follows:

The exits on the ground are close to the Richelien and the Denon exhibition halls, so we can guide some of the visitors in the Sully exhibition hall evacuate from underground.

According to Table 3, all floors in Richelien exhibition hall congested and Denon exhibition hall congested on the first floor during the evacuation. So we guide some tourists in the two halls to the Sully exhibition hall on the first floor, and guide some visitors from the Richelien to Sully on the ground floor similarly.

The flow density varies between 1 and 2(Net5).

α_1 is the transfer rate of the visitors on the first floor of the Richelien exhibition hall， α_0 is the transfer rate of visitors on the ground of the Richelien exhibition hall， β_1 is the transfer rate of visitors on the first floor of the Denon exhibition hall， γ_0 is the transfer rate of visitors from the ground to the downstairs of the Sully exhibition hall， R_i is the corresponding number of people represented by i， $change$ is the corresponding data after changes. The optimal goal model requires us to add the following formulas to the basic model:

$$\begin{cases} min \quad T_e^{final} = max\left(T_{e0}\ , T_{e-2}\right) \\ min \quad T_{e0} + T_{e-2} \\ R_{sully1}^{change} = R_{sully1} + \alpha_1 R_{Richelien1} + \beta_1 R_{Denon1} \\ R_{sully0}^{change} = R_{sully0} + \alpha_0 R_{Richelien0} - \gamma_0 R_{sully0} \\ R_{All-2}^{change} = R_{-2} + R_{-1} + R_{All\ sully}^{change} \\ 1 \le \rho_{door} < 2 \end{cases}$$

5.1.2 The Effectiveness of TEM Model

We find the best ρ_{door} and the best transfer rate of tourists α_1、 α_0、 β_1、 γ_0. The optimal results are shown in the first row in Table 4.

Table 4: Evacuation time for different flow density and transfer ratios

ρ_{door}	α_1	α_0	β_1	γ_0	T_e^{fimal}
2	1.2%-9.3%	0%	1.1%-9.1%	2.87%	6.4667min
2	1.2%-9.3%	0%	1.1%-9.1%	14.2%	6.4833min

As we can see from Table 4, the optimal flow density is to maintain just the perfect congestion. So emergency personnel only need to avoid overcrowding and stampede during evacuation. If we only modify the flow density, the total evacuation time can be shortened to 7.1min. This result shows that it is meaningful to ensure the appropriate flow density in evacuation.

In the optimal solution, the transfer rate of tourists on the first floor of the Richelien exhibition hall is between 1.2% and 9.3%, the transfer rate of tourists on the first floor of the Denon exhibition hall is between 1.1% and 9.1%. This result shows that it has no effect on the final result if the number of tourists within the same floor transferred in an appropriate range. The results are according with the reality. It is hard for emergency personnel to determine the number of people to transfer during the guidance, but they could depend on the circumstances.

When the transfer rate of tourists from the ground to the underground of the Sully exhibition hall is 2.87% , that is, 61 people are transferred, the evacuation time is the least. When the transfer rate of tourists of the Sully exhibition hall rise to 14.2%, that is, 300 people are transferred, the total evacuation time increased one second. At this time, the range of transfer rates between exhibition halls on the first floor remains unchanged. This means the upstairs transfer rate has no effect on the evacuation time, it is only related to the number of people transferred from the ground to the underground in emergency evacuation.

In the actual evacuation process, tourists in different exhibition halls on the same floor can be transferred according to the actual situation to avoid excessive flow density of people in a certain area. In this example, transfer the visitors from the Richelien and the Denon exhibition halls on the first floor to the Sully exhibition hall can reduce the flow density of people at the stair of the Richelien and the Denon exhibition hall. This can reduce stampedes and increase the safety of evacuation.

We add emergency personnel to the evacuation process, which can reduce the overall evacuation time from 8 min to 6.47 min. This shows the importance of adequate emergency personnel in the evacuation process. If emergency personnel enter from the normal exits, it will form a crowd hedge during evacuation and increase the total evacuation time. Therefore, emergency personnel should enter quickly from the Pyramid entrance or emergency exits and work with the museum officials to carry out evacuation work in emergency.

5.2 Route damage evacuation Model

5.2.1 The Design of RDE Model

In this model, we divide the potential dangers into two categories. One is the terrorists are located at an exit or the exit is dynamited. If tourists continue to use the exit, the safety of tourists will be greatly threatened. The other is that some of the stairs are unusable because of the terrorist attacks. If tourists still head to this stairs, it will lead to congestion. This type of congestion cannot be resolved because the stairs are not available. During the process of evacuate, the sudden discovery of potential threats will increase the pressure of the tourists. This is prone to stampede and reduce security.

If the above two potential threats happened, it is easy to occur congestion or stampede. This will increase the evacuation time and reduce the safety factor of evacuation.

From the above analysis, we found that the essence of the potential threat is the reduction of the number of exits and stairs available.

$N_{\mathrm{stair}}^{\mathrm{damage}}$ is the number of stairs that cannot be used; $N_{\mathrm{door}}^{\mathrm{damage}}$ is the number of exits that cannot be used. So we need to change the number of exits and stairs in the PEM model:

$$\begin{cases} N_{\mathrm{door}}^{\mathrm{change}} = N_{\mathrm{door}} - N_{\mathrm{door}}^{\mathrm{damage}} \\ N_{\mathrm{stair}}^{\mathrm{change}} = N_{\mathrm{stair}} - N_{\mathrm{stair}}^{\mathrm{damage}} \end{cases}$$

5.2.2 The Effectiveness of RDE Model

By using the software, we get the evacuation process data with different degrees of damage, and the results are shown in Table 5.

Table 5: Evacuation process data with different degrees of damage

$N_{\mathrm{stair}}^{\mathrm{damage}}$	location	$N_{\mathrm{door}}^{\mathrm{damage}}$	location	T_e^{fimal}
1	Sully showroom on the first floor	0		7.53min
0		1	One side of Portes Des Lions	8.62min
1	Sully showroom on the first floor	1	One side of Portes Des Lions	10min

From Table 5, when the number of stairs is reduced by 1, the total evacuation time is 7.53 min. When the number of exits is reduced by 1, the total evacuation time is 8.62min. When the number of stairs and exits are both reduced by 1, the total evacuation time is 10 min. The effect of stair damage is less than that of exit damage.

The escape time of high-rise buildings is recommended as 5-7min(Net8). The above results show that the total evacuation time will be more than 7 minutes when the route is damaged. This can not meet the basic requirements of safe evacuation.

The more serious the route damaged, the longer the evacuation time is cost. Therefore, in the actual evacuate, if the route is damaged, it is necessary to open the emergency exits. The number of the emergency exits is determined by the specific degree of damage. Meanwhile, it needs more emergency personnel at emergency exits to increase the safety of evacuations.

5.3 Multi-type Tourist evacuation Model

5.3.1 The Design of MTTE Model

When a terrorist attack causes a certain number of casualties, the evacuation of the injured will affect the total evacuation time.

The injured needs emergency personnel's help to evacuate, so it will affect the movement speed of the people in the process of evacuation. Therefore, we need to analyze the impact of the different number of the injured on the evacuation time, and then find out the solutions.

η_{people} is the proportion of tourists not injured, $\eta_{injured}$ is the proportion of tourists injured, F is a unit horizontal projection area(Net5, Net9), ρ^*_{aisle} is the initial flow density of the aisle, W is the cover area of the people, d_0 is the width of the stairs, D_{aisle} is the width of the aisle. When there are different types among people, the initial aisle flow density needs to be recalculated:

$$\begin{cases} F = \eta_{people} F_{people} + \eta_{injured} F_{injured} \\ \rho^*_{\text{aisle}} = RFW/\left(d_0 D_{aisle}\right) \end{cases}$$

5.3.2 The Effectiveness of MTTE Model

We calculate the total evacuation time after the gradual increase of the proportion of the injured to observe the influence of the proportion of the injured in the evacuation process. We acquire the data during the evacuation process for tourists with different degrees of injury, and the results are shown in Table 6.

Table 6: Evacuation process data for tourists with different degrees of injury

η_{people}/%	$\eta_{injured}$/%	T_e^{fimal}
90	10	6.45min
80	20	6.46min
70	30	6.47min
60	40	6.52min

From Table 6, we find that with the increase of the proportion of the injured, the total evacuation time increases. For every 10% increase in the proportion of injured, the total evacuation time increases by about 6 seconds. If the injured account for a large proportion, the total evacuation time will increase by 18 seconds. The results show that when the proportion of the injured is small, the impact on emergency evacuation is small. When the proportion of the injured increases to a certain ratio, the museum should consider opening emergency exits, and the injured should be evacuated from the emergency exits under the assist of emergency personnel.

6. Model Evaluation & Sensitivity Analysis

We test the sensitivity of the model from three aspects: language barriers, the proportion of different types of tourists and group travel. The main features of these three aspects are as follows:

Language barriers

75.5 percent of Louvre visitors come from different countries. Language barriers will make the guidance of emergency personnel ineffective, cause congestion or stampedes, and increase total evacuation time. This aspect is the sensitivity analysis of TEM model.

Proportion of different types of tourists

The Louvre is a museum of art, which is visited by young people, the elderly and the disabled. The elderly and the disabled move slowly, so we need to consider the proportion of these three categories of tourists when calculating the movement speed of the people. This aspect is the sensitivity analysis of MTTE model.

Group travel

Tourists are divided into three types: individual, family and group. People tend to escape with acquaintances and family members in emergency. However, if parents bring their children together, the overall speed is slower than that of the individual. So we need to consider the proportion of these three categories of tourists when calculating the movement speed of the people This aspect is also the sensitivity analysis of MTTE model.

6.1 The Sensitivity of TEM Model

French and English are used in emergency evacuations. If tourists cannot understand the guiding language, the situation becomes a basic evacuation under no guidance. Therefore, if emergency personnel guide by language, some tourists who do not understand will disobey the arrangement. We simulate these tourists evacuating from the original route.

According to the information(Net2), we could obtain the proportion of tourists from different countries visited the Louvre in table 7:

Table 7: proportion of tourists from different countries

France	America	England	China	Others
24.5%	13.3%	4.2%	3.8%	54.2%

From Table 7, a total of 58% of tourists may have language barriers, of which 11.6% will buy and use voice guides. These tourists with speech translators will not be affected by the language barriers. So 51.27% of the visitors will have language barriers when evacuating. They may escape randomly. It manifest in two points. One is that when emergency personnel reassign tourists, this part of the tourists will not listen to the arrangement and maintain the original evacuation route. The other is that when emergency personnel control the flow density of people, this part of the tourists are not controlled, so the overall flow density is not controlled.

Using the TEM model to simulate the evacuation and we get the results in figure 11:

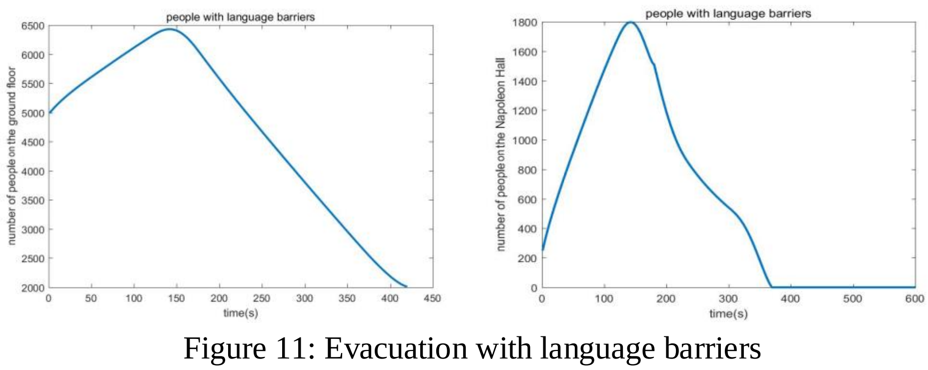

Figure 11: Evacuation with language barriers

From figure 11, we know that the total evacuation time is 7 min, the ground evacuation time is 7 min, and the underground evacuation time is 6.17min. We can find that in the case of language barriers, the total evacuation time increased by 32 seconds, which has a greater impact. The results suggest that museum should encourage visitors to use speech translators to eliminate the impact of language barriers.

6.2 The Sensitivity of MTTE Model

Proportion of different types of tourists

There are three types of visitors: the youth, the elderly and the disabled. According to the information(Net2), 18.6 percent of visitors are elderly and disabled and 81.4 percent are the youth.

When we calculate the unit projection area, we should separate different types of the tourists. Considering the speed of the three types of tourists(Net5), we sort out the differences between the three types and show in Table 8:

Table 8: Projection area of the youth, the elderly and the disabled

	The disabled	The old	The young
Shadow Area/m2	4	2	1

We use TEM model to simulate the evacuation. The relative proportion of the elderly and the disabled is changed when the model is simulated. The results are shown in Table 9:

Table 9: The impact of changes in the relative proportion of the elderly and the disabled

The old	The disabled	T_e^{fimal}
5%	13.6%	7 min
9.3%	9.3%	7 min
13.6%	5%	7 min

From Table 9, we can find that when the proportion of young tourists remains unchanged, the changes in the relative proportion of the elderly and the disabled has little effect on the total evacuation time.

In the example calculated earlier, when we assume all tourists are young people, the total evacuation time is 6.467 min. After taking into account of the elderly and the disabled among tourists, the total evacuation time increased to 7 min. Therefore, we can know that the total proportion of the elderly and the disabled has an impact on the total evacuation time. The elderly and the disabled will slow down the movement of people and it will increase the total evacuation time.

Group travel

There are three types of visitors: group, family and individual. According to the information(Net2), 13.8% of the visitors are group tourists, 54.9% are families and 31.3%

are individuals. The differences between the three types(Net5) are shown in Table 10:

Table 10: Characteristics of teams, families, individuals

	Team	Family	Personal
People Number	7 - 9	3	1
Shadow Area/m2	1.5	1.3	1

Using the MTTE model to simulate the evacuation, we obtain the results in figure 6:

From figure 6, the total evacuation time is 6.98 min. In the example calculated earlier, we assume the tourists are all visiting alone and the total evacuation time is 6.467min. After considering the group travel and family travel among tourists, the total evacuation time increases.

So we can know that when the proportion of tourists from a group or a family increases, the moving speed of people is slow and the total evacuation time increases. The more the proportion of group and family travel, the worse the impact. And the total evacuation time will also increase.

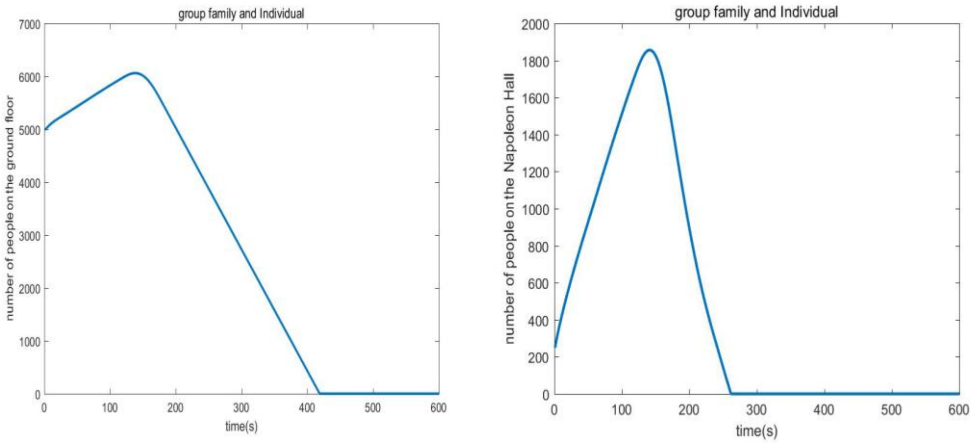

Figure 6: Consider the different types of tourists

7. Conclusion

7.1 Strengths and Weaknesses

7.1.1 Strengths

Our models are adaptable to different conditions.

In our model, we simulate realistic evacuation situations such as route defects, casualty evacuation, the group travel, evacuation of persons with disabilities, and language barriers. The results we obtained are reasonable and can give us some advice in realistic evacuation situations.

Our models have extensive applicability.

The model we used is based on the evacuation velocity model(Net5), which is

designed for a variety of evacuation situations, so our model can also adapt to a variety of situations. In particular, the MTTE model can be used to solve some evacuation situation with different types of tourists.

Based on reasonable assumptions, we uses scientific models to obtain suitable results.

The result of our model is visible and easy to understand.

By analyzing the chart and the picture of results , we can predict the realistic emergency evacuation process at the Louvre. The conclusions are in line with reality and easy to understand.

7.1.2 Weaknesses

The data we used to test the model is not enough.

Some of the data we used are based on theoretical calculations, which are slightly different from actual data.

Our model does not consider the impact of an emergency situation, like explosion.

7.2 Suggestions to the evacuation management

In the event of an emergency, emergency exits should be opened to allow emergency personnel to enter quickly the Louvre. From the simulation results, we find that the guidance of emergency personnel can greatly reduce the total evacuation time. In order to avoid the collision of emergency personnel and tourists during evacuation, emergency personnel should enter quickly through Pyramid entrance and emergency exits.

In the emergency evacuation, emergency personnel and museum officials should guide tourists to maintain an appropriate flow density, not overcrowded. At the same time, they need to keep tourists as calm as possible in order to prevent stampedes.

Emergency personnel and museum officials should use the "Affluences" and "My Visit to the Louvre" APP and surveillance cameras in the museum to know the distribution of the number of tourists on the different floors and the damage of the evacuation route. During evacuation, some emergency personnel should pay close attention to the evacuation situation in the museum so as to arrange work for other emergency personnel at each location.

When the damage of the evacuation route is serious, emergency exits should be opened for tourists. Meanwhile, the emergency personnel should be added to the emergency exits to ensure the safety of tourists in the evacuation to the greatest extent.

When the proportion of injured becomes large, the emergency personnel should help the injured to evacuate from the emergency exits, so as to reduce the influence of the injured on the normal route and reduce the total evacuation time.

7.3 Suggestions to the Tourist management

Tourists are suggested to use speech translators to eliminate the impact of language barriers.

Tourists are supposed to cooperate with the arrangements of emergency personnel and museum officials in evacuation.

In case of emergency evacuation, tourists are advised to attach less importance to their property and not to return to the luggage area.

When congestion occurs in the evacuation, tourists are suggested to keep calm in order to reduce the occurrence of stampedes.

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