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Summary Sheet

Evacuation Of The Louvre With Virtual Stairs

Summary

In order to have all visitors leave the Louvre as quickly and safely as possible, we build a single-layer evacuation model, define "a virtual stair" to connect several layers and optimize the model by using additional exits. The model is applied to the Palace Museum to analyze the effectiveness of models.

We divide the flight from the Louvre into two processes: intra-flight and inter-flight. For intra-flight, 'Single-layer with Several Exits Evacuation Mode' is developed. We use graph theory to mesh the structure of each layer and design a feasible path evacuation algorithm. Through it, the shortest path is obtained and the shortest evacuation time of the single floor is calculated. Finally, the simulation using VISSIM shows that error is only 3.9%, which indicate our model is acceptable.

For inter-flight, the single-layer model is upgraded to 'a multi-layer with several exits evacuation model'. We introduce the idea of "dimensionality reduction" and use "a virtual stair" to connect layers. According to the characteristics of interactions between layers, we optimize the visitors flow model. Finally, sensitivity analysis is carried out and the results are found to be in line with the actual situation.

In order to find out the bottlenecks, we get the data of five exits and seven stairs of the Louvre through simulation. We found bottlenecks appear in the choices of exits, relationship between stair capacity and corridor capacity.

Considering the diversity of visitors, we decide to make full use of the exits. For vulnerable groups of visitors, they should be evacuated by emergency personnels. We conduct 'a dynamic adaptive conditional exits model'. The analysis results show that the number of additional exits should be set dynamically according to the proportion of vulnerable.

Then we apply the model to the evacuation of the Palace Museum to test the validity. By analyzing the difference between two museums, we adjust the model slightly. Finally, we get the shortest evacuation path under fixed conditions. For the evacuation of vulnerable groups, the maximum benefit can be achieved by opening two additional exits under the 10% vulnerability ratio. Through sensitivity analysis, our models have high stability, high error-tolerant rate and extensive applicability.

Finally, based on the results of our study, we put forward suggestions and improvements to the staff of the Louvre in the form of a letter.

Keywords: Emergency Evacuation Graph Theory Dimensionality Reduction Sensitivity Analysis

Contents

1 Introduction

1.1 Background

1.1.1 An Overview of the Problem

The Louvre, the first of the world's four major museums, is one of the world's largest and most visited art museum. The 380,000 exhibits located on these five floors cover approximately 72,735 square meters, with building wings as long as 480 meters or 5 city blocks. The number of visitors to the Louvre is nearly a thousand every year and the number of guests varies throughout the day and year, which provides huge challenges for making evacuation in an emergency even more challenging.

1.1.2 The Process of emergency evacuation

The entire evacuation can be divided into following processes:

- Evacuation system startup process: firstly, evacuation guide personnel get the distribution of tourists through the APP. Then gather visitors from each floor to the assembly point and wait to be guided to evacuate. At the same time, rescue workers arrived at the accident site from the nearest entrance. According to relevant regulations, we set the evacuation system startup time as one minute.
- Intra-flight process: visitors search the exit in the floor -horizontal movement
- Inter-flight process: visitors move between floors-vertical movement.

1.2 Literature Review

In recent years, countries around the world have increased the investments and researches about the emergency evacuation management. Many scholars at home and abroad have adopted different methods to study this problem based on different practical backgrounds, mainly including computer simulation and mathematical analysis methods. On the basis of network flow optimization, large-scale evacuation is transformed into an evacuation network problem. [1] establish the point-weight traffic network to solve the minimum cost flow in the point-weight network. [2] used the fast flow control algorithm to solve the real-time emergency evacuation of large indoor places (such as shopping malls and subway stations). We expect to find some work and intuitive modifications for emergency evacuation -based on the previous wisdom and some necessary math knowledge.

1.3 The Task at Hand

Now the Louvre are especially interested in an adaptable model to evacuate visitors, and the goal of evacuation is to have all occupants leave the building as quickly and safely as possible. Our works are as follows:

- Construct an adaptive mathematical model to evacuate visitors in the Louvre as quickly and safely as possible, and provide a range of options for the museum leaders.

- Consider what the potential threats exist, and make adjustments to the model against these potential threats.
- Discuss what time additional exits should be utilized at and how additional exits should be used.
- Apply the model to other large buildings to verify the effectiveness 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:

1. The position of accident fix after occurring. We assume that the accident randomly and uniquely happens in any location of the Louvre. And the accident point will not move or spread.

2. All tourists follow the command, do not act without authorization, and there is no stampede or other accidents. Chaotic scenes can make it very difficult to carry out the evacuation process, and we think the museum staff can maintain good order.

3. Evacuation system operates normally without breakdown. The quality of security equipment needs to be reliable to avoid unnecessary trouble.

4. Evacuation time for guiding personnel is not concerned. The guiding personnel have been trained and are able to leave safely after their evacuation task.

5. The structure of each floor is the same. Since the plane projection of the Louvre is roughly the same on each floor, the layout differences between the floors are ignored.

6. A certain proportion of the tourists are vulnerable and need to be evacuated from extra exits with the help of the staff. There must be old people, infants and disabled people among the visitors, that are unable to follow ordinary tourists to leave together. After the evacuation began, they were led by staff to evacuate from extra exits on the floor.

7. Extra exits are safe. Unlike ordinary stairs, once visitors enter the extra exits on any floor, they are deemed to have safely evacuated, regardless of the specific situation in extra exits.

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
q	the total number of visitors in the building
S	collection of disaster nodes
D	collection of exit
N	other intermediate nodes
Q	flow density
$v_i(t)$	actual moving speed of visitor i at time t
$\varepsilon_i(t)$	perturbation force of visitor i at time t
DC_k	the maximum capacity
C_{ij}	capacity of each arc
$t_{l\to k}$	the time of a visitor through path P_l to exit k

3 The Louvre's Emergency Evacuation Model

3.1 The Design of the Model

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

- **Visitors speed model**: This model is designed to calculate the speed of the visitors under the influence of personal will, crowd drive and obstacles.
- **Visitors flow model**: In this model, we define "flow density" in order to get the number of visitors cross a section in unit time.
- **A layer with several exits evacuation model**: This model studies the optimal evacuation route of a single floor when visitors are informed of an emergency.
- **Several layers with several exits evacuation model**: The best route to flow between floors for the all visitors are discussed in this model.

3.2 Visitors Speed Model

In the process of evacuation, there are two parts: individual movement and group movement. As individuals move, they seek out and move closer to the group. Helbing [3] used the principle of mutual forces in mechanics to analyze different forces exerted on an individual in the process of movement, including member's self-drive force, group member's attractive force, Obstacle Repulsion Force and tiny winding force.

- Member Self-drive Force: it is a kind of inertia force and a trend force for visitors to go to the nearest exit spontaneously $f_i(t) = \alpha_i m_i.$, Where α_i is the self-drive coefficient.

- Group members' attractive force: It is a kind of group attraction under the effect of group psychology, which makes the individual follow the evacuation trend of the group in the evacuation process $\sum_j f_{ij}(t) = \beta$. Where β is the attraction coefficient of the group.

- Obstacle Repulsion Force: To avoid the effect of obstacles, often keep their distance from obstacles, which produces the repulsive force between themselves and obstacles. $\sum_w f_{iw}(t) = \lambda$, Where λ is the obstacle coefficient.

Through the three force, we can get the visitors' evacuation speed from Equation (1). $v_i(t)$ is actual moving speed of visitor i at time t and $\varepsilon_i(t)$ is perturbation force of visitor i at time t.

$$m_i \frac{dv_i(t)}{d(t)} = f_i(t) + \sum_j f_{ij}(t) + \sum_w f_{iw}(t) + \varepsilon_i(t). \tag{1}$$

PS: For the convenience of calculation, we take the average weight of the visitor as 55kg and $\alpha_i = 0.05$, $\beta = 10$, $\lambda = 5$.

3.3 Visitors Flow Model

In emergency evacuation model, the number of visitors in the channel are more or less, and the area of channel are big or small. In order to describe the degree of crowdedness, we define "$flow\ density$":

$$Q = \frac{N}{S}. \tag{2}$$

Where

- N is the number of visitors in the channel;
- S is the area of channel.

In Equation (3), we take the average value of all individual speed of evacuation through this path $\overline{v}$ as the flow speed in this path, where b is the road width, and we take the general building road width of 5 meters:

$$f = Q \times \overline{v} \times b \tag{3}$$

3.4 Single-layer with Several Exits Evacuation Model

3.4.1 Network Node Evacuation Model

We establish static network stream according to graph theory, which describes the evacuation paths for the Louvre's single layer structure. Then we assume $G(V, E)$ indicates evacuation network, where V represents node set including three subsets: collection of disaster nodes $S = \{w|w = 1, 2, \cdots, W\}$, collection of exit $D = \{r|r = 1, 2, \cdots, R\}$, other intermediate nodes $N = \{i|i = 1, 2, \cdots, I\}$, arc set E including the connections among all nodes, where e_{ij} represents the arc between node i and node j ($i, j \in V$).

According to the above settings, the Louvre's floor can be abstracted to network node diagram. Only when DC_k: the maximum capacity allowed through each exit, C_{ij}: capacity of each arc and T_{ij}: time required for personnel to pass through the arc are determined, will we transforme emergency evacuation problem into the optimal route problem with minimum evacuation time.

According to the floor plans of the Louvre, we know there are multiple staircases on each floor. So it is a typical single disaster point evacuation problem with some exits. What we need to consider is how to divide visitors into groups reasonably and choose appropriate paths, making the total evacuation time T minimum. Based on this, we denote the time of a visitor through path P_l to exit k by $t_{l\to k}$, and build objective function as Equation (4).

$$\min \quad T = \max(t_{l\to k}). \tag{4}$$

Assume the total number of visitors to be evacuated leaving path at time τ according to dynamic network flow is denoted by

$$x_{l\to k}(\tau) = \sum_{t=0}^{\tau} f_{l\to k}(t) \tag{5}$$

Where $f_{l\to k}(t)$, the decision variables, indicates the flow to exit k at time t through path P_l.

Constraint condition:

- All flow on paths are equal to q: the total number of visitors in the building, as shown in equation (6)

$$\sum P_l x_{l-k}(\tau) = q. \tag{6}$$

- The flow of each arc should not exceed it's maximum capacity, otherwise some paths will be blocked. We define $0-1$ variables $\delta_{ij\to k}$ and let $\delta_{ij\to k} = 1$ if $e_{ij} \in P_l \to k$, so the condition is described as

$$\sum P_l \delta_{ij\to k} f_{l\to k}(t) \le c_{ij} : \forall (i,j) \in E, t = 1, 2, \cdots, T. \tag{7}$$

Thus, we establish minimum time evacuation model according (4)(6)(7).

3.4.2 Join Virtual Super End Point

In fact, degree of crowdedness is depended on the capacity of paths and exits in the process of emergency evacuation. In the research of Yang's [5], the time of visitors evacuated is limited by the smaller of the capacity of paths and exits. Thus, we could regard exit as an arc whose capacity is equal to exit's and travel time is zero. In this case, the problem only relate to path capacity limit.

First we join super end point D_0 with infinite capacity as virtual exit and let it link each exit with D_0. Then we define the maximum capacity of arc (D_k, D_0) as $c_{k0} = DC_k$, travel time $t_{k0} = 0$, and get the new evacuation network $G^*(V, E)$. For $G(V, E)$ as shown in **Figure 1**, the numbers in brackets represent the maximum capacity and travel time of each arc, such as $(8, 3)$ in S to v, 8 shows the maximum capacity of arc and 3 shows travel time from S to v. In the same way, we could draw $G^*(V, E)$ when we join the super end point as shown in **Figure 1**.

Due to the capacity limit of arc in $G^*(V, E)$, the evacuation time is depended on the travel time through the arc and the time waiting to join the path. That is to say, we only

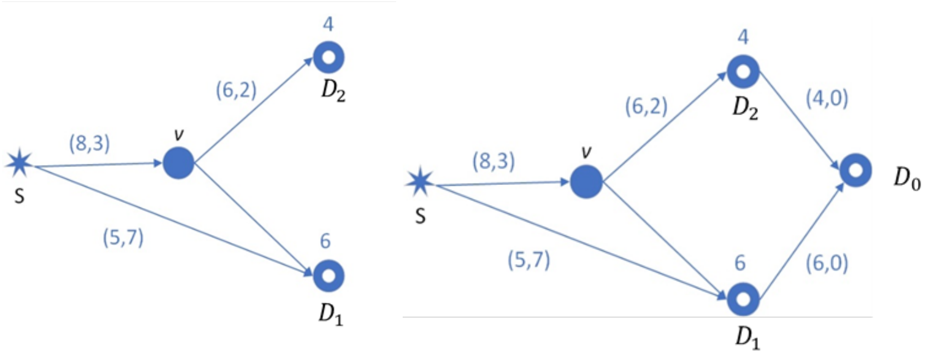

Figure 1: $G(V, E)$ and $G^*(V, E)$

need to select some suitable paths, then we could make evacuation plan according to the visitors number on each arc.

3.4.3 Feasible Path Evacuation Algorithm

First, we need to search for paths used for evacuation. When designing evacuation paths, we find out the shortest path from disaster point to super end point, where saturation evacuation is carried out. At the same time, we calculate the actual flow and record the path and its travel time. Then, we update the capacity of each arc on the path: the initial capacity of each segment minus the actual flow on the shortest path. If the result after update is 0, delete the arc from the network and repeat the process until the network is disconnected.

Detailed steps are shown below:

$Step\ 1:$ Input the transformed network $G^*(V, E)$ and the flow of each arc c_{ij}. Define path number $l = 1$, collection of paths $P = \emptyset$, flow collection of each path $F = \emptyset$, evacuation time collection of different path $TP = \emptyset$.

$Step\ 2:$ Search the shortest path from disaster s to super end point D_0 using **Dijkstra algorithm**, and sign the shortest path P_l, $T_{p_l} = \sum\limits_{e_{ij} \in P_l} t_{ij}$, $P = P \cup P_l$, $TP = TP \cup T_{P_l}$.

$Step\ 3:$ Calculate the max capacity of path P_l, and let $f_{l \to k} = \min\{c_{ij} | e_{ij} \in P_k\}$, $F = F \cup f_{l \to k}$.

$Step\ 4:$ Update max capacity $c_{ij} = c_{ij} - f_k$ of every arc on this path. If $c_{ij} = 0$, delete the arc e_{ij} and update network.

$Step\ 5:$ If the updated network is disconnected, go to $step\ 6$. Otherwise, let $k = k + 1$, and go to $step\ 2$.

$Step\ 6:$ Export collection of path P, evacuation time collection of different path TP and flow collection of each path F.

According to ..., we get $f_{l \to 0}$. Assume when all paths are scheduled, the flow will moving at a constant speed. The total number of flow which leaves the path P_l at moment t and reaches super end point D_0 is denoted by $x_{l \to 0}(t)$, satisfying

$$x_{l\to 0}(t) = \begin{cases} (t-(T_{P_l}-1))f_{l\to 0}, & t \geq T_{P_l} \\ 0, & otherwise. \end{cases} \tag{8}$$

For the total flow number q on this floor, the number of paths m_1 actually selected should meet

$$\sum_{k=1}^{m_1} (T_{P_{m_1}} - (T_{P_{m_1}} - 1))f_{m_1} < q < \sum_{k=1}^{m_1+1} (T_{P_{m_1+1}} - (T_{P_{m_1}} - 1))f_{m_1}. \tag{9}$$

Through calculation, we get the collection of optimal paths for actual evacuation regarded as $\{P_1, P_2, \cdots, P_{m_1}\}$, therefore we can denote total flow number by sum of the flow number passing on all paths as shown in Equation 10.

$$q = \sum_{l=1}^{m_1} x_{l\to 0}(t) = \sum_{l=1}^{m_1} (t-(T_{Pl}-1))f_{l\to 0}. \tag{10}$$

In combination with these equations, we get the total evacuation time T, shown as in Equation 11.

$$T = \frac{q + \sum_{i=1}^{m_{11}} T_{P_l} f_{l\to 0} - \sum_{l=1}^{m_1} f_{l\to 0}}{\sum_{l=1}^{m_1} f_{l\to 0}}. \tag{11}$$

After that, we could get the visitors' number of each path selected by Equation 12 and find the best evacuation plan.

$$x_{l\to 0}(t) = (t-(T_{P_l}-1))f_{l\to 0}. \tag{12}$$

3.4.4 The Result of Model

Without considering the influence of difference floors, we select the ground floor in the Louvre as the example to apply model. Firstly, we simplify the ground floor as a network node graph. Then, find the maximum capacity of arc c_{ij} and travel time t_{ij} between node i and j. According to data on the Louvre site [4], the number of visitors evacuated on each floor is almost 1300 when the numbers of five floors obey uniform distribution. After using measuring scale, we let 30 seconds as a time unit and abstract the model to a floor evacuation model as **Figure 2** shown:

Table 2: Feasible evacuation path

label	path P_l	actual flow f_l	total travel time T_{P_l} (s)	number of evacuation s_l
1	S-10-7-D_1	350	90	350
2	S-10-7-4-3-D_1	350	150	350
3	S-20-19-18-D_2	550	180	350
4	S-13-12-18-D_2	550	180	350
5	S-13-19-18-D_2	550	180	300
6	S-15-16-11-9-8-7-4-D_1	350	330	200

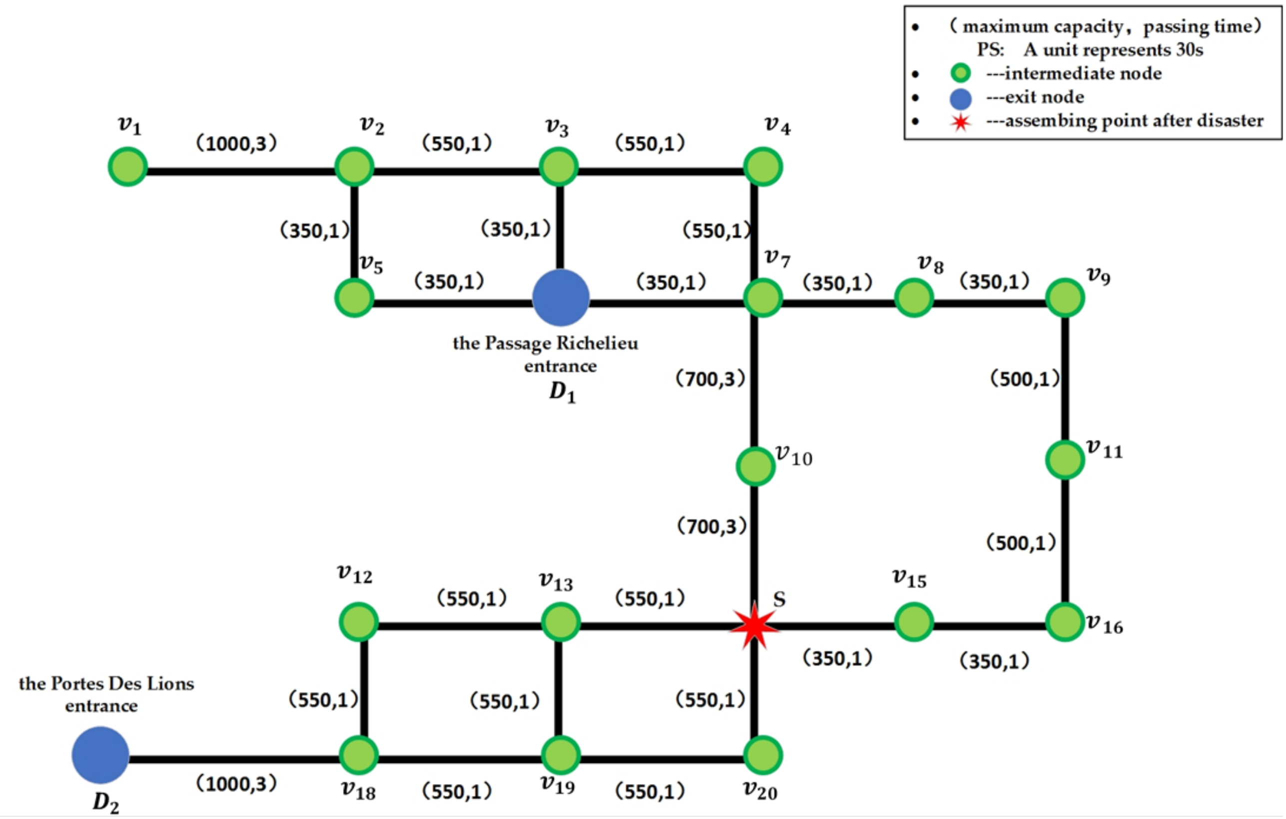

Figure 2: Simplified evacuation network figure of the Louvre's gound floor

By calculating the shortest distance from each node to exit, we discover the 14th node is the suitable for collection point, denoted by S. In **Figure 2**, the Passage Richelieu entrance is denoted by D_1 and the Portes Des Lions entrance.is denoted by D_2. Based on the assumption 1,2,3, making use of the feasible evacuation path algorithm, we get the collection of export paths P, collection of evacuation path time TP and collection of path flow F. **Table 2** describes these collections and relevant parameters.

According to the Equation 9, we know $m_1 = 4$ and the actual paths selected in evacuation is P_1. At the same time, we calculate total evacuation time **T=180 s**, less than the travel time of path P_5 and P_6. That is to say, if we only use the first four paths to evacuate, the visitors along path P_5 and P_6 hasn't reached the exit yet when all visitors is evacuated. Therefore, it is practical not to select path P_5 and P_6.

3.4.5 Verify Model

In order to verify the model and calculation results, we decide to use **VISSIM** software to simulate the situation. First of all, we draw evacuation route at the Louvre's plan in the proportion of 1 to 1. Then we set the ground floor as the example and simulate with exits position, disaster point and visitors' number. the plan of the Louvre is displayed as **Figure 3**. The Process of simulation is displayed as **Figure 4**.

For ensuring the accuracy of results and avoiding contingency, we test a few times and compare with 180 s (the calculated result), as shown in **Table 3** .

We take the average of the simulated result, and get the time **187 s**. Compared with the calculated result, the error is only **3.9%**, so we accept this result.

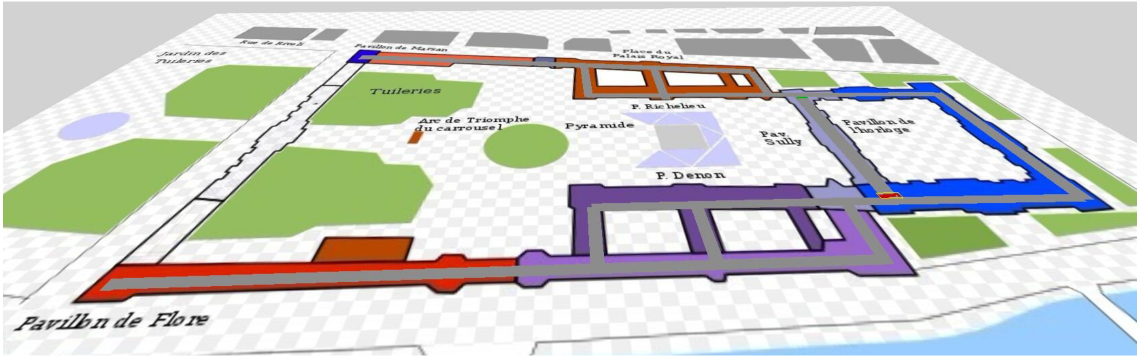

Figure 3: Plan of the Louvre

Figure 4: The Process of simulation

Table 3: calculated results and simulation results

the result	the first	the second	the third	the fourth	the fifth
180s	192s	184s	177s	189s	193s

3.5 Multi-layer with Several Exits Evacuation Model

It is well known that the Louvre has five floors, whose ground floor and Napoleon Hall has exits. It is obvious that the distance from each floor to the exit and the number of visitors evacuated on each floor are both different, so there exists a situation that some floors have been evacuated, but others are still on their way. Thus, a layer evacuation model can't be used in multi-layer evacuation problem simply.

3.5.1 The Influence of Emergency Point

As shown in **Figure 5**, the paths become unavailable because of unreachable point when emergency happens. Therefore, we remove relevant node and arcs, generating a new graph to calculate next time. If the collection point is just the emergency point, let the less optimal 13th point as alternate collection point.

3.5.2 Dimension Reduction—-Multi-layer Translate into Single-layer

For multi-layer emergency evacuation in the Louvre, we can establish the numerical relations between the layers based on a layer with several exits evacuation model. In this way, based on the assumption 5 , we can convert a 3D multi-layer structure into

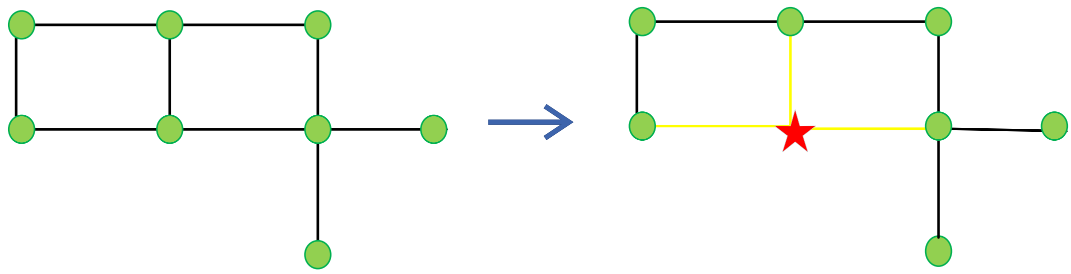

Figure 5: The influence of emergency point

a 2D planar structure by "a virtual stair" which connect all floors as **Figure 6** shown. However, the flow on each floor changes dynamically and the speed of flow on stairs slow down. So we need optimize single-layer with several exits evacuation model.

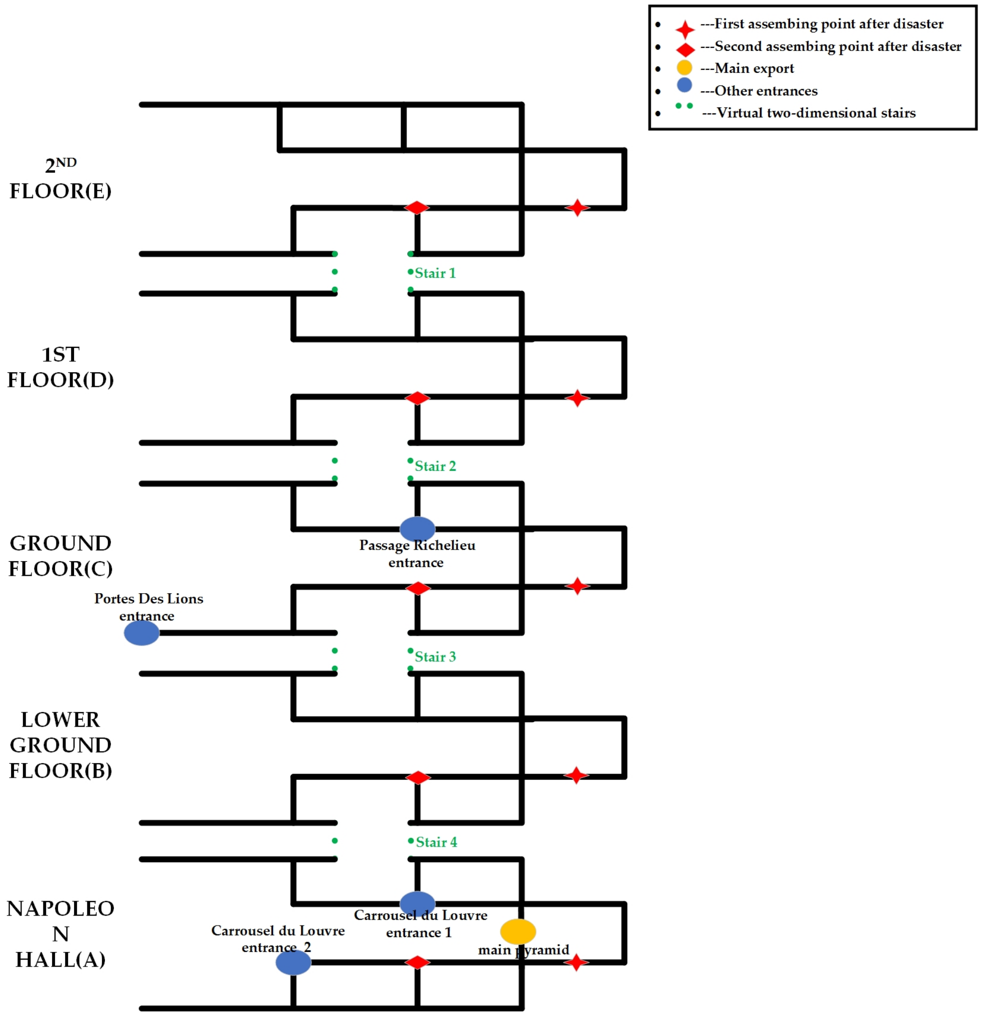

Figure 6: evacuation simulation figure of the Louvre's five floors

3.5.3 The Optimization of Visitors Flow Model

It is obvious that lower levels share some paths with upper levels, so that the flow of each floor doesn't satisfy simple linear relation rather than changing over evacuation time.

For example, we assume floor **a** is the higher and floor **b** is the lower. Firstly, we calculate the collection of the shortest paths $P^w = \{P^2, P^1, P^0, P^{-1}, P^{-2}\}$ that reaches exits (including stairs) on each floor . After that, we let $K' = P^i$ denoting the collection of feasible evacuation route and collection of practical evacuation route is denoted by K.

Select the shortest path of floor **a** $P_l^a \in K'$. For any path of b floor $P_k^b \in K' \cup K\ (a \neq b)$, if the collection $\{e_{ij}|e_{ij} \in P_l^a \cap P_k^b\} = \emptyset$, then

$$f_{l\to k}^a(t) = \begin{cases} \min\{c_{ij}(t)|e_{ij} \in P_l^a\}, t > T_{P_l^a} \\ 0, else \end{cases} \tag{13}$$

otherwise there is shared section. The only intersection starts from a floor along P_l^a to P_k^b. T_{a-l} and T_{b-k} are defined as the travel time on path P_l^a and P_k^b. Then we define P_l^a and P_k^b as the dynamic flow of exit at time t:

- When $t < \min\{T_{a-l}, T_{b-k}\}$,
$$f_l^a(t) = f_k^b(t) = 0.$$
- When $\min\{T_{a-l}, T_{b-k}\} < t < \max\{T_{a-l}, T_{b-k}\}$,
$$f_l^a(t) = \min\ \{c_{ij}(t)|e_{ij} \in P_l^a\}\ \& f_k^b(t) = 0$$
or
$$f_k^b(t) = \min\ \{c_{ij}(t)|e_{ij} \in P_k^b\}\ \& f_l^a(t) = 0.$$
- When $\max\{T_{a-l}, T_{b-k}\} < t < T^a$, $f_l^a(t) = \min\ \{c_{ij}(t)|e_{ij} \in P_l^a\}$.
Update the path capacity c_{ij} using a layer with several exits evacuation model, and let
$$f_k^b(t) = \min\{c_{ij}(t)|e_{ij} \in P_k^b\}.$$
- When $t > T^a$, if the evacuation isn't over, let
$$f_k^b(t) = \min\{f_l^a(T^a) + f_k^b(T^a), c_{ij}(t)|e_{ij} \in P_l^b - P_l^a\}\ \& f_k^a(t) = 0.$$

Based on the four situation above, we could apply a layer with several exits evacuation model to several layers with several exits evacuation problem.

3.5.4 Solutions of Model

According to evacuation simulation figure of the Louvre, we get every path's transit time and max capacity under the consideration of the impact of distribution of exhibition gallery and stairs on each floor to visitors flow. Denote five floors of the Louvre from higher to lower by A/B/C/D/E and the nodes of each floor are the same as the zero floor in A layer with several exits evacuation model. In consideration of the difference of exhibition gallery's number in exch floor, we believe that the number of each floor's flow distribute with 2:3:3:4:2 from higher to lower. After calculating, we find a set of feasible evacuation paths for each floor. **Table 4** describes the actual set of evacuation paths on the 2nd floor (for the rest to see appendix).

In this table, we let $S(A)$, $S(B)$,...,$S(E)$ as the the collection point from the Napoleon Hall to 2nd floor, X_i as the point i of floor X , D_1 as the Passage Richelieu entrance,

Table 4: The actual evacuation paths of 900 visitors

label	path P_l	actual flow f_l	total travel time T_{P_l} (s)	number of evacuation s_l
1	S(E)-E14-D14-C14-C10-C7-D_1	550	180	550
2	S(E)-E14-E10-E7-E4-E3-E6-D6-D_1	150	240	150
3	S(E)-E14-E13-E12-E18-E17-D17-D_2	550	270	200

D_2 as the Portes Des Lions entrance, D_3 and D_5 as the exit of inverted pyramid, D_4 as main exit of the pyramid.

As is shown in **Figure 7**, we could observe the change of visitors number on different floors. The visitor number of 2nd floor changes slowly and smoothly when the evacuation starts by analyzing the .blue curve. After few minutes, it reduces dramatically because all visitors has been informed emergency happened and escape to exits. However, the visitor number of Ground floor shows a tendency of increasing because other floors' visitors flow to Ground floor resulting that number of flowing in is more than flowing out. The last emptied is Napoleon hall because visitors number is very much and the speed of flow is quite low. Therefore, we can conclude that this model describes the actual situation appropriately so that we could see the changing situation on the Napoleon hall as all evacuation process in order to simplify problem's analysis.

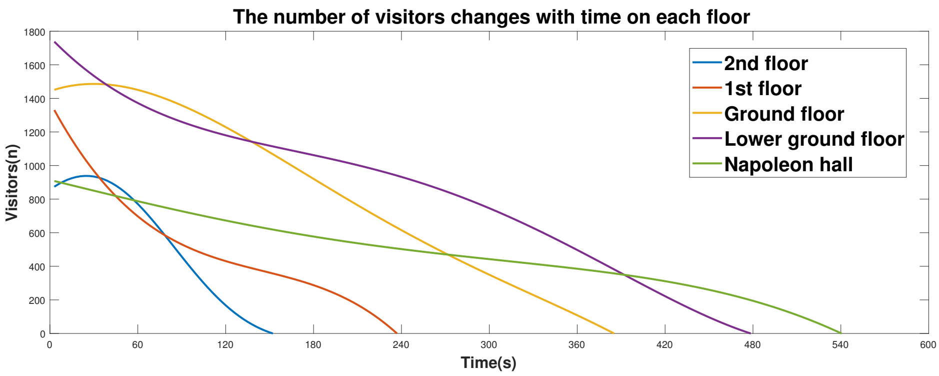

Figure 7: The number of visitors changes with time on each floor

3.5.5 The Sensitivity of Model

To test the sensitivity of multilayers, we adjust the number of visitors in the Louvre, drawing the number of Napoleon Hall into **Figure 8** because it is the last to be evacuated completely.

It is discovered that the trend of number changing is approaching to a straight line with the growth of number. That is to say, the time needed becomes longer when adding the same number.

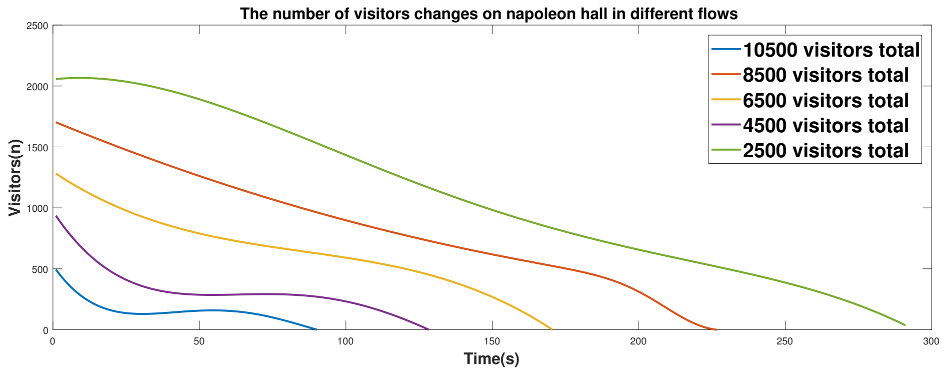

Figure 8: The number of visitors changes on Napoleon Hall in different flows

4 The Analysis of Bottleneck

4.1 Choose exits

Figure 9 describe porprotions of the main exit: the pyramid entrance and three other entrances:the Passage Richelieu entrance, the Carrousel du Louvre entrance, and the Portes Des Lions entrance. According to the analysis chart, although the pyramid entrance is the main exit and the exit with the largest capacity, visitors will escape from the nearest exit without the guide of emergency personnels, making visitors is the most at the Passage Richelieu entrance yet the pyramid entrance is the least. That is to say, visitors often confuses to choose the best exit, so emergency personnels need to arrive at the fastest speed.

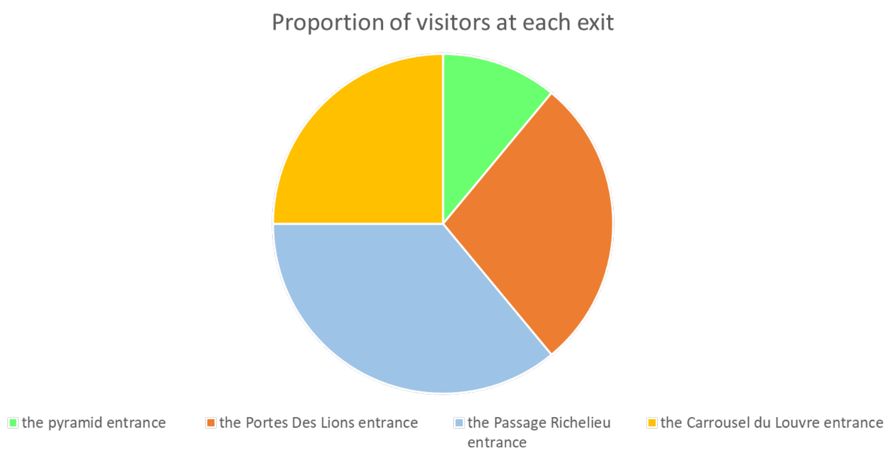

Figure 9: porprotions of visitors at each exit

4.2 Choose Stairs

In general, stairs are the easiest places to block in evacuation process. In order to search the main block reason, we calculate the flow of 7 stairs in the multilayer model in real time, drawing 4 stairs of the most flow into graph(Stair1: the Passage Richelieu main stair, Stair2: the Portes Des Lions west stair, Stair3: the Portes Des Lions norstwest stair and Stair4:the Sully main stair). As shown in **Figure 10**, the Passage Richelieu main stair takes the longest time and visitors flow reduces stepwisely with each floor down. It infers that visitors occupy all area on each floor, that is to say, there is so much visitors blocked at this stair. The situation of Portes Des Lions norstwest stair is similar to the Sully main stair but they are slightly better than the Passage Richelieu main stair. For the Sully main stair, it mainly blocks at lower floor and the highers' flow is quite less.

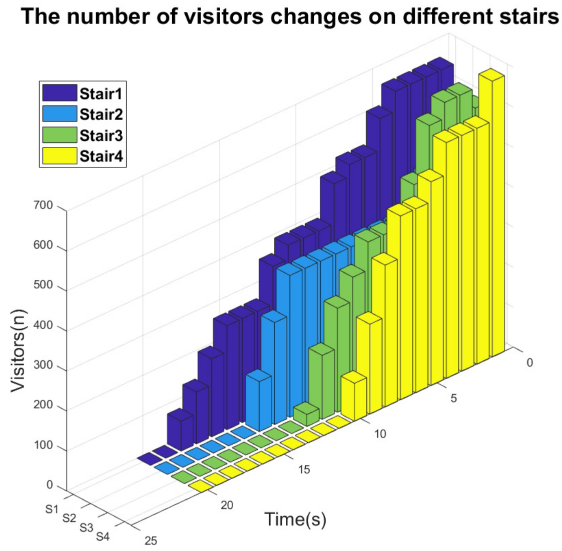

Figure 10: The number of visitors changes on different stairs

Although the flow often blocks at stairs, the width of corridor also makes a difference of the evacuation time. Under this consideration, we try to get evacuation time with different corridors and stairs as **Figure 11** shown.

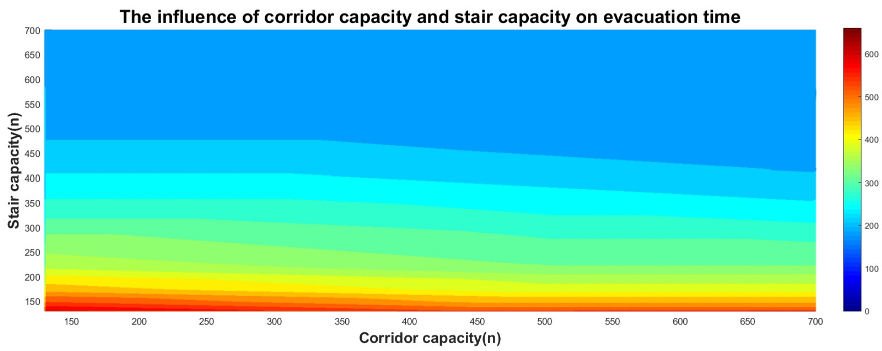

Figure 11: The influence of corridor capacity and stair capacity on evacuation time

It is obvious that the influence of corridor capacity is less significant, which infers the main factor is still stairs capacity. Due to construction cost and design specification, we believe the system has the best evacuation capability when stairs capacity is designed as 470 and corridor capacity is designed as 130.

5 Dynamic Adaptive Additional Exit Model

5.1 The Design of Model

We don't consider the influence of visitors' type and emergency personnel in the former discussion. However, vulnerable groups such as the old, the weak, the sick, the disabled and the pregnant are included in visitors, who have difficult in moving fast in emergency evacuation. It is obvious that they will make visitors flow slow down and influence others if nobody help them. At the same time, they often tumble themselves in emergency evacuation, even meet life danger. In this case, based on the assumption 6, emergency personnel need to find them and help them escape from the building. In order to make the speed of evacuation faster, we decide to schedule additional exits (service doors, employee entrances, VIP entrances, emergency exits, and old secret entrances built by the monarchy, etc.) in the Louvre. Then, we join emergency personnel into the model to let them help vulnerable groups evacuate through searching the number of open additional exits by the rate of vulnerable groups.Based on the assumption 4, the emergency personnels leave by themselves.

It is not difficult to know that the accident point has been found when emergency happen. Thus, we make a rule that open additional exits close to disaster point in turn when we start to open some additional exits. We set the percentage as 5% and 10% respectively. In this condition, we study the evacuation time will change in how way when opening different numbers of emergency exits.

Based on the definition of the additional exits in assumption of 7, we assume there are 5 additional exits at node 1st, 3rd, 11th, 17th and 19th . At the same time, the emergency channels are divided from regular channels whose capacity is 50, protecting vulnerable groups from rapid flow.

5.2 The Effectiveness of Model

As is shown in **Figure 12** and **Figure 13**, when the percentage is 5% on the premise of 6500 visitors, we find that the effect of opening 3 additional exits, 4 additional exits or 5 additional exits, but the time of opening 2 additional exits is more than opening 3 additional exits (3rd, 11th, 19th) and the distance is about 1 minute. Like as 5%, the effect of opening 4 additional exits (1st, 3rd, 17th, 19th) is better. Therefore, the number of opening additional exits is determined by the number of vulnerable groups in a large degree.

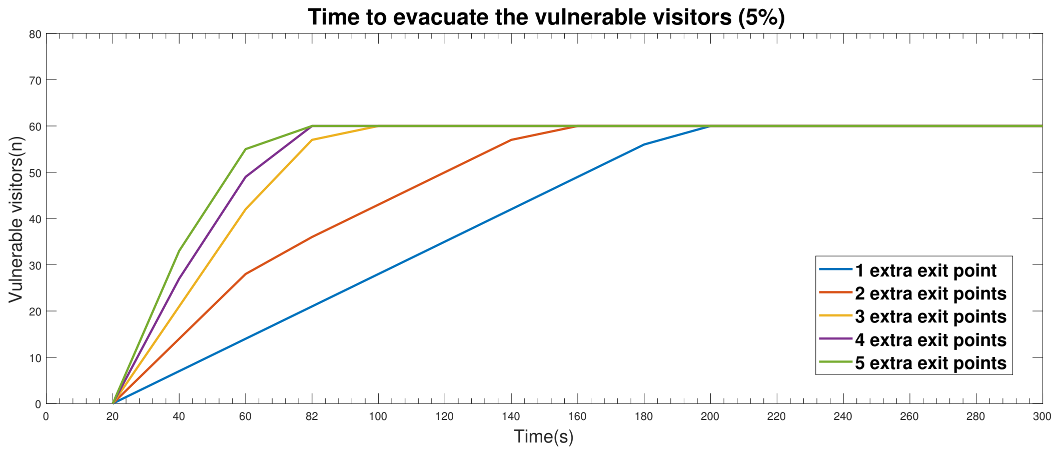

Figure 12: Time to evacuation the vulnerable visitors(5%)

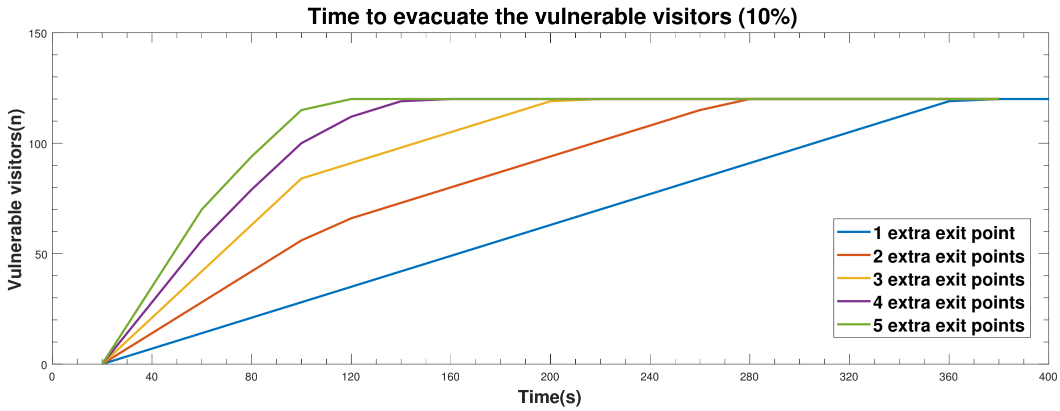

Figure 13: Time to evacuation the vulnerable visitors(10%)

6 Model Verification—-Take the Palace Museum as An Example

We operate the model in the condition of the Palace Museum in china to test its sensitivity.

6.1 Evacuation Simulation of the Palace Museum

The Palace Museum, also known as the Forbidden City, and the vast holdings of paintings, calligraphy, ceramics, and antiquities of the imperial collections make it one of the most prestigious museums in China and the world. The Palace Museum looks as **Figure 14** demonstrates.

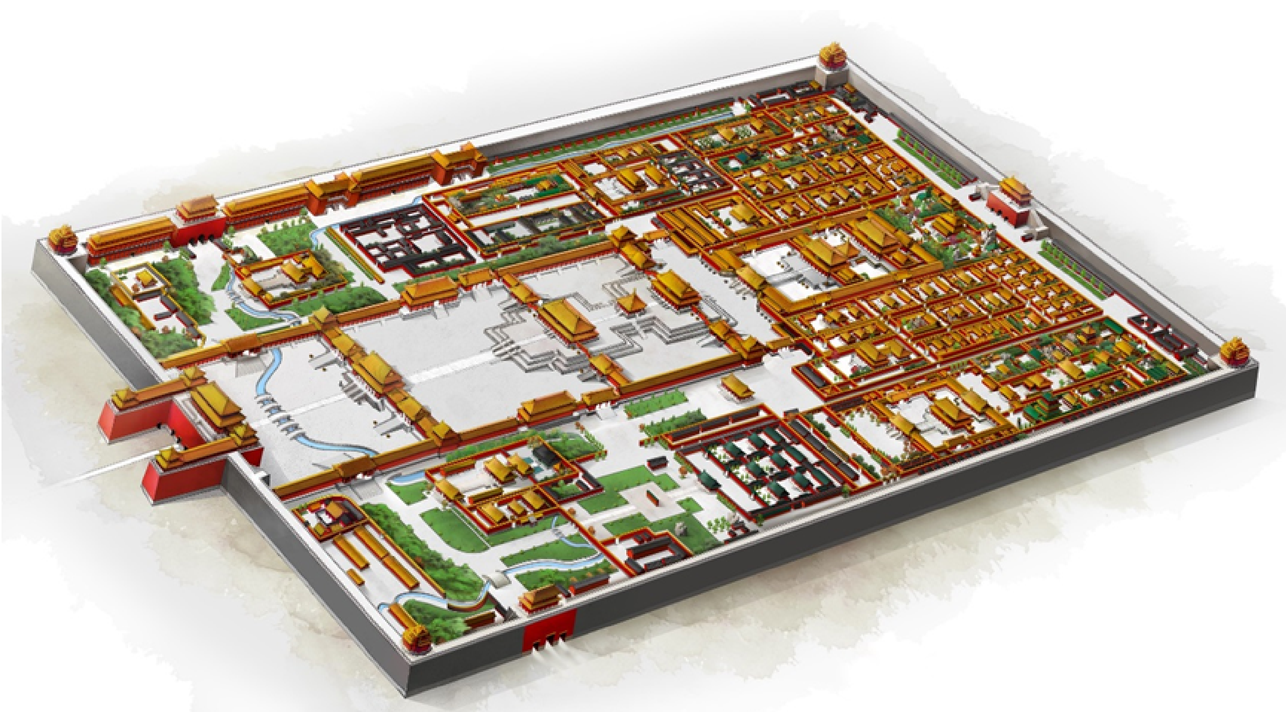

Figure 14: the Palace Museum

The Palace Museum is a layer structure with a few exits, including a main exit and three other exits. Compared with the Louvre, there are some difference as follow:

- For the evacuation model, the Louvre belongs to multilayer multi-exit evacuation with considering the impact of different floors' flow, but the Palace Museum belongs to single-layer multi-exit evacuation whose horizontal distance is quite far.
- For the evacuation structure, the structure of the Louvre is simple so that visitors can find exits easily. However, the structure of the Palace Museum is more complex where visitors hardly find any exits and rely on emergency personnels' help more.
- For the application of additional exits, additional exits of the Louvre barely coincide with regular exits. But the Palace Museum is surrounded by moat, only having four exits. Therefore, the key of solving the Palace Museum's emergency evacuation is to schedule emergency channels.

6.2 The application of single-layer multi-exit evacuation

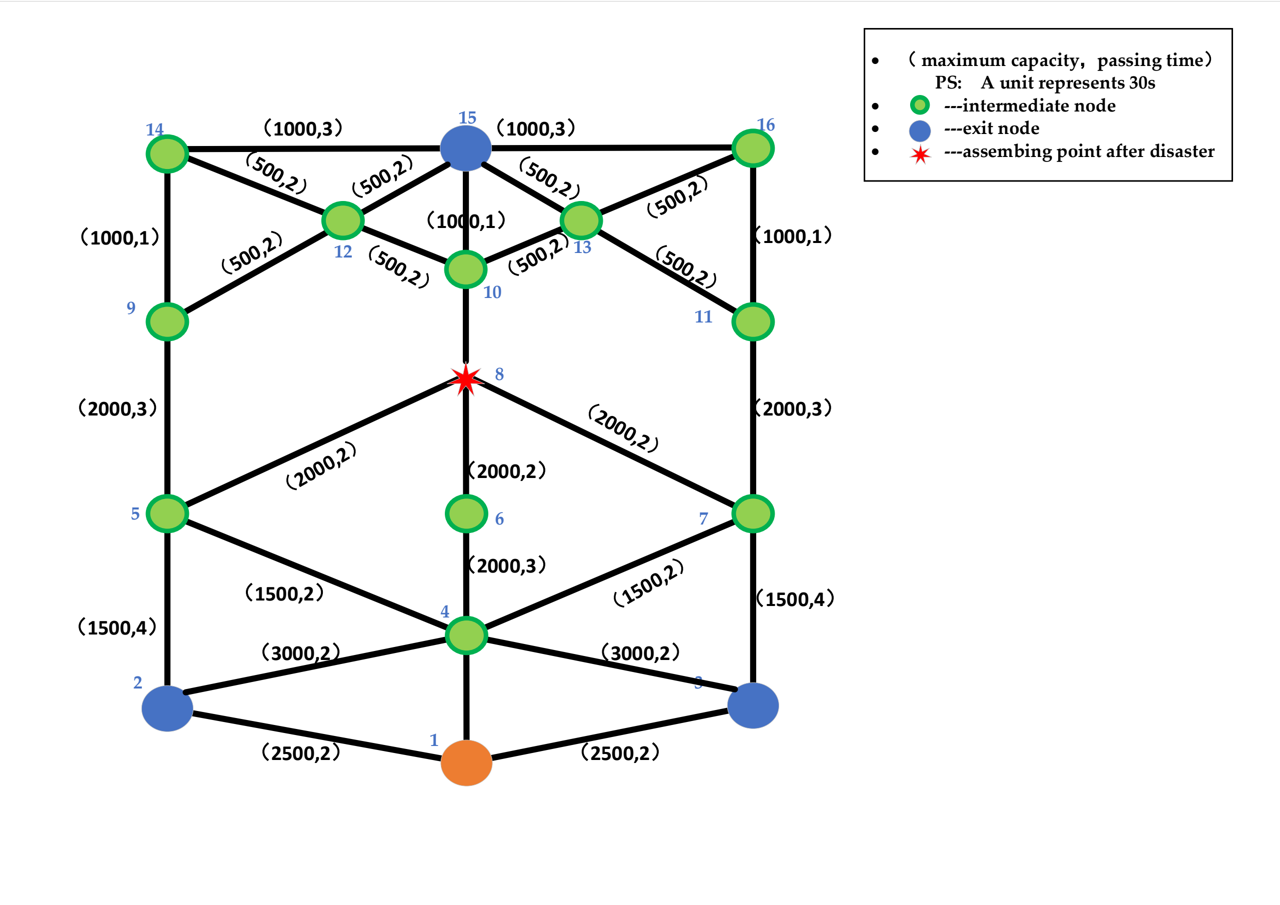

Figure 15: the evacuation network of the Palace Museum

Figure 15 describes the evacuation network of the Palace Museum. The numbers in bracket around arc are maximum capacity and travel time of the arc respectively. Assume 7000 visitors need to be evacuated at the point 8, we get the collection of export paths P, collection of path evacuation time TP and collection of path flow X. **Table 5** describes these collections and relevant parameters.

Table 5: The evacuation paths of 7000 visitors at the Palace Museum

label	path P_l	actual flow f_l	total travel time T_{P_l} (s)	number of evacuation s_l
1	8-10-15	1000	120	1000
2	8-10-13-15	500	300	500
3	8-5-2	1500	360	1500
4	8-7-3	1500	360	1500
5	8-5-4-2	500	360	500
6	8-7-4-3	500	360	500
7	8-6-4-2	2000	420	1500

6.3 Sensitivity Analysis

Select different visitors flow, and draw a trend chart with time changing as **Figure 16** demonstrates. With the growth of visitors flow, evacuation time grows more and more, showing our model is effective and applicable.

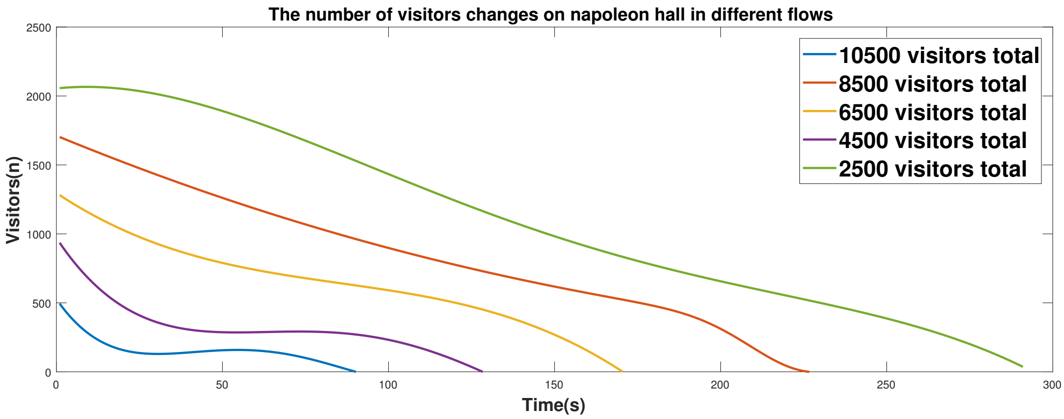

Figure 16: The number of visitors changes with time in the Palace Museum

7 Conclusion

7.1 Strengths and Weaknesses

Strength:

- Considering the evacuation speed of visitors and the flow of people in each evacuation path, we discuss the single-layer and multi-layer evacuation of the Louvre and establish the evacuation model.
- Considering multiple staircases on each floor, a single-layer with multi exits evacuation model is established. The evacuation area is networked by graph theory, the feasible path evacuation algorithm is used to get the feasible path of the network graph, and the evacuation time is simulated.
- We reduce the dimension of the Louvre's multi-layer structure, connect each floor through "a virtual staircase", consider the interaction of the flow of people after the connection, establish a multi-layer with several exits evacuation model, and analyze the bottleneck.

- In order to ensure that the vulnerable groups such as the old, the weak, the sick, the disabled and the pregnant do not affect the evacuation process, we establish a dynamic adaptive additional exit model to determine the number of additional exits according to the proportion of vulnerable groups.
- We apply our model to the evacuation of the Palace Museum, draw a practical evacuation route, and summarize the use of additional channels.

Weaknesses:

- In our model, the capacity and time for each arc are determined, which will be different from the actual situation.
- In the multi-layer evacuation model, we neglect the influence of vulnerable groups on evacuation, but consider vulnerable groups separately. Nor do we consider the potential risks during the evacuation.
- In the dynamic adaptive additional exit model, we assume that the emergency exit of the Louvre is in four corners of each floor, but it may be different in real life.

7.2 Future Plans

Our Louvre evacuation plan can effectively solve the problem of single accident with non-proliferation evacuation in dynamic environment, but in many places our setting is too idealized. For example, in real-life environment, when the fire happens or the gas leak, the scope of accidents will be enlarged with time. In a terrorist attack, terrorists usually hold a large number of hostages, which prevent the evacuation of the crowd. Solutions to these problems will be considered in future work.

In terms of the applicability of our model, we tried to apply the Louvre-evacuation-model to the Imperial Palace. Although the result is acceptable after analyzing and adjusting, it still needs to make a lot of work to adapt to different buildings. In later work, we can continue to improve the applicability of the model.

7.3 Suggestions Recommendations Paper

Dear sir/Madam:

Along as terrorist attacks and other emergencies occur in France more and more frequently, we need to pay attention to the Louvre this popular building's emergency evacuation plan.

First, we establish a multi-story multi-exit evacuation model to get practical results and we find that there are bottlenecks: the choice of exits and the congestion of stairs. Based on this conclusion, we propose the following suggestions:

- For the guiding staff in the building, they need to be equipped with an application software which can show the real-time traffic of each exit, so as to achieve rapid and accurate guidance.

- In the later decoration of the Louvre, the width of corridors and stairs can be more reasonably considered, so that people can be successfully evacuated.
- In terms of personnel management, they should have professional emergency response training, so that they can leave as soon as possible after the completion of the evacuation of visitors.

Then, we optimize the previous model, to consider the impact of vulnerable groups such as the elderly, the weak, the disabled and the pregnant. In view of this problem, we put forward the following suggestions:

- For vulnerable groups, extra exits should be opened, and further advance the safety equivalence of these channels, such as increasing ground friction to prevent falls, and installing protective fences on both sides of the path.
- For vulnerable groups, extra exits should be opened, and further advance the safety equivalence of these channels, such as increasing ground friction to prevent falls, and installing protective fences on both sides of the path.
- For emergency personnel, a special emergency personnel should be designated to evacuate the vulnerable groups.

Finally, since we believe that language differences will not have a significant impact in the emergency response process, and body movements can replace oral expression, so we suggest that:

- In the venue, on the basis of setting multi-language signs, some billboards of body language teaching should also be set up so that visitors can understand some emergency gestures in case of emergency and protect their own safety.

All of above are the bottlenecks and solutions we find through our model. However, due to time constraints, our research has its limits. But we really hope our recommendations can help you in some way and we also hope you can handle the emergency management of the Louvre very well. The greatest hope is that there is no danger and everything is safe.

Thanks for your attention

References

[1] Gao M.X. , He G.G., Study on evacuation traffic route considering characteristics of intersections[J].Journal of civil engineering.2007, 40(6): 80-83.

[2] Chen Pohan, Feng Feng. A fast flow control algorithm for real-time emergency evacuation in large indoor areas [J]. Fire Safety Journal(S0379-7112), 2009, 44(5): 732-740.

[3] HELBING D, FARKASI, VICSEK T. Simulating dynamical features of escape panic [J]. Nature, 2000, 407(6803):487-490.

[4] https://www.louvre.fr/zh.

[5] Yang J.F., Gao Y., Wang H.J., Emergency evacuation model and algorithm for multistory buildings, 2014,26(02):267-273.

[6] Yang J.F., Gao Y., Li L.H., Emergency evacuation model and algorithm for multi-export building emergencies, 2011,31(S1):147-153.

A Appendix

Table 6: 1800 visitors on the 1st floor

label	path P_l	actual flow f_l	total travel time T_{P_l} (s)	number of evacuation s_l
1	S(D)-D14-D10-D7-D6-D_l	550	150	550
2	S(D)-D14-D10-D7-D4-D3-D6-D_l	150	210	150
3	S(D)-D14-D13-D12-D18-D17-D_2	300	240	300
4	S(D)-D16-D11-D9-D8-D7-D4-D3-D6-D_l	200	270	200
5	S(D)-D16-D11-D9-D8-D7-D4-D3-D2-D5-D6-D_l	550	330	550
6	S(D)-D16-E16-E15-E14-E20-E19-E18-E17-D17-D_2	150	360	50

Table 7: 1400 visitors on the Ground floor

label	path	actual flow	total travel time	number of evacuation
1	SC-C14-C10-C7-	150	180	150
2	SC-C14-C13-C12-C18-	550	180	550
3	SC-C14-C20-C19-C18-	200	210	200
4	SC-C16-C11-C9-C8-C7-C4-C3-	200	240	200
5	SC-C16-C11-C9-C8-C7-C4-C3-C2-C5-	300	270	300
6	SC-C16-D16-E16-E11-E9-E8-E7-E4-E3-E2-E5-E6-D6-	500	420	500

Table 8: lower ground floor

label	path	actual flow	total travel time	number of evacuation
1	SB-B14-B10-	700	90	700
2	SB-B14-B13-B12-	300	120	300
3	SB-B16-B11-B9-B8-B7-B6-	550	210	550
4	SB-B16-B11-B9-B8-B7-B10-	550	240	150

Table 9: 900 visitors on the Napoleon Hall

label	path	actual flow	total travel time	number of evacuation
1	SA-A14-	700	60	700
2	SA-A14-A13-A12-	250	90	250
3	SA-A16-B16-C16-C11-C9-B9-B8-B7-B4-B3-B2-B5-B6-	150	540	50