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2019
MCM/ICM
Summary Sheet

Race against time —Emergency evacuation plan for the Louvre

Summary

Emergency will result in a large scope of damage. If there is no effective evacuation strategy, it is very likely to cause unnecessary congestion or even secondary damage during the evacuation process. To this end, it is necessary to generate evacuation plans, assign reasonable routes to people in dangerous locations as soon as possible, make maximum use of the capacity of the passage and reduce congestion so that visitors can reach safe places as soon as possible.

Our aim is to develop an **emergency evacuation plan** for the Louvre, for which we develop two models at the macro and micro levels. Then we develop an adaptive model related to potential threats. We obtain total evacuation time in different situations and optimal route by solving our model.

In Macro emergency evacuation model, we simplified the Louvre into a graph . To obtain optimal route, we use **time expanded graph** to transform the problem into minimum cost flow theory. To solve the problem, we use algorithm based on **Capacity Constrained Route Planning(CCRP)**. Then we draw a conclusion that the time taken by the latest person arriving at the exit is 330s. The results of the optimal route are shown in Table 1. We also explore the utilization of app "Affluences" to help us improve our plan.

In Crowd evacuation behavior model, we analyze people's **pre-movement time** and people's **movement velocity**, which will influence the whole evacuation process. What's more, we did some simulation of several evacuation scenarios in the Louvre.

In Potential threats of circumstances model, we explore the reason that bottlenecks occur. We find that although people arrive at exit quickly, they have to wait for a long time to go out. It takes about 1860s. To improve the model, we introduce the node capacity and utilize additional exits. It takes about 450s to leave the Louvre by utilizing 2 exits at 150s and 4 exits at 180s. We also build an emergency personnel entering model to explore when they can enter the Louvre to prevent potential threats.

Besides, we do some sensitivity analysis about the speed of movement and potential threats. We also propose some policies and suggestions for the Louvre. Finally, we briefly state the application of our models in other large, crowded structures.

Keywords: Evacuation CCRP optimized route potential threats bottlenecks

Contents

1 Introduction

Problem Background

In recent years, an increasing number of terror attacks in Paris have triggered new thinking on urban security and contingency measures, especially how to safely and effectively evacuate people in public places. As one of the most visited landmarks in France, the Louvre is marked by rich and marvelous exhibitions which appeal to tens of thousands of people from across the globe.

In an effort to decrease the damages that result from emergencies, it is of utmost importance for the museum to design emergency evacuation plans. To come up with a comprehensive and optimal plan, there are lots of factors related to the actual situation of the Louvre to be considered.

Interpretation of the Problem

1) We should develop an emergency evacuation model that allows individuals egress to and through an optimal exit in order to empty the building as quickly as possible, while also allowing emergency personnel to enter the building as quickly as possible.

2) We should take the fact that the number of guests in the museum varies throughout the day and the diversity of visitors into consideration. Further more, we should figure out how technology such as Affluences could be used to facilitate our evacuation plan.

3) Considering the public awareness of total exit points(service doors, employee entrances, VIP entrances, and old secret entrances built by the monarchy, etc.) serves as a double-edged sword, we should analyze carefully when and how any additional exits might be utilized.

4) We should build an adaptable model that can address a broad set of considerations and various types of potential threats. Validate the model and discuss how the Louvre would implement it.

5) Propose policy and procedural recommendations including applicable crowd management and control procedures that are necessary for the safety of the visitors for emergency management of the Louvre.

Overview of our work

First, we develop a Macro emergency evacuation model to explore the optimized evacuation routes. We also consider how technology helps to facilitate our plan.

Second, we analyze people's behavior during specific evacuation process, including pre-movement time and movement time. In this way, we can optimize our first model by considering something detailed. We also do some simulations of evacuation scenarios in the museum.

Then, we solved other problems raised by the topic.

- How to prevent bottlenecks? To solve the problem, we should decide when and how to utilize additional exits.

- When should emergency personnel enter the museum.

Last, we make a sensitivity analysis about the speed of movement and potential threats.

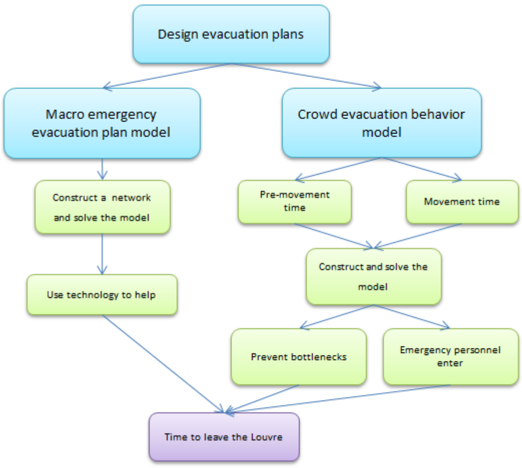


Figure 1: Overview of our work

2 Preliminaries

2.1 Constructing the Louvre evacuation network

According to the Louvre Museum Plane Map, the Louvre has five floors, and there are three exhibition halls on each of the upper four floors: RICHELIEU, DENON and SULLY. We assign a specific number to each exhibition hall and get a simplified floor plan of Louvre as shown in Figure 2.

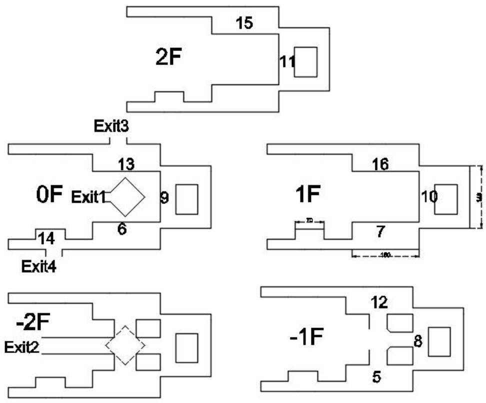


Figure 2: The floor plan of Louvre

We begin to build the Louvre evacuation network by making some reasonable assumptions:

- Under normal circumstances, tourists gather in exhibition halls. For simplicity and without loss of closeness to reality, we do not consider the tourists scattered on the stairs and corridors before an emergency.
- The evacuation channel between the exhibition halls has a limited capacity and can only allow a certain number of people to pass at a time.

Define $V(G) = v_1, v_2, \ldots v_{16}$ as the set of all exhibition halls and exits, where $v_1 \ldots v_4$ denotes the four main entrances/exits—the pyramid entrance, the Carrousel du Louvre entrance, the Passage Richelieu entrance and the Portes Des Lions entrance respectively, $v_5 \ldots v_{16}$ denotes the three exhibition halls situated on the upper four floors of Louvre: RICHELIEU, DENON and SULLY. Define $E(G)$ as the set of edges of the network. Each edge denotes all available evacuation routes between two nodes. $(v_i, v_j) \in E(G)$ if one of the followings holds:

- i and j are neighboring exhibition halls on the same floor.
- i and j are the same exhibition hall on the directly-related floors.
- i is an exhibition hall and j is a directly-connected exit.
- i and j are neighboring exits.

$G = \{V(G), E(G)\}$ is defined as the graph of Louvre evacuation network. Additionally, edge ij is marked by two attributes: travel time and edge capacity, which will be involved in our following models. We then visualize this network in Figure 3.

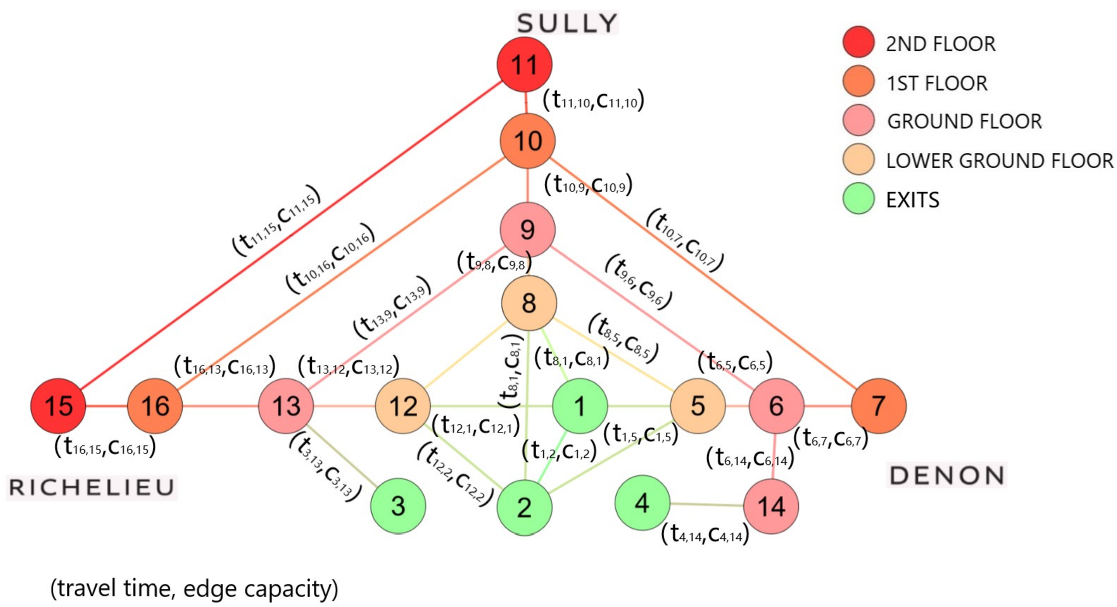


Figure 3: Louvre evacuation network

3 The Model

3.1 Macro emergency evacuation model

We introduce a Linear programming based method to model the emergency evacuation on the basis of the above Louvre evacuation network. Firstly, We summarize some basic rules:

- The emergency departments in authority broadcast emergency announcements which are always clearly heard by individuals. And people evacuate to safe places in the guidance of emergency personnels.

- The Louvre received 10.2 million visitors in 2018[1]. In this model, we assume that the number of visitors is uniform. (we will discuss the variety of number of guests in the following section.)

- We assign numbers of visitors to each exhibition hall based on their popularities among people. For example, the treasure "Mona Lisa Smile" on the first floor of DENON WING will attract more visitors than others.

- The distance between different exhibition halls is defined as the straight-line distance. Note that the distance between the same exhibition halls on directed-related floors is the path length of the stairs.

- Due to the lower security level at the additional exits compared to four main entrances, we prioritize the four main entrances in our original model.

3.1.1 Mathematical notations

In order to clearly illustrate our model, we now settle down some mathematical notations:

- n_i: the initial occupancy of visitors in node i, $i = 5 \ldots 16$,which denotes an exhibition hall

- D_{ij}: the length of path between node i and node j

- $v = \begin{cases} v_1, \text{visitor's moving speed on the ground} \\ v_2, \text{visitor's moving speed on the stairs} \end{cases}$

- t_{ij}: average time period required for a visitor to move from node i to node j. $t_{ij} = \frac{D_{ij}}{v}$

- U_{ij}: the maximum capacity of edge ij

- f_{ij}: the number of visitors evacuating through edge ij from node i to node j

3.1.2 The model construction

To solve the original problem, we introduce a **Linear programming based method**. More specifically, we transform the network into its time-expanded graph and solve the minimum cost flow problem on the graph.

- **Time expanded graph**

The time expanded graph needs to be expanded by a multiple of the time. We have to copy the nodes of the original image according to how many units of time that are required for the evacuation process. A time expanded graph based on the original network is shown in Figure 4.

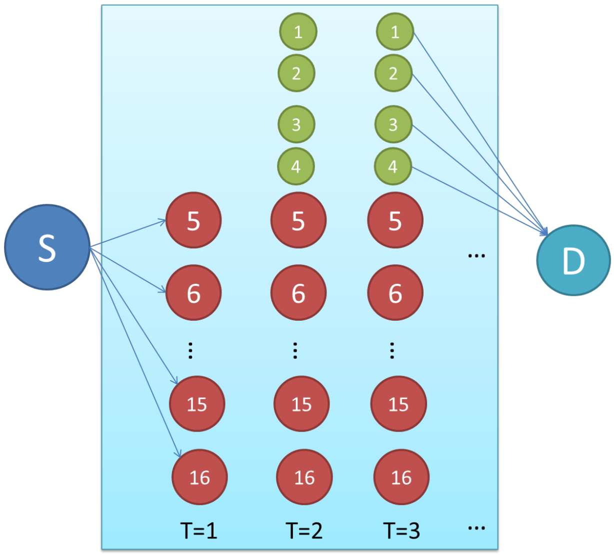


Figure 4: Time expanded graph of the Louvre evacuation network

As is shown in the graph, nodes 5-16 are source nodes, from which visitors evacuate. Nodes 1-4 are destination nodes, which represent the safe exits. S denotes the virtual Super source node. The population to be evacuated in S is the sum of the population to be evacuated in all source nodes. Similarly, D denotes the virtual Super destination node, it can accommodate all the population to be evacuated. Note that we have omitted the specific edges between the nodes for simplicity.

- **Minimum cost flow theory**

We introduce a novel method to model the evacuation process, which is conceptually similar to Minimum cost flow theory.

The objectve for the model is:

– the minimum time taken for all visitors to move from exhibition halls to exits.

The constraints for the model are:

– All the visitors must be evacuated to safe places. Thus total number of visitors evacuating to safe places(exits) must be equal to the total initial occupancies of all exhibition halls.

– During the evacuation process, the total number of people who flow out of the exhibition hall and that of people flowing into the exhibition hall are dynamically balanced, that is, the number of people who flow out minus that of people flowing into the exhibition hall is equal to total initial occupancies.

– The number of visitors evacuating through edge ij from node i to node j at a time must be no greater than the max capacity of edge ij.

These objectives and constraints are realized by:

$$\min \sum_{(i,j)\in G} t_{ij} f_{ij} \tag{1}$$

$$S.T. \begin{cases} \sum_{k=1}^{4} \sum_{j \in V(G)} f_{jk} = \sum_{i=5}^{16} n_i \\ \\ \sum_{i=5}^{16} (\sum_{j \in V(G)} f_{ij} - \sum_{j \in V(G)} f_{ji}) = \sum_{i=5}^{16} n_i \\ \\ 0 \leq f_{ij} \leq U_{ij} \end{cases} \tag{2}$$

3.1.3 To solve the model

The method based on linear programming has certain drawbacks. For example, the increasing number of nodes and time steps in time expanded graph will introduce expensive computatinal costs. As a result, we introduce an algorithm based on **Capacity Constrained Route Planning(CCRP)**[2].

Step 1 Input a graph G with a set of nodes N and a set of edges E. Define S as the set of source nodes, D as the set of destination nodes, $S, D \subseteq N$. Each node n has a property: Initial node occupancy. Each edge e has two properties: Maximun edge capacity and Travel time.

Step 2 For a source node $s \in S$, if it still has evacuees, use Dijkstra Algorithm to find the route $R < n_0, n_1 \ldots n_k >$ with time schedule $< t_0, t_1 \ldots t_k >$ from source node s to all destinations, and then determine the Earliest Arrival Path.

Step 3 Determine the flow on the Earliest Arrival Path. It follows: $flow{=}Min\{$number of evacuees still at source node s, available capacity of edge $i\}$, where edge i lies on the Earliest Arrival Path.

Step 4 "Reserve" edges on the Earliest Arrival Path. Subtract the value of flow from the available capacity of each edge on the Earliest Arrival Path, and return to **Step 2**.

The basic results of evacuation routes are as Table 1:

Notes: the percentages in the table present the allocating proportion of evacuees on the corresponding route.

According to the analysis of Table 1, we can conclude:

Law one Two exhibition halls of SULLY and RICHELIEU on the 2nd floor need the longest evacuation time: 330 seconds, which is also the time required to evacuate all visitors in Louvre.

Law two More effective evacuation path is the path between the same exhibition halls on different floors, while the path between different wings on the same floor is almost not used. This is partly because of the long length of path between wings on the same floor. Further more, movement between different exhibition halls not significantly reduce evacuation time because the exits are on the lower floors.

Law three It can be seen that the No.2 exit (i.e. the Carrousel du Louvre entrance) is hardly used alone because it is rather far. When the available capacity of the path to the No.1 exit is insufficient, the No.2 exit will be selected.

Law four No.1 exit (The pyramid entrance) is the most used exit for evacuation because it is located in the center of the Louvre and is near to all wings.

Table 1: Evacuation routes

Source node	Arrival time(s)	Routes
5	100	5→1
6	144	6→5→1(36%) 6→14→4(64%)
7	240	7→6→14→4(22%) 7→6→5→1(33%) 7→6→5→2(45%)
8	60	8→1
9	160	9→8→1(75%) 9→8→2(25%)
10	240	10→9→8→1(78%) 10→9→8→2(22%)
11	330	11→10→9→8→1(80%) 11→10→9→8→2(20%)
12	50	12→1
13	96	13→3
14	64	14→4
15	330	15→16→13→12→1(66%) 15→16→13→3(34%)
16	180	16→13→12→1(66%) 16→13→3(34%)

- **Using technology to facilitate evacuation plan**

The number of guests in the museum varies from day to day. Evacuation plan should consider the adjustments resulting from changes in the number of guests. We can use Affluences to help us estimate the number of guests in Louvre.

In macro emergency evacuation plan, we use the average number of guests in a certain period of time as the real-time visitors in the museum. In fact, the number of guests varies from weekday to weekend.

In weekday, the number of guests is less than the average. From Affluences, we know the average time required for queuing is 5 minutes and the longest is no more than 10 minutes. While in weekend, the number of guests is more than the average. And the average time required for queuing is 15 minutes and the longest is 20 to 30 minutes.

In the former case, we do not need to adjust the evacuation plan, and the final evacuation time will be less than the previous result. While in the latter one, adjustments should be made.

Queuing results from waiting for security check. We assume that the rate of guests passing the security check is 1 person per second. The peak period of the queuing time is 15 to 25 minutes more than the average, so the number of guests is 900 to 1,500 more than the average. Use Macro emergency evacuation model to calculate an increasing number of guests. Due to space limitations, the result is omitted. After calculating, it takes 350s-370s to get all the guests who arrive at the exit in the peak period. There is an increase in evacuation time compared to the initial plan.

Figure 5 shows relationship between museum guests and evacuation time, which can help facilitate evacuation plan.

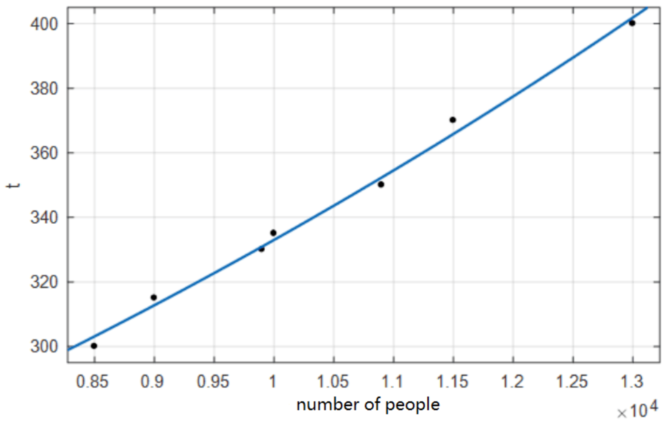


Figure 5: the relation between population and evacuation time

In reality, people's evacuation during emergency is a complex task. The implementation of evacuation plans is influenced by many factors. In the following sections, we will discuss how the behavior of evacuated people and the potential threats in the emergency environment affect the evacuation process.

3.2 Crowd evacuation behavior model

Our first model does not consider the complex terrain of the Louvre, so we develop the second model to analyze specific passing time during evacuation process. We first divide the evacuation process into two period: Pre-movement and Movement. The former describe people's recognition and response to the emergency alert, while the latter involves the evacuating behavior after recognition.

3.2.1 Pre-movement

The response time to an emergency will largely determine the damage caused by the disasters. It is necessary to analyze pre-movement behavior in making evacuation plans. In this period, we focus on two factors: evacuation information and human relations.

- **Evacuation information**

Evacuation information refers to signals of emergency events, emergency conditions, evacuation routes etc., which are usually released by announcements from those in authority and disseminate among evacuees. The more evacuees be infomed of the evacuation information in the pre-movement period, the more people safely evacuaed. To begin with, our added assumptions for the diversity of visitors of Louvre are listed below:

- Considering the international practices and cultural background, evacuation notices are only announced in English and French. Visitors from other countries may have difficulty in understanding the information rapidly.
- Because a large proportion of visitors come from France, The United Kingdom, The United States, Germany, Italy, Brazil and China, we neglect visitors from other countries to simplify our model.

As a result of the diversity of visitors—speaking a variety of languages, evacuation guidance information issued by relevant security departments cannot be quickly and effectively transmitted. We have the following proportion of tourists from different countries[3]:

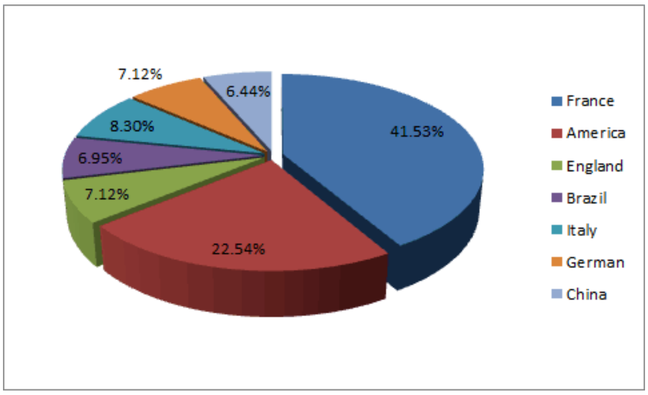


Figure 6: The proportion of tourists from different countries

According to Figure 6, although the visitors from France, the United Kingdom and the United States accounted for nearly 70%, a significant number of tourists come from countries that are not native speakers of French or English. We analyze the effect of the diversity of tourists on the propogation of evacuation information from the following two aspects:

Understanding difficulty Due to the language diversity, different visitors have different levels of understanding on evacuation information. Some visitors may have difficulty in understanding the information quickly. From the individual level, we define U as the Understanding difficulty coefficient:

$$U = \begin{cases} 0, \text{visitors from France,The United States or The United Kingdom} \\ 1, \text{visitors from non-Franch or non-English speaking countries} \end{cases} \tag{3}$$

Communication among evacuees Visitors from the same country will continue to improve their evacuation information through communication during the evacuation process. People communicate and share information among themselves and adjust their actions and behaviors accordingly[4]. We calculate Communication coefficient C as:

$$C = \frac{1}{e^{kp}} \tag{4}$$

where p is the normalized proportion of visitors from different countries. k is a parameter reflecting the influence of communication. We set $k = 5$ in the follwing simulation in this part. The informtion tend to propogate at a fast speed. So the exponential term in this expression can depict the effect of communication.

We use weighted sum to incorporate the two factors, the Evavuation information indicator is defined by:

$$E = t_1 U + t_2 C \tag{5}$$

where $t_1 + t_2 = 1$.

- **Human relations**

When considering groups traveling together in Louvre, the factor of human relations influences evacuees' mental states in evacuation process. Furthermore, previous work shows that the pre-movement time could be significantly influenced by the phenomena of attachment to people (waiting to be reunited with family members and friends)[5]. For a visitor, the more people in his group, the more effects of attachment on his pre-movement time. The groups traveling together in Louvre are roughly classified as follows:

Table 2: Groups classification

	proportion	numbers of people in a group(num)
Big grouo(>=7)	13.8%	$num \sim N(8, 4^2)$
Small group (2–6)	70%	$num \sim N(4, 2^2)$
Single	16.2%	$num = 1$

For a visitor, the Human relations factor affecting his pre-movement time in terms of attachment to people is defined as:

$$H = \frac{a \times num}{a \times num + 1} \tag{6}$$

where num presents the numbers of people in his group, a is a parameter.

- **To solve the model**

In this part, we present our simulation results of visitors' pre-movement time coefffi-cien which indicates the pre-movement time span by incorporating the two indicators of Evacuation information and Human relations. We have the coefficient of pre-movement time: $t_k = c_1E + c_2H$, and set $a = 3, t_1 = 0.3, t_2 = 0.7, c_1 = 0.7, c_2 = 0.3$. With 500 people involved in the simulation, Figure 7 shows the distribution of pre-movement time among visitors.

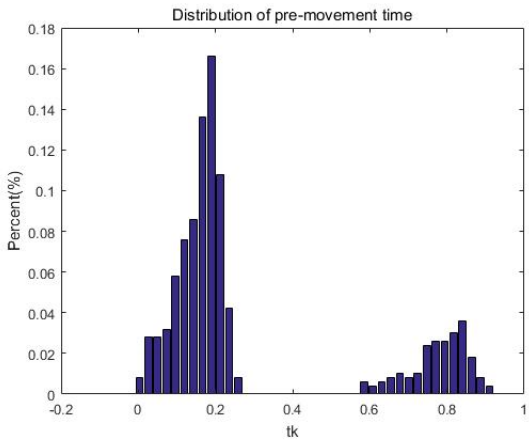


Figure 7: the distribution of pre-movement time

The pre-movement time of tourists from Franch and English speaking countries gather around 0.1, while that of tourists from other countries gather around 0.8. Both of two parts showed a normal distribution trend. It is because the tourists from Franch and English speaking countries have better and more timely understanding of the evacution information due to the language convenience and communication among evacuees. The normal distribution trend of two parts is attributed to the factor of Human relations.

Increased pre-movement time will lengthen evacuation time, so the time that the latest person arrives at the exit will be extended. Museum should try to reduce pre-movement time.

3.2.2 Movement

In this section, we introduce a velocity analysis model to ananlyze the movement of evacuees in the Louvre. Taking the instantaneous velocity, ecucuees density and collision in the process into consideration, we mainly focus on the movement direction of evacuees under the guidance of museum staffs. We first set some mathematical notations:

- r : Through physical abstraction, we see the individual as a sphere of radius r.
- Δt : a tiny time interval.
- $\rho^{(k)}(x, y)$: the crowd density distribution function at time $k\Delta t$.
- $\overrightarrow{r_i{}^{(k)}} = (x_i^{(k)}, y_i^{(k)})$: the displacement vector of ecacuee i at time $k\Delta t$, where $x_i^{(k)}$, $y_i^{(k)}$ indicate position coordinates.
- $\overrightarrow{r_L^{(k)}}$: the displacement vector of museum staffs at time $k\Delta t$, who serve as evacuation guides.
- $\overrightarrow{v_i^{(k)}}$: the velocity vector of evacuee i at time $k\Delta t$.

- **The crowd density distribution function**

Population density distribution can be considered as continuous change. Based on Spatial Continuous Surface Model [6], we get the density distribution function of Louvre. The basic rules is summarized as follows:

- Divide the area into grids;
- Convert the population of the area into population density;
- Place a central point in each area and assign the population density to the center point;
- Use an interpolation method to interpolate the population density at the point into the grid surface.

- **Determine the velocity at time $k\Delta t$**

The velocity of evacuee i at $k\Delta t$ is composed of three velocity components. We give the expression and then analyze the components respectively.

$$\overrightarrow{v_i^{(k)}} = v_f \overrightarrow{d_{fi}^{(k)}} + v_c \overrightarrow{d_{ci}^{(k)}} + v_r^{(k)} \overrightarrow{d_{ri}^{(k)}} \tag{7}$$

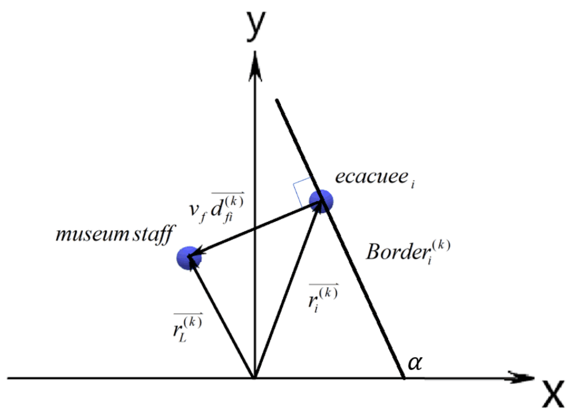


Figure 8: Spatial positional relations of vectors

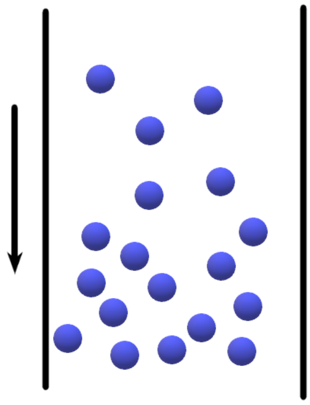


Figure 9

- **Following velocity**: $\overrightarrow{v_{fi}} = v_f\overrightarrow{d_{fi}^{(k)}}$, where v_f is a constant, and $\overrightarrow{d_{fi}^{(k)}}$ is the unit vector in the direction of following velocity. During the evacuation process, the evacuated crowd will move under the guidance of museum officials and have a following velocity component. As Figure 8 shows,

$$\overrightarrow{d_{fi}^{(k)}} = \frac{\overrightarrow{r_L^{(k)}} - \overrightarrow{r_i^{(k)}}}{||\overrightarrow{r_L^{(k)}} - \overrightarrow{r_i^{(k)}}||} \tag{8}$$

- **Corrected velocity**: $\overrightarrow{v_{ci}} = v_c\overrightarrow{d_{ci}^{(k)}}$.

Due to the large number of evacuees, it is obviously impossible to move straight toward the guidance. It can be reasonably assumed that the evacuated people will adjust the moving direction according to the surrounding environment while generally maintaining the following trend. They tend to move toward the smaller density area and to avoid walls and obstacles.

Next, we discuss the corrected direction $\overrightarrow{d_{ci}^{(k)}}$ of evacuee i located in $\overrightarrow{r_i{}^{(k)}} = (x_i^{(k)}, y_i^{(k)})$ at time $k\Delta t$. Considering the evacuee tend to move in the direction with the fastest decline in density, based on the knowledge of calculus, it is just the negative gradient direction of $\rho^{(k)}(x,y)$ in $(x_i^{(k)}, y_i^{(k)})$ i.e. $-\nabla\rho(x_i^{(k)}, y_i^{(k)}) = (-\frac{\partial\rho}{\partial x_i^{(k)}}, -\frac{\partial\rho}{\partial x_i^{(k)}})$. Thus we have

$$\overrightarrow{d_{ci}^{(k)}} = \frac{-\nabla\rho(x_i^{(k)}, y_i^{(k)})}{||\nabla\rho(x_i^{(k)}, y_i^{(k)})||} \tag{9}$$

In fact, as shown in Figure 9, in spite of the smaller density behind the crowd, it is obviously impossible for the evacuees to run backwards. Therefore, it is necessary to further optimize the corrected direction $\overrightarrow{d_{ci}^{(k)}}$.

As is shown in Figure 8, make a line $Border_i^{(k)}$ perpendicular to $\overrightarrow{d_{fi}}$ through $(x_i^{(k)}, y_i^{(k)})$. We define the angle between $Border_i^{(k)}$ and the positive direction of x-axis as α, and that between $\overrightarrow{d_{ci}^{(k)}}$ and the positive direction of x-axis as θ. The direction with the fastest decline in density can be solved in a constrained optimization problem:

the objecive : the direction with the fastest-decreasing density, which correspond to the corrected velocity.

the constraint: the corrected direction must be roughly consistent with the direction of guidance.

Realized by:

$$\min f(\theta) \tag{10}$$

$$S.T. \begin{cases} f(\theta) = \dfrac{\partial \rho}{\partial x_i^{(k)}} \cos\theta + \dfrac{\partial \rho}{\partial y_i^{(k)}} \sin\theta \\ \theta \in [\alpha, \alpha + \pi] \end{cases} \tag{11}$$

- **Random velocity**: $\overrightarrow{v_{ri}} = v_{ri}\overrightarrow{d_{ri}^{(k)}}$. The actual evacuation direction is also affected by many factors such as the psychological state of ecacuees and the surrounding environment. For other complicated factors, we use random velocity to indicate. Here v_{ri} denote random velocity magnitude, $v_{ri} \sim N(0, 0.1)$. The angle between $\overrightarrow{d_{ri}^{(k)}}$ and the positive direction of x-axis is defined as θ', and $\theta' \sim U(0, 2\pi]$.

- ## Movement process

At each time interval of Δt, we can get a corresponding crowd density distribution function $\rho^{(k)}(x, y)$ and the velocity $\overrightarrow{v_i^{(k)}}$. However, in reality there are some special situations that cannot be ignored. We need to do some necessary illustration.

- **Situation 1: Lean against the wall**: As is shown in Figure 10. When a person touches a wall (or obstacle) during evacuation, we decompose the velocity $\overrightarrow{v_i^{(k)}}$into a direction perpendicular to the wall $\overrightarrow{v_\perp}$ and parallel to the wall $\overrightarrow{v_{//}}$. When the component in the direction perpendicular to the wall is not 0, he will change the original velocity into $\overrightarrow{v_i^{(k)}} = \overrightarrow{v_{//}}$.

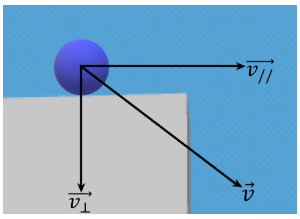
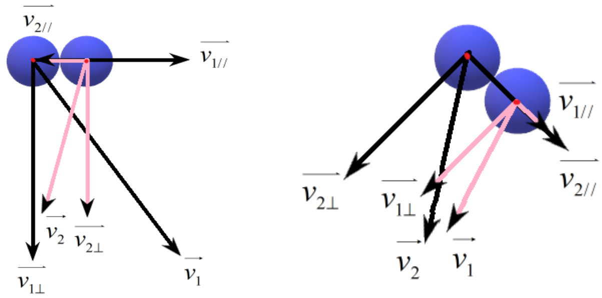


Figure 10: Situation 1: Lean against the wall

- **Situation 2: Collision between evacuees**: When two people collide with each other, similarly, we decompose the velocity into two directions: parallel to the centroid connection $\overrightarrow{v_{1//}}$, $\overrightarrow{v_{2//}}$ and perpendicular to the centroid connection$\overrightarrow{v_{1\perp}}$, $\overrightarrow{v_{2\perp}}$. This situation is illustrated as follows:



(a) collision 1 (b) collision 2

Figure 11: Situation 2: Collision between evacuees

In collision 1, where the $\overrightarrow{v_{1//}}$ and $\overrightarrow{v_{2//}}$ hold th opposite direction, the original velocity change into $\overrightarrow{v_1} = \overrightarrow{v_{1\perp}}, \overrightarrow{v_2} = \overrightarrow{v_{2\perp}}$. In collision 2, where the $\overrightarrow{v_{1//}}$ and $\overrightarrow{v_{2//}}$ hold the same direction yet $\overrightarrow{v_{2//}} > \overrightarrow{v_{1//}}$, we set $\overrightarrow{v_{2//}} = \overrightarrow{v_{1//}}$ to correct the original velocity.

In fact, there are many more complicated situations such as collision within several people, we can deal with them in the same way as the above cases: correcting the velocity to meet the reality. Lack of space limits further discussion at this point.

- **Simulation and analysis**

With the model above, we set proper initialization state and ran the simulation. Specifically we set $\Delta t = 1s, v_f = 1.8\ m \cdot s^{-1}, v_c = 0.5\ m \cdot s^{-1}$.

At the beginning(time after pre-movement process), the flow of people began to move orderly with the guidance of museum staffs. Figure 12 is a part of passage connecting RICHELIEU WING and SULLY WING on the 1st floor.

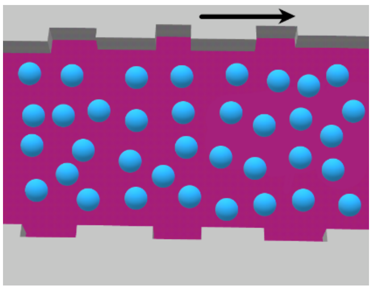


Figure 12: a passage connecting RICHELIEU WING and SULLY WING in the 1st floor

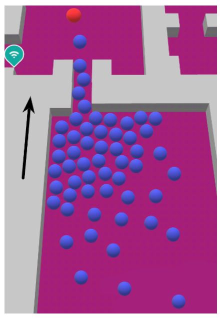


Figure 13: Clogging in the narrow escape of SULLY on the 1st floor .Red ball: Museum staffs; Blue ball: evacuees

As we can see, there is a suitable distance between the evacuees, and the crowd density is relatively low in an unobstructed evacuation process. According to our simulation results, it took about 25s for 500 people to cross the area. However, the orderly flow will transit to disorder in some specific situations.

Figure 13 is a narrow passage in the 1st floor of SULLY WING .The crowd formed a funnel-shape obstruction in this narrow passage. Based on our model, evacuees tend to move to a less dense direction while generally following the guidance. What's more, when a evacuee leans against the wall, his velocity remains only the component parallel to the wall. Our model helps to better explain this clogging phenomenon.

With a great amount of evacuees piling up, it's rather hard for those who got stuck in the middle of the crowd to move(collision 1), so a lot of time would be wasted here. In our simulation results, it took more than 150s for 500 evacuees to cross this narrow escape.

3.3 Potential threats of circumstances model

In addition to the behavior of the evacuated population, potential threats in the evacuation environment can also have an impact on the evacuation process. We improve our previous model by considering environmental factors.

- **The pyramid entrance—a bottleneck**

Bottlenecks refers to places where movement is dramatically slowed or even stopped. Due to space limitations, we take the Pyramid exit as an example.The pyramid exit is the most commonly used entrance and exit. It consists of two revolving doors and one automatic door, while the revolving door rotates at a slow speed, the number of passing evacuees is less at a time, the efficiency is lower during evacuation.

It can be reasonably assumed that when an emergency occur, no one will enter the Louvre through the pyramid entrance. all three doors will be used to evacuate tourists. Based on the revolving door speed and the passing flow, we estimate that the flow rate is 3 people/s, which is much lower than that in the exhibition hall. It may cause people to gather too much at the exit, generating a funnel-shaped blockage i.e. bottlenecks. The results are: it takes a long time of 1860s to evacuate all the visitors at the exit to safe places.

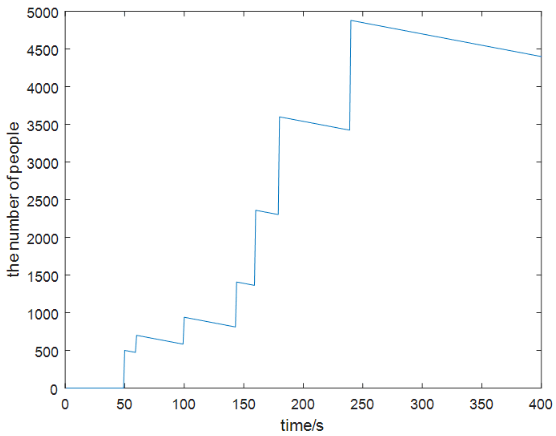


Figure 14: numbers of people at Pyramid entrance

In fact, the evacuation plan in the former Macro emergency evacuation model does not take into account the capacity of nodes, resulting in too many people gathering at the destination node. Moreover, the time spent on congestion at the exit should be involved in the total evacuation time. Taking the node capacity into consideration, we use the same method to find the optimal routes. Define V_i as the capacity of node i, we get an added constraint:

$$f_{ji} - f_{ij} \leq V_i(i = 1.2.3.4) \tag{12}$$

- **To solve the bottleneck—additional exits utilization**

Based on the improved model, in order to evacuate people gathering at the exit quickly, additional exits near the main exits should be utilized. We assume that additional exits are evenly distributed in Louvre. Because these entrances and exits are not commonly used, security personnel are insufficient and the safety coefficient is low, we need to utilize them cautiously.

We calculate the average evacuees density within a certain area near the Pyramid entrance to determine how to utilize the additional exits to facilitate our evacuation plan. Specifically:

$$\bar{\rho} = \frac{1}{S} \iint\limits_{s} \rho(x, y) d\sigma \tag{13}$$

we set the threshold: $\rho_{threshold\_1}, \rho_{threshold\_2} \cdots \rho_{threshold\_k}$. If $\bar{\rho} > \rho_{threshold\_k}$, we then utilize k additional exits. Note that we will close the additional doors when the average evacuees density drops below the corresponding threshold.

Figure 15 shows: two additional exits are opened in around 150s, and the increasing trend of population at Pyramid entrance has slowed down compared with the original one, while the number is still rising. And then four exits are opened in about 180s, after which the number of people has dropped significantly. After closing two exits at about 240s, the number of people can still keep a relatively low level. It takes 450s for all people to safely evacuate. Overall, the strategy of utilizing additional exits based on actual conditions not only greatly reduces evacuation time, but also takes into account security issues.

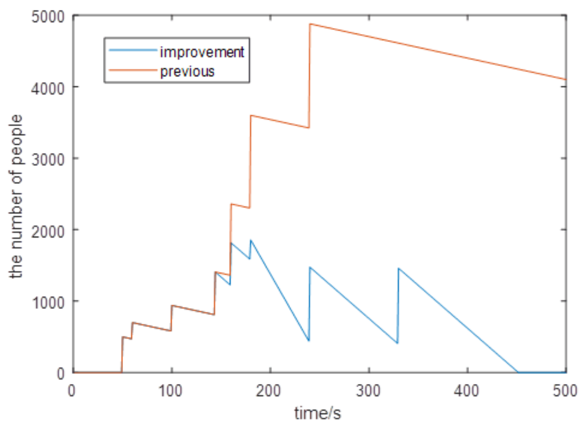


Figure 15: the number of people at Pyramid entrance in the improved model

- **Emergency personnel entering model**

Emergency personnel refers to people who help in an emergency, such as guards, fire fighters, medics, etc. Professional emergency personnel can help us effectively prevent potential threats of circumstances. To allow emergency personnel to enter the building as quickly as possible, we need to analyze the opotimal time when they enter the Louvre. Figure 16 illustrate the trend of numbers of people at the four main entrances.

Emergency personnel should enter the building from each exit at the time when there are fewer evacuees.

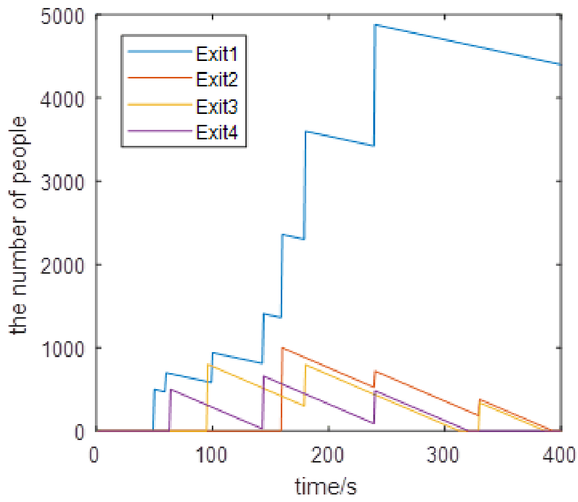


Figure 16: the trend of numbers of people at the four main exits

Table 3: optimal entering time of emergency personnel

	optimal time
Exit 1	t<50s
Exit 2	t<160s
Exit 3	t<96s or 312s<t<330s
Exit 4	t<64s or t>320s

4 Policies and Suggestions

From our specific analysis of the evacuation plan, the following recommendations can be drawn:

- Broadcast in multiple languages when broadcasting emergency notifications, in order to make more people understand in time, reducing pre-movement time.
- Because the guests do not know much about the route of the museum, the evacuation plan must be guided by the museum staffs. They can lead guests to escape. What's more, escape signs can be placed in a conspicuous place to attract peoples attention.
- During the process of evacuation, staffs should maintain an appropriate speed, which is not only beneficial to speed up evacuation but also prevent potential threats like stampede event.
- The Louvre can consider canceling the design of the revolving doors, for they can pass only a few people in unit time. It is not suitable for evacuation. For the same reason, the design of narrow passages should be minimized.

- During evacuation process, the museum should send certain staffs to help people who with disabilities due to their limited mobility and they should take full advantage of fire elevators.

5 Sensitivity Analysis

- **Crowd evacuation behavior model**

In the Crowd evacuation behavior model, we choose identical speed of all followers as $v_f = 1.8\ m \cdot s^{-1}, v_c = 0.5\ m \cdot s^{-1}$. Since the speed of all evacuees is a factor in determining the time through a narrow passage, we make a sensitivity analysis about it. Change the speed, the time changes a lot.

We choose different speed to run simulation and the result is shown in Figure 17.

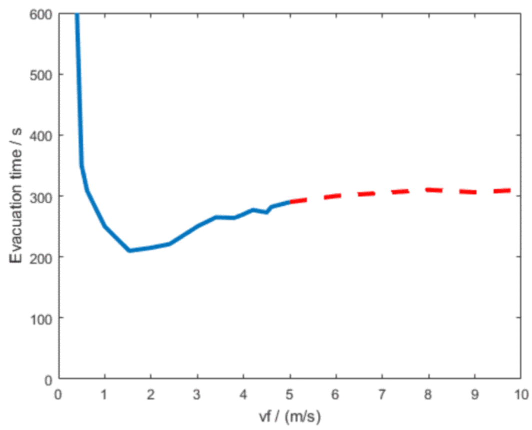


Figure 17: the sensitivity analysis of v_f

Through the results, we can find as the speed increases, the evacuation time becomes significantly smaller firstly and then gradually increases. And the red dotted line indicates that it is virtually impossible to achieve such a large speed.

The reason for this situation is because of faster-is-slower effect[7]. Within a certain range, increasing the evacuation speed is conducive to speeding up evacuation, while too fast will play the opposite role. Too fast speed can overcrow the crowd and make it difficult to pass through narrow passages. So museum staffs should try to calm everyone down during the evacuation process.

- **Macro emergency evacuation model**

Potential threats may occur in the path which is of great importance to evacuation. Some threats have the potential to alter optimized route. We make an analysis about potential threats.

If threats occur in key path (e.g. path between node13 and node3), it will change the route to a large extent, because many guests in Richelieu rely on this path to escape. If it is damaged, they have to turn to other exits, which will cause guests in other wing to change routes.

If threats occurs on a channel that is not often used (e.g. path between node15 and node11), then the optimal path does not change greatly because of the threats.

6 Further study

The Macro emergency evacuation model we develop can be adopted and implemented for other large, crowded structures. Application and implementation steps are as follows

- Determining the clustering of people in the structure and all the path to escape, simplified to a graph.
- Determine the length of time each escape route passes according to the specific details of the structure.
- Use the CCRP algorithm to calculate the optimal evacuation path and the shortest time.

So our adaptive model can apply to other large and crowded structures.

7 Strengths and Weaknesses

Strengths

- **Comprehensive**:From both macro and micro perspective, we analyze the emergency evacuation plan. Macro evacuation plan help us make optimized route, while micro analysis during the process makes the evacuation plan more detailed and accurate.

Weaknesses

- Because few data are available, the data we estimated may not accurate enough.
- For the simplified graph of the museum is too simple, we can choose more nodes as a crowd gathering point.
- In crowd evacuation behavior model, we ignore the acceleration of peoples movement.

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Appendices

Here are simulation programmes we used in our model as follow.

Input matlab source:

```
%Dijkstra Algorithm for calculating the shortest path
function [dis,pa] = Dijk( W,s,d )%W--adjacency matrix
%s--starting point   d--destination
n=length(W);%number of nodes
D = W(s,:);
visitflag= ones(1,n); visitflag(s)=0;%determine if the node is accessing
parent = zeros(1,n);%record the previous node of each node
pa =[];
for i=1:n-1
    temp = [];
    %Starting from the starting point, find the next point of the shortest
    %distance, do not repeat the original track every time
    for j=1:n
       if visitflag(j)
           temp =[temp D(j)];
       else
           temp =[temp inf];
       end
    end
    [value,index] = min(temp);
    visitflag(index) = 0;
    %if the index node is smaller from the starting point to the path of each node,
    %it is updated, and the predecessor node is recorded, which is convenient for backtracking.
```

```
    for k=1:n
        if D(k)>D(index)+W(index,k)
           D(k) = D(index)+W(index,k);
           parent(k) = index;
        end
    end
end
dis = D(d);%the shortest distance
%Retrospective method
t = d;
while t~=s && t>0
 pa =[t,pa];
  p=parent(t);t=p;
end
pa =[s,pa];%the shortest path
end
```