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MCM/ICM

Summary Sheet

(Your team's summary should be included as the first page of your electronic submission.)

Type a summary of your results on this page. Do not include the name of your school, advisor, or team members on this page.

Summary

According to the large inner-area and complex inner-structure of the Louvre Museum, making a proper emergency evacuation plan is always a serious task for museum officials to ensure the safety of visitors in emergency situations. Our goal is to establish a real-time dynamic planning model to calculate and search a best escaping path for every visitor. We are expected to simulate the evacuation process with various factors taken into consideration and validate the efficiency and adaptability of the model.

According to the sketch map of the structure of the Louvre we draw, we establish our basic model, which mainly focuses on real-time calculating the shortest evacuation paths, by a combination of Cellular Automata Models and Dijkstra's algorithm. Based on the structure and realities of the Louvre Museum, we regard individual visitors as cells with separate movements and exhibition rooms as nodes. According to the graph we draw, we calculate the shortest path from any vertex to the exit door with Dijkstra's algorithm. As for the simulation process, we define the parallel update rules for cells. Introducing a concept of transition probability, we discuss the influence of obstacles, distance from exits and individual psychological state on single cell's movement.

In consideration of more realistic situations, we refine our model by taking possible bottlenecks, risk levels, resistance to guidance and some extreme cases into account. We define an evaluation criterion and compare the evacuation performance with or without the real-time dynamic planning model. Then we determine the influence of some factors: distribution of visitors, running speed and total number of people in the museum. We focus on the influence of those factors to the number of escaped people and then conduct sensitivity analysis. The results indicate that using our dynamic planning model, with real-time evacuation guidance, visitors will evacuate faster and safer.

Based on our model analysis and conclusions, we propose the optimal strategy for the emergency evacuation plan of the Louvre. In addition, we find that our model is also well applicable for other large, crowded structures.

Content

1 Introduction

1.1 Background

Nowadays, the whole society is more and more concerned about public security than ever, because a series of deadly terrorist attacks struck many places around the world in recent years. Thus, almost everyone is engaged in the heated discussion over how can large public structures guarantee the safety of people in it when emergency appears. Since large crowded public structures such as tourist spots and shopping malls often have complex inter-floor structures and ultra-big areas, the evacuation plans for these structures are more difficult to make. Additionally, visitors' unfamiliar to the locations of escape routes and exits undoubtedly increases the difficulty of escaping.

Aimed to save occupants in the buildings from any kind of threat quickly and safely, a proper and effective evacuation plan must be made for officials to help evacuate visitors. In face of the problems of evacuation from buildings, some methods in modelling pedestrian dynamics [1] have been proposed, such as the social force model [2] and the floor field model [3-4].

Although these models obtained many remarkable and valuable results, there are still many things needed to be taken into consideration in order to apply the models to practical situations. For example, the five-floor structure and various exhibits (which are regarded as obstacles during evacuations) in the Louvre lead to a trouble when applying the existing models. Thus, based on the situation of the Louvre, our task is to build a model to provide a more applicable evacuation plan for visitors to escape quickly and safely.

1.2 Our Work

Our work begins with drawing a sketch map of the inner structure of each floor in the Louvre in equal proportion using a software called Sketchup. The map was used to show the data of the length, width and height of each floor and exhibition room which we measured by Google Map, and the locations of the exits and stairs. This helped with the modelling and calculating process.

Then we built a model using a combination of Cellular Automata and Dijkstra's Algorithm. In this model, each visitor is treated as a particle, or to say, a cell. Since the movement of visitors are separated, their escape routes can be simulated using Cellular Automata model. And we use the Dijkstra's Algorithm to find the shortest escaping route.

Three criterions are employed to judge the feasibility of evacuation plans: the time taken for all the visitors to escape; the sum of every visitor's escaping time; the sum of every visitor's escaping time with corresponding weights. The less time visitors use to escape, the better the evacuation plan performances.

Moreover, since our task is to develop an emergency evacuation model that suits for various types of threat, we discussed how the model is influenced by different factors and how it is able to apply to other large, crowded structures.

2 Problem Restatement

The problems that we need to solve in this paper are:

- Develop a model of the evacuation of the visitors in the Louvre to determine the best evacuation routes in different situations which makes the evacuation time shortest and the evacuation process safest.
- Taking the number and distribution of visitors, the appearing locations of emergencies, herding behavior of visitors, the instructions of staffs during evacuations into consideration, observe the influences these elements have on the model we build.
- Interpret how our model is suitable for the Louvre and other large structures, and what evacuation plan should be applied to them.

3 Terminology

3.1 Terms

- **Herding Behavior:** Individuals in a group might act collectively, that is to say, when in panic, people are likely to follow others and go towards the direction that most of other people goes. This will affect the evacuation route people choose and the time taken.
- **Obstacles:** All of the articles that hinder the evacuation process, including exhibits and the walls.
- **Exhibition room:** The rooms in the museum.
- **Routes:** The corridors connecting the rooms. Stairs are regarded as routes as well.
- **Capacity:** A factor used to describe how many people can be contained by an exhibition room or a route. It may be dynamically adjusted by emergency. For exhibition rooms, we assume that an area of one square meter can contain up to two visitors. So the capacity of the rooms is twice as much the room's area. For routes connecting the rooms, we assume that the width of route is a constant and approximately equals to the width of ten visitors. So the capacity of routes is in proportion to its length.
- **Load:** Equals to the present number of visitors in the museum versus the capacity of the museum. Load describes to what extent the museum is fulfilled by visitors.

3.2 Symbols

Symbols	Descriptions
$f(Num_{per,i}, V_{per,i}, P_{per,i}, Pr_{per,i}, \rho_{psy,i}, t_i)$	Function which shows the state of every person
$Num_{per,i}$	Label number of each person
$V_{per,i}$	Velocity of movement of each person
$P_{per,i}$	Position of each person
$\rho_{psy,i}$	Psychological state of each person
t_i	Escaping time of each person
p_{jk}	Transition probability neighboring nodes
N	Normalization factor to ensure $\Sigma p_{jk} = 1$
S_{jk}	Effect of the distance from node to the exit
p_W	Effect of obstacles
p_{psy}	Effect of visitors' psychologic states
$k_s, k_W, k_{psy}, k_\lambda$	Sensitivity parameters
L	Distance between the visitor and the exit doors
D_{max}	Restricted distance
d	Distance from the cell to the closest wall
λ_{jk}	Risk level of each part of path
σ_{jk}	Distance from the threat source
λ_{total}	Total risk level of a path
α, β, k_γ	Sensitivity parameters

4 General Assumptions

- A visitor can only have one certain location at a certain moment.
- Visitors that have already escaped from the museum will not come back into the museum again.
- There are enough security staff in the Museum helping with the process of evacuation.
- When emergency appears, all the electricity for escalators is cut off and the escalators are treated as common stairs, which can be safely used.

5 Scale Down the Original Map of Louvre

In order to show the whole structure of the Louvre Museum intuitively and visually, we used a software called Sketchup to draw a scaling-down map.

- Thanks to the Google Map [6] and the scale with it, we cut out the outer contour of the Louvre.
- With the help of Louvre Plan Information [5] (a guide book with inner structure of each floor), we measured all the data of inner structure of the Louvre by software, including length, width and height of each exhibition room and the locations of exits and stairs.

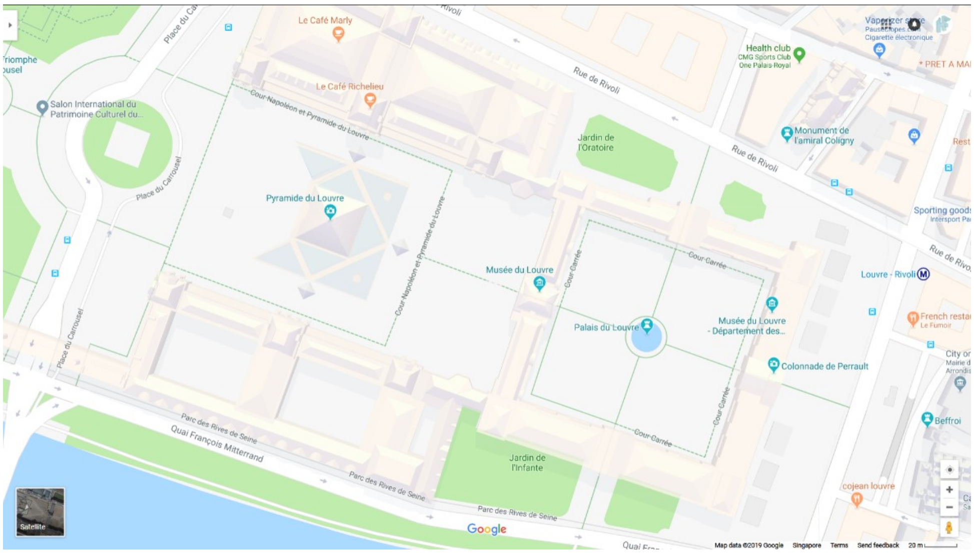

Figure 1 The Louvre Museum in Google Map [6]

- Using three-dimensional modeling software, we restored the inner distribution of exhibition rooms based on the two-dimensional maps. The 3D model is completely proportional to the Louvre in reality, so it helps with our later works.

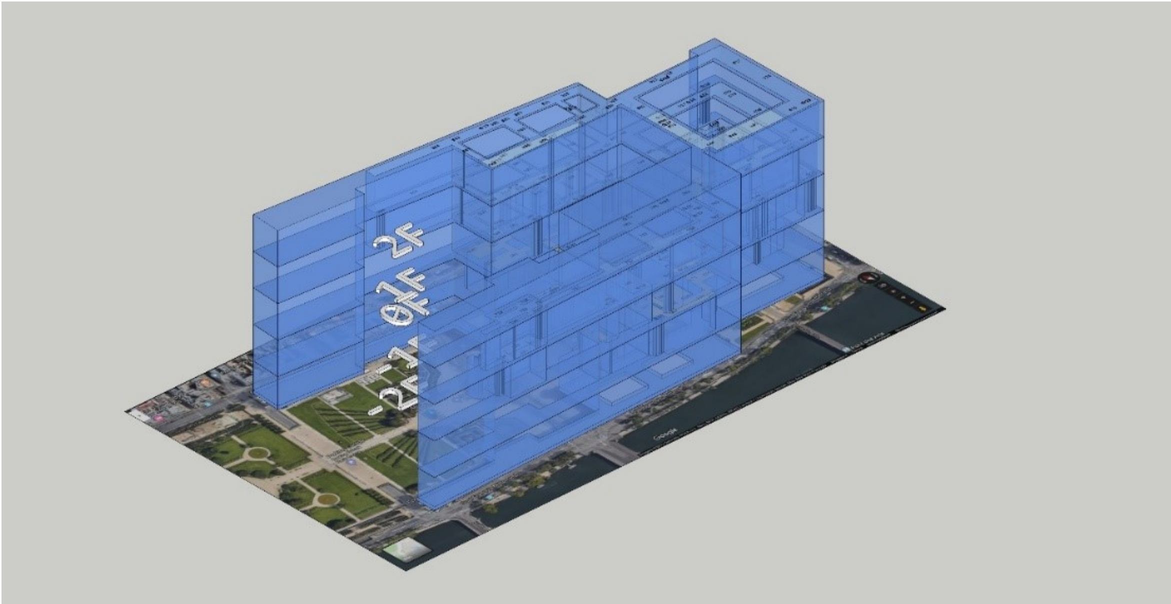

Figure 2 3D Model of the whole Louvre Museum

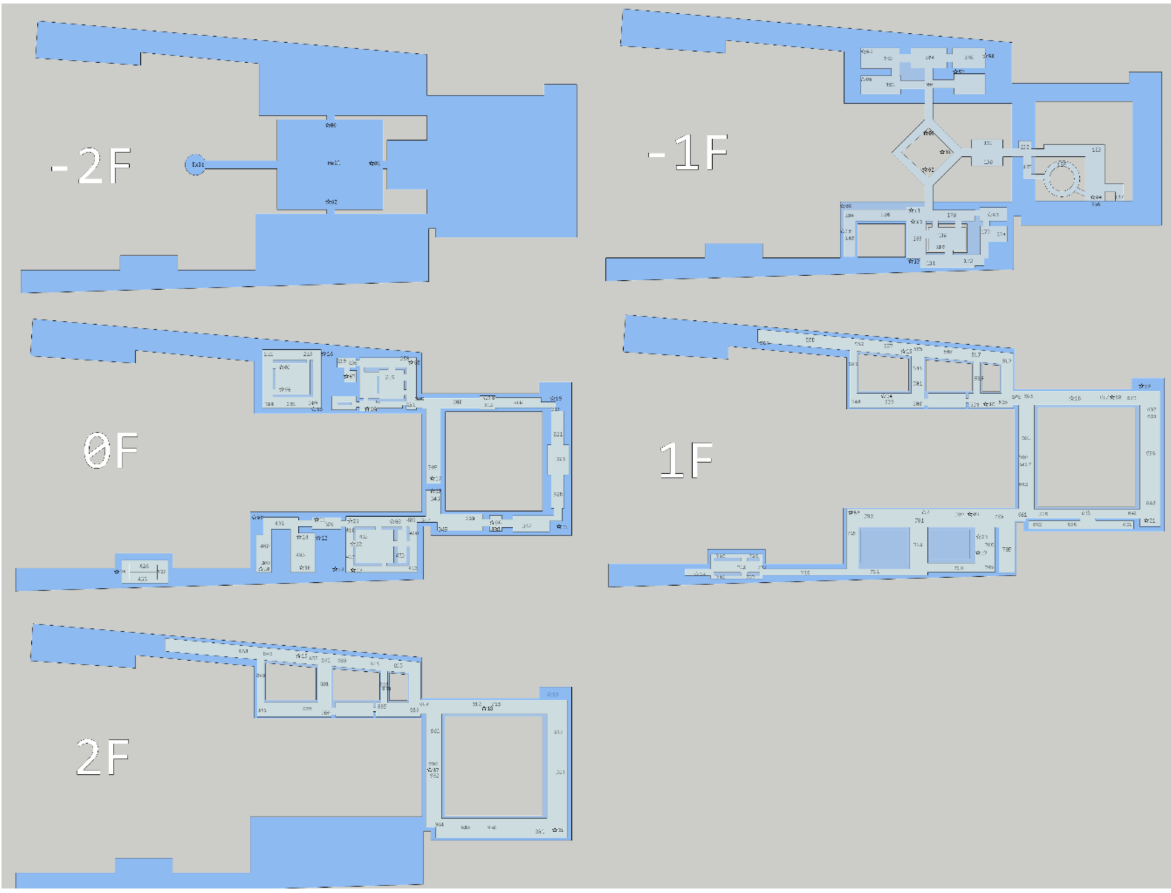

Figure 3 Structure Maps of the five floors

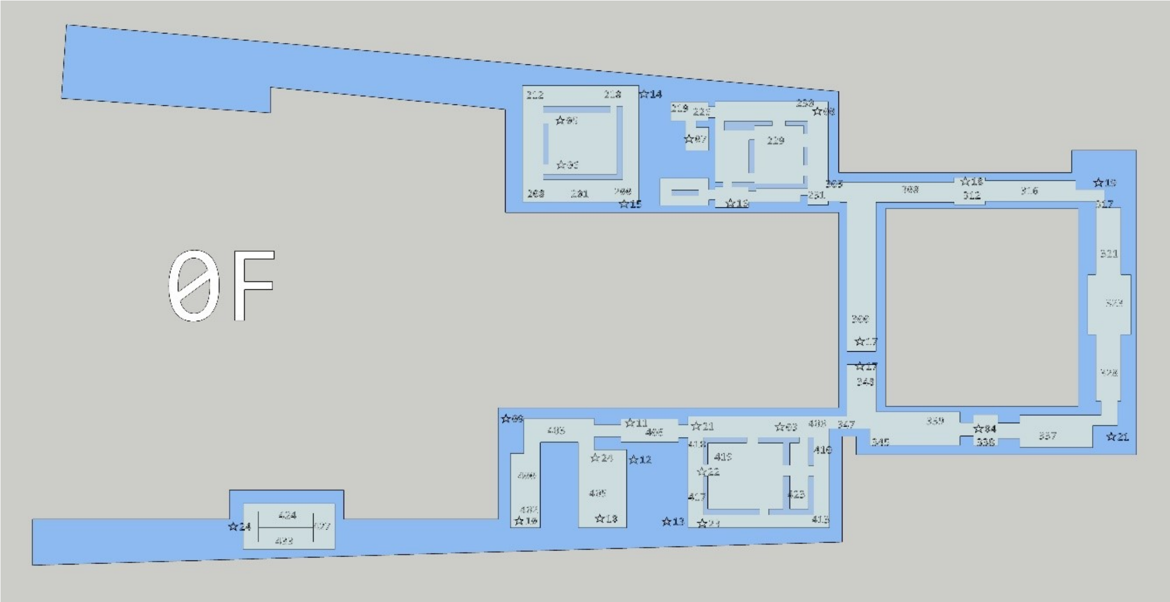

Figure 4 The Structure Map of 0 Floor

- The numbers on the map indicate the exhibition rooms. The stars represent stairs.

6 The Evacuation Model

Visitors, especially those who come to the museum for the first time, are not familiar with the inner structure of the museum, let alone the escape routes and safe exits. Undoubtedly, this is the main reason that it is difficult for visitors to escape in a short time. According to this, we assume that if the museum security officials could give visitors proper evacuation guidance when in emergency, visitors' performance would be better in evacuation since they are told which path is the best choice to escape. Thus, we designed a controlling system which can calculate the best escape path for each visitor based on the position the visitor is standing at. The escape guidance could be transmitted to the visitors simultaneously by the e-guide which visitors get at the entrance of the museum, official application on mobile phones, and the help of security staff in the museum.

In this section, we build a model with Cellular Automata Model and Dijkstra's algorithm, with a function of calculate the shortest escape path for every visitor in the museum according to their positions, respectively. Then simulate the whole process of evacuation, count the time taken in different situations and evaluate it. The results of the assessment include the number of escaped people and the performance of the model. How to evaluate the model will be discussed later.

6.1 Cellular Automata Model

Cellular Automata (CA) models are interesting choices to study pedestrian evacuation systems according to several researches [3,7] because of the simplicity of computation and suitability for simulations of discrete individual's movement. Here we use Cellular Automata model to simulate the process of visitors' evacuation from the Louvre Museum.

In our model every visitor is described by a particle, or to say, a cell. Each cell has its own characters including $Num_{per,i}$, $V_{per,i}$, $P_{per,i}$, $\rho_{psy,i}$ and t_i. Every visitor occupies a node in exhibition rooms or routes. At each discrete time step $t \rightarrow t+1$ each cell can move to one of the unoccupied next-neighbor nodes, or stay at the present node, according to a transition probability p_{jk}. The probability is affected by several elements, we will explain this in the below parts. The movement mode is shown as Fig. 5. Since there might be obstacles (such as exhibits and walls) occupying the space and hindering visitors to move to that direction, it is not always available for cells to move to any directions they want. So in Fig.5, there are no available adjacent nodes in some directions. Moreover, if a node is occupied by other cells (that is to say, another visitor is already on this node) or by occurring emergency, it is also not available for a cell to move to.

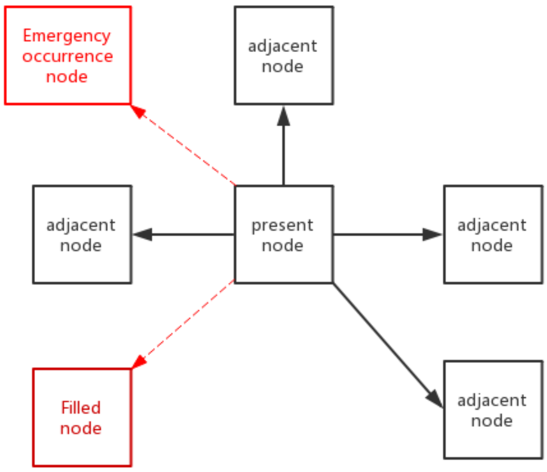

Figure 5 Target nodes for a visitor at the next time step.

6.1.1 Basic update rules

The update rules for our CA model are parallel updated, that means, applied to every cells at the same time. The rules are as follows:

1. For each cell, the transition probabilities p_{jk} for each move are determined by several elements including the shortest distance to an exit, obstacles and individual's psychology factors.

$$p_{jk} = Nexp(S_{jk})p_W p_{psy} \tag{6.1}$$

Here N is the normalization factor to ensure $\Sigma p_{jk} = 1$ where the sum is over all the possible target nodes around each cell. S_{jk} represents the effect of the distance from the node to the exit. generally, the shorter distance between the node and the exit, the larger S_{jk} we get, which means visitors are more likely to choose this node in the next time step. p_W indicates the effect of obstacles and p_{psy} shows the influence of visitors' psychologic factors.

All the factors will be detailly explained in the follow parts of this paper.

2. Each cell randomly chooses a target node to move in the next time step according to the transition probabilities p_{jk} calculated by (6.1).
3. If two or more cells choose to move to the same node in the next time step, there will be a possibility μ that all the cells choose to stay at the present node (μ is a number between 0 and 1). And at a possibility of $1 - μ$, one of the cells will be selected to move to the target node. Which one is selected is decided by a probabilistic method [3].

The explicit form of the influencing elements, S_{jk}, p_W, p_{psy}, and their influences on visitors' choice of evacuation route will be specified in following sections.

6.1.2 Calculation of the Shortest Distance to Exit Doors

We use a combination of visibility graph method and Dijkstra's algorithm to calculate the shortest distance from a cell to exit doors.

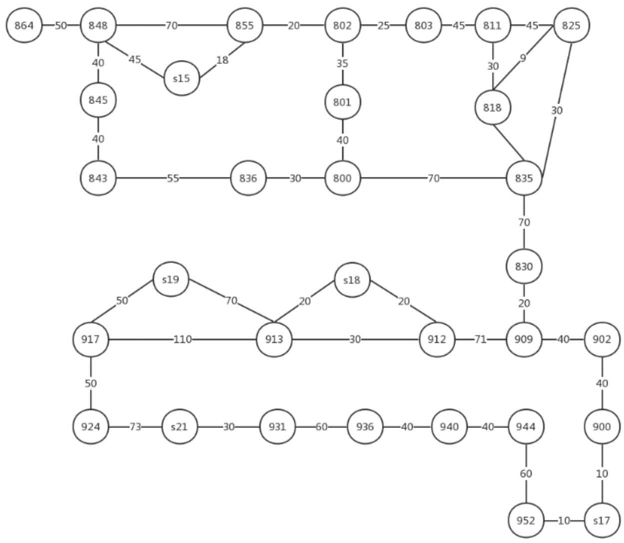

Figure 6 The Floor 2 Part of Our Whole Graph

After measuring all the length of the routes, we draw a graph of the five-floor structure of the Louvre. Exhibition rooms are regarded as vertexes and all of the stairs are regarded as the same as rooms, that is to say, regard the stairs as vertexes, joining all the floors together. The Fig.6 below is part of our whole graph and it shows the situation of Floor 2.

According to the whole graph of the Louvre Museum, we use Dijkstra's algorithm to find a shortest path from the exit doors to the node where each visitor is standing on currently. The calculation and update process is as follows [8]:

- Set the vertex of exit door as the source, called *S*. Assume a function *d(x)*, which is used to describe the shortest path from vertex source to vertex *x*.

$$d(x) = \begin{cases} 0, & x = S \\ +\infty, & x \neq S \end{cases} \tag{6.2}$$

- Find vertex j which has a smallest value of *d(j)* among the uncalculated vertexes.
- If vertex *j* has a neighbor i, calculate the length *L* of path from *S* to each of the neighbors i in condition that the path goes through vertex *j*,

$$L = d(j) + w(j, i) \tag{6.3}$$

$$\mathrm{d(i)} = \min\{L, d(i)\} \tag{6.4}$$

where $w(j, i)$ is the weight of $\mathrm{edge(j, i)}$ in the graph.
If there are no neighbors, the calculation for vertex *j* ends.

- Repeat the previous steps until all the vertexes have been calculated.

Since $\mathrm{d(i)}$ represents the shortest path from vertex source *S* to vertex i, in condition that the path goes though all the vertexes that we had calculated, if $\mathrm{d(i)}$ does not represent the shortest distance, there must be an uncalculated vertex *j* which makes the path going through it the shortest one. That is to say, (6.5)

$$\mathrm{w(j, i) + d(j) < d(i)}$$

Obviously, this inequality is impossible because if it is possible, the following inequality must be provable:

$$\mathrm{d(j) < d(i)} \tag{6.6}$$

However, according to our known conditions, $\mathrm{d(i)}$ is the smallest among $\mathrm{d(x)}$. So this algorithm is able to find the shortest path from visitors to the exit doors.

According to the proving process above, we calculate the shortest distance from every node to an exit door. The distance from exit doors would affect visitors' actions because a visitor would be more likely to choose to move towards to the directions of exit doors during the evacuation process.

Here we introduce a factor S_{jk} to indicate the influence of distance toward exit doors on the actions visitors make,

$$S_{jk} = \exp(k_s / L) \tag{6.7}$$

where k_s is a sensitivity parameter, and L is the distance between the visitor and the exit doors. The smaller the distance is, means the visitor is closer to exit doors, the larger S_{jk} will be, offering a larger transition probability.

6.1.3 Effect of Obstacles

Obstacles, including exhibits and walls, are expected to modify the evacuation routes and therefore influence the evacuation time. In our model, nodes can be either empty and ready for a cell to move to it, occupied by a cell, or by an obstacle. During evacuation process, visitors will tend to avoid running close to obstacles in order to gain larger escape speed. We take this phenomenon into consideration by setting a factor, p_W, in order to improve the realism of the model. It is decided by

$$p_W = \exp(k_W \min(D_{max}, d)) \tag{6.8}$$

Where d is the distance from the cell to the closest wall, D_{max} is the restricted distance, and k_W is a sensitivity parameter. $k_W = 0$ if we do not take the effect of obstacles into consideration.

6.1.4 Effect of Individual Psychology

The emergency would cause a panic among visitors; thus they might act irrationally. According to a study of evacuation that was conducted in a large supermarket in Japan[9], people's choices on escape routes differ largely depending on their psychological characteristics. Only 46.7% people would choose to follow the guidance of broadcast and shop girls, others choose to simply trust their instinct or feel too nervous to do anything. We see that people's behaviors are influenced by their psychological state. So we should take the effect of individual psychology into account when discussing which evacuation route visitors would choose.

Here we introduce a factor p_{psy}, which is related to the psychological state of visitors $\rho_{psy,i}$.

$$p_{psy} = \exp(K_{psy}\rho_{psy,i}) \tag{6.8}$$

The larger $\rho_{psy,i}$ a visitor has, the larger p_{psy} will be, and the transition probabilities p_{jk} will become larger, so that the choice of routes would be affected.

6.2 Amelioration of Our Model

In the section above we discussed our basic CA model to simulate the evacuation process in the Louvre. To obtain the probability that some special cases may take place in a realistic situation, we need to take more elements into consideration. Hence, an improved model is discussed here.

6.2.1 Blockings During Evacuations

In our basic model, we used Dijkstra algorithm as the basic method to find a shortest path from the exit doors to the node where each visitor is standing on currently. The system uses this method to inspect all the vertexes and routes, then searches for a shortest evacuation path for each visitor to escape. In this basic model we focused mainly on how to find the shortest way for everyone. However, consider that some path might be the shortest way for many visitors in the same area, those paths might be blocked by the jostling crowd and the evacuation speed would therefore be slowed down. On the contrast, some paths might be a little longer but have less people running on it. In this situation, guiding some of the visitors to the longer paths might be a better plan, which can both alleviate the blockings in the shortest paths and enhance the utilization of those longer ones.

In the improved model, we draw lessons from a concept from railway transportation, called "time windows". Here a new character, ***Capacity***, of the rooms and routes is defined as the maximum number of people they are able to contain. If the number of people on the path reaches the capacity of the room or route, blockings appear in this path. Before moving to the target nodes, system will check if the original-planned path is blocked. If blocking happens, the system will re-plan a new route for the visitor or choose to stay still at current location.

6.2.2 Risks on the Paths

Since in the process of evacuation the planned path might go through some dangerous area, it is necessary for us to evaluate the risk level of each part of the path. A factor λ_{jk} is introduced to describe the risk level. Obviously, the risk level of each room and route is set inversely proportional to the distance from the threat source σ_{jk} because it is more dangerous if a visitor is closer to the treat.

$$\lambda_{jk} = k_\lambda / \sigma_{jk} \tag{6.9}$$

where k_λ is a sensitive parameter.

Therefore, the total risk level of a path can be calculated by

$$\lambda_{total} = \Sigma \lambda_{jk} \tag{6.10}$$

If the total risk level of the path is higher than the maximum permitted value λ_{max}, the system will try to re-plan the evacuation path, if there are any paths whose risk level is lower than λ_{max}, select the shortest path among them. If there aren't any paths with a risk level lower than λ_{max}, choose the one with the least risk.

6.2.3 Visitors in Panic

According to the study on human actions in emergency situation [9], people will get flurried when emergency occurs. This panic will lead to an erratic behavior during evacuation, for example, wander about without destinations. The circumstance becomes worse if there is no evacuation guidance from broadcast and the security staff. According to the statistics in the study, 26.7% of people will feel too nervous in emergency situation and walk randomly around even when there is guidance from the official, and the proportion raises to 53.3% if there is no guidance around.

Since not all the people would follow the evacuation plan we make by our model, which means that it is impossible for the plan to implement in an ideal situation, the real evacuation speed must be slowed down. So we quantize the possibility of not following the planned evacuation paths as the psychological state of visitors $\rho_{psy,i}$.

Visitors with a low value of $\rho_{psy,i}$ tend to act randomly, and will not follow the evacuation instructions. Instead, they will choose to get downstairs once they meet stairs downward, until they calm down.

6.2.4 Very Unfortunate Cases

In some really unfortunate cases, some visitors might face a situation that all of the paths connecting to the exit doors are cut because of the emergency situation, and there will not be possibilities that the paths would be available in a period of time. Under these circumstances, these people will not be able to be rescued by simply searching for the best path by the system. We will upload the locations and information of those people to rescue crews and call for help.

6.2.5 Ways to Simplify Calculation Process

According to human's Herding Behaviors and the similarity of evacuation process in the same area, when in panic, people are likely to follow others and go towards the direction that most of other people goes. Therefore, at a certain moment, visitors in the same areas would have same evacuation plans. These people can be regard as a group and move together, in order to simplify the calculation process when we make evacuation plans. If the number of people in one group is too large to go through a vertex or a route together (because of the restriction of Capacity), the large group will split into several smaller groups and routed into different directions or go through the vertex or the route in order.

7 Evaluation Formulas

We considered three ways to evaluate and measure the efficiency of an evacuation plan:

- **Take the longest escaping time among all the visitors as standard.**

  This means that we take the escaping time of the last escaper as the standard.

  $$score = \alpha max(t_i) \tag{7.1}$$

  where α is a normalization factor, and t_i is the escaping time for each visitor. The less time it cost to rescue all the visitors, the better performance the plan shows.

  - **Advantages:** Cast higher requirements on decreasing the escaping time of the last visitor; Increasing the possibility of non-injury evacuation.
  - **Disadvantages:** Cannot reflect whether the majority of visitors has successfully escaped in a short time; as we discussed above, some visitors might encounter a dilemma that all possible paths are cut down by obstacles, and their escaping time will be infinite. In this situation, it is impossible to count the longest escaping time.

- **Take the sum of escaping time of all the visitors as standard.**

  $$score = \beta \sum_i t_i \tag{7.2}$$

  where β is a normalization factor, and t_i is the escaping time for each visitor.

  The less time all the visitors cost to escape, the better performance the plan shows.

  - **Advantages:** Give consideration to the total time taken for everyone to escape.
  - **Disadvantages:** Cannot guarantee a non-injury evacuation. In addition, in different time period, we cannot regard the worth of unit time step as the same. For example, for the first 5 seconds just after the emergency appears and the 5 seconds at several minutes after the emergency appears, the escaping difficulties of the two time periods are different. As the time passes away, the threat might spread in the building and escaping process would be more and more difficult.

- **Take the sum of escaping time of all the visitors with weights as standard.**

  $$score = \sum_i (t_i)^{k_\gamma} \tag{7.3}$$

  where k_γ reflects the weight change as time passes.

  - **Advantages:** Take the value of different periods of time into consideration. Lower the comprehensive loss to a least level.

➢ **Disadvantages:** Cannot directly increase the possibility of non-injury evacuation.

When evaluating an evacuation plan, we should take a lot of elements into consideration, not only the total evacuation time it cost, but also the risk it takes, rates of injuries, etc. For example, two plans are proved to have the same evacuation time, but one of the plans let 90% visitors escape in the first 5 minutes and 10% in the rest 20 minutes, and the other one evacuates visitors evenly in the total 25 minutes. When evaluating evacuation plans, there might be different requirements under various situations. Based on the interests of the majority, here we employ the second criterion, that is to say, take the sum of escaping time of all the visitors as standard, in our model. Undoubtedly, in some special cases, other criterions could also be applied in evaluation process.

8 Results and Analysis

As we introduced in the very beginning, we assume that visitors' performance would be better in evacuation if the museum security officials could give visitors proper evacuation guidance when in emergency, since the visitors are told which path is the best choice to escape. Here we simulate the evacuation process by our model in situations with or without the guidance of staff.

According to what we discussed above, visitors are impossible to be completely calm during evacuation, and the influence of panic is reflected in the psychological state of visitors $\rho_{psy,i}$. In the simulations, we set three different situations:

- **Ideal model:** Assume that visitors keep completely calm and follow the instructions of the staff.
- **Real model with staff:** Take psychological factors into consideration. The model is set with a high level of $\rho_{psy,i}$, and a high S_{jk}, which indicates that most people will follow the guidance and know which way is the best to go.
- **Real model without staff:** The model is set with a low level of $\rho_{psy,i}$, and a low S_{jk} to simulate a situation without guidance and people tend to move randomly.

The result of the simulation is shown in Fig.7.

The scores of models are listed as follows:

State	Cost
with staff	319811.7
without staff	384192.8
ideal model	44773.0

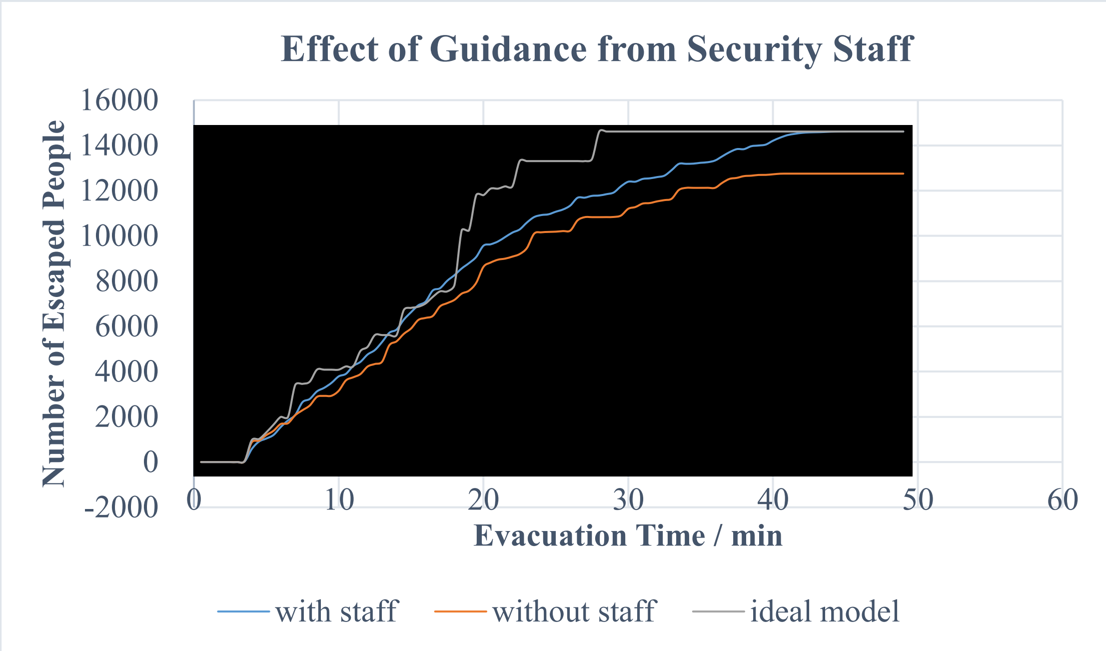

Figure 7 Effect of Guidance from Officials

We could see that as the evacuation time passes, the number of escaped people of three situations varies. At a certain moment, the ideal model has the largest number of evacuated people, the number of people in the real model with guidance follows behind, and the one without guidance has the least number of evacuated people.

The result confirms our assumptions in the former part of our paper that proper guidance based on our calculation model from the museum contributes to the process of fast evacuation. Thus, a mechanism of emergency management is as follows:

- Install all the e-guides and the official App in the museum with position systems (e.g. GPS).
- When emergency situation occurs, use the e-guides and Apps on the mobile phones to identify the locations of every visitors and the system will plan the best routes for everyone. The instructions will be transmitted to every visitor by either e-guides or Apps.
- The locations of visitors will appear on the maps in the controlling center, and the security officials can learn real-time distribution of the evacuating visitors. Officials and staff can give extra help to visitors when necessary.
- Since the use of secret exit points (service doors, employee entrances, VIP entrances, emergency exits, and old secret entrances built by the monarchy, etc.) might cause security problems because these paths might be too narrow for crowded people to run through, these routes are only opened for the entering of emergency personnel. This can at the same time avoid the congestion caused by the bidirectional movement of escaping visitors and entering emergency personnel.

Since all of the data in our model is fully parameterized, so the evacuation model can be applied to various types of potential threats for not only the Louvre Museum and other large, crowded structures. Just import the maps, inner structures (lengths, widths, heights of rooms and the locations of stairs and exit doors) and the occurring locations of the emergencies into the model, when emergency situation appears, the model will automatically calculate the best evacuation route for every person in the building and give instructions.

9 Sensitive Analysis

To provide large, crowded structures with strategy to evacuate visitors better, in this part, we discuss the influence of the distribution of visitors in the museum, the running speed of visitors and number of people in the museum.

First, we research the influence of the distribution of visitors in the museum. The visitors might distribute unevenly in the museum, for example, they might concentrate in some exhibition rooms with more famous and popular exhibits. This uneven distribution might cause a difference in the result of simulation. So we use the data of popular rankings of the exhibits to estimate the possible distribution of visitors in each rooms. Then we initialize the visitors with the distribution and simulate the evacuation process.

Second, we research the influence of running speed of visitors. During the evacuations, improper running speed might cause blockings and slow down the process. Moreover, risk level might increase when running speed is too fast or too slow. We changed the speed and operate the simulations.

Lastly, we research the influence of the number of people in the museum. Here we introduce a concept called ***"Load"***, which equals to the present number of people in the museum versus the capacity of the museum. Load describes to what extent the museum is fulfilled by visitors. We changed the initial number of visitors in the museum to simulate the evacuations.

9.1 Change in the Distribution of Visitors

We change the distribution of visitors in the museum according to the reputation and popularity of the exhibits, the result is shown in Fig.8

where:

x-axis in Fig.8 represents the passing time;

y-axis in Fig.8 represents the number of escaped people.

Surprisingly, the concentrated distribution does not affect the result of simulation so largely. In a period of 10-20minutes, visitors distributed evenly seem to escape faster than those distributed concentrated. But about 20 minutes after the emergency, visitors distributed concentrated seem to escape faster, this is possibly because after so much time, most of the people has escaped, and the distribution's influence is small enough to be ignored.

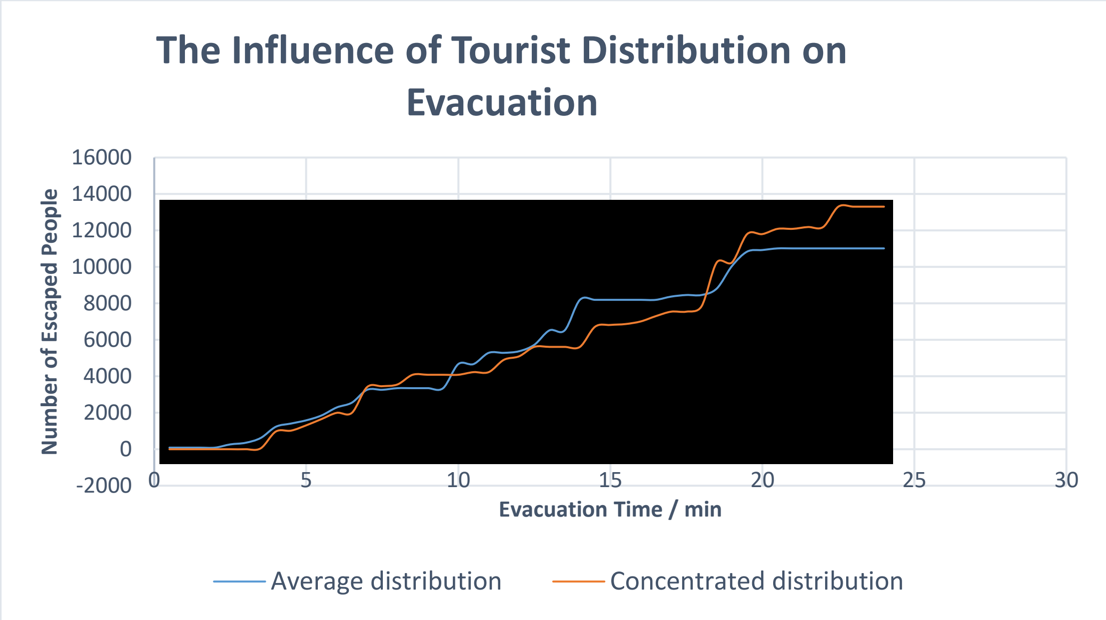

Figure 8 The Influence of Visitor Distribution

The scores of models are listed as follows:

Distribution	Cost
Average distribution	33435.72
Concentrated distribution	44773.00

9.2 Change in Running Speed of Visitors

We change the running speed of visitors, and get the change of number of escaped people with time. The result is shown in Fig.9.

The scores of models are listed as follows:

Speed	Cost
0.6	32106
1.0	33109
1.4	36676
1.6	44773
1.8	38059

Generally, at a certain moment, the number of escaped people increases with increasing running speed of visitors. This is because a slower speed might cause blockings in the routes, thus lower the evacuation speed.

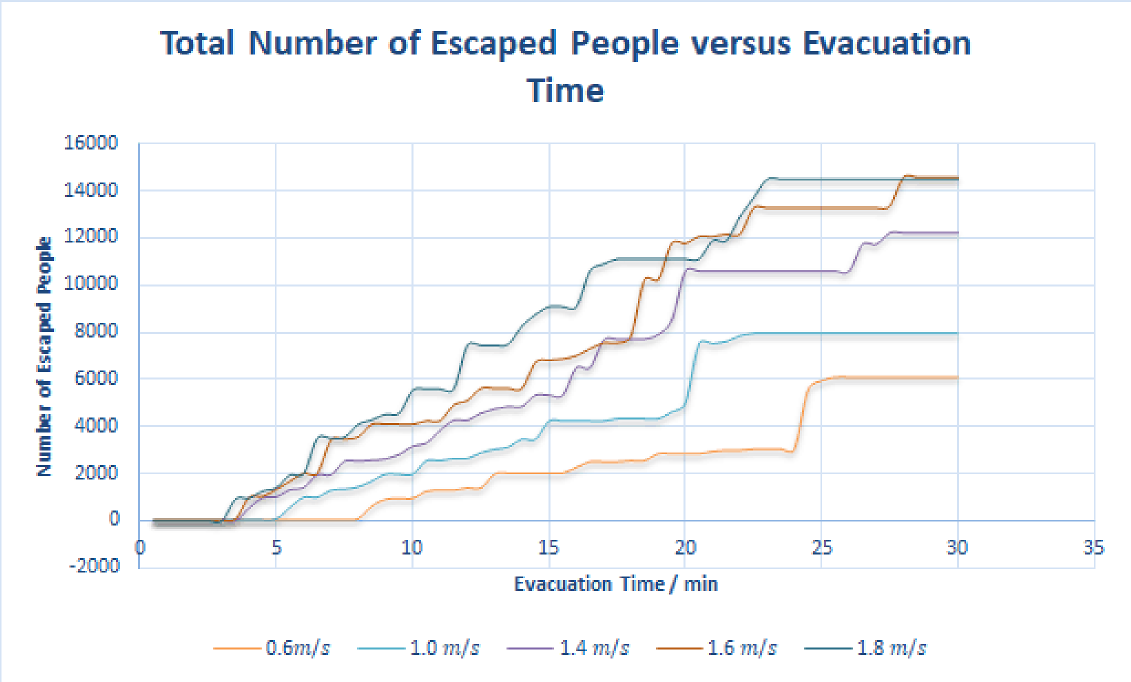

Figure 9 The Influence of Running Speed

9.3 Change in Number of People in the Museum

We change the "load" in the museum, and run the simulation to observe the influence. When the load is 1.0, it means the number of people in the peak period. The results are shown in Fig.10.

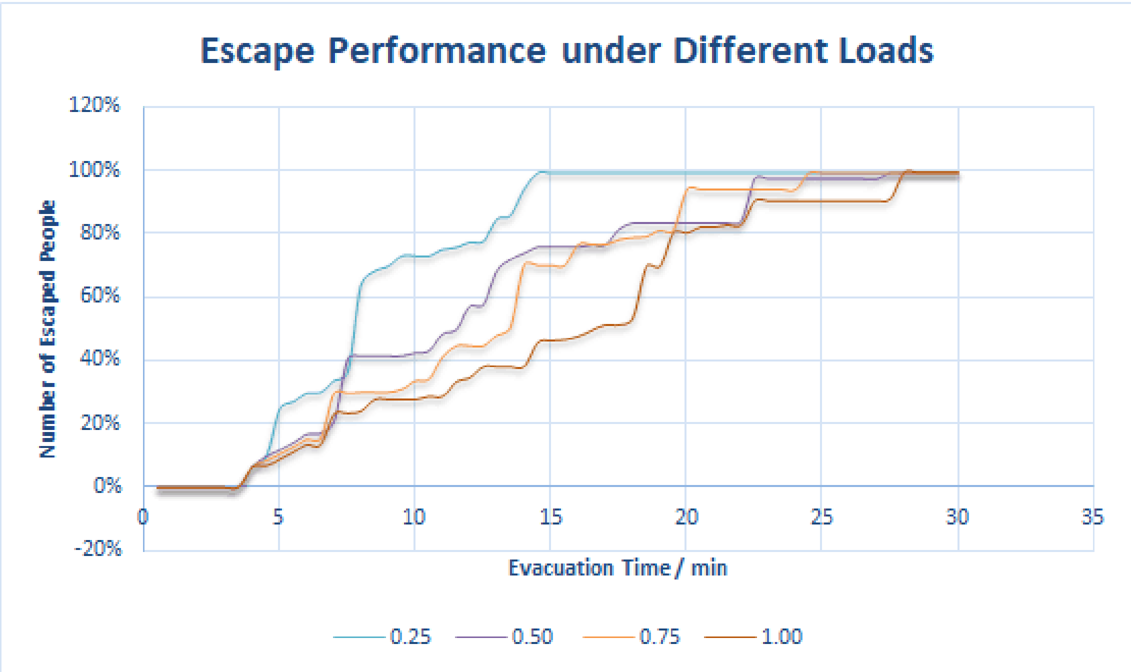

Figure 10 The Influence of "Load" in the Museum

The scores of models are listed as follows:

Load	Cost
0.25	24703.25*4
0.50	32376.50*2
0.75	$36029.75*\frac{4}{3}$
1.00	44773.00*1

In order to compensate for the difference in numbers, the score is multiplied by a factor. According to the result, we see that the lower load it has, the faster people escape. That is because a higher load means the museum is crammed by visitors, lead to a higher possibility of blockings. Thus, the evacuation speed decreases.

10 Strengths and Weaknesses

10.1 Strengths

- **Robustness and flexibility:** All of the data is fully parameterized, so the evacuation model can be applied to address a broad set of considerations and various types of potential threats for the Louvre Museum and other large, crowded structures.
- **Simplicity and efficiency:** Compared to the existing escape model, our model uses some optimization methods such as abstraction, dimensionality reduction, and encapsulation, and the algorithm is efficient.
- **Adaptability and Practicability:** Our model takes many factors into consideration, such as the spread of emergencies, the diversity of visitors, potential bottlenecks, and the psychology of tourists. Therefore, it is close to reality and reliable.

10.2 Weaknesses

- **Data Limitations and possible impreciseness:** Some special data can't be found, and this lead us to do some proper assumptions before we build our models. More accurate data, for example, precise inner structure information of the museum and visitor numbers might guarantee a better result in our models.
- **Some assumptions might not be so close to reality:** Because there are only escalators and no stairs between the -2 and -1 floors in the Louvre Museum, we assume that the escalator can be used safely as stairs in emergency situations. But the correctness of this assumption depends on the quality and the product description of the escalator.
- **Model limitations:** Our model has the potential to be inadequately fitted to non-uniform paths or room capacity and velocity distributions. The capacity of these paths may change under different conditions.

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