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2019
MCM/ICM
Summary Sheet

Time to Leave the Louvre

Summary

In this paper, we establish a cellular automata based model to simulate the evacuation process of the Louvre. Then, we analyze three strategies that can help evacuate: technical methods, extra exit points, and emergency personnel access strategies. Finally, we make three recommendations that can greatly improve the emergency strategy.

First, we adopt the classic cellular automata model to simulate crowd flow in the evacuation process. We discretize the interior of the Louvre into 0.5m * 0.5m patches, each of which can only be occupied by one person. We analyze three factors that have influence on the flow of people: the probability of neighborhood optimal path, herd behavior, and panic. Then, we introduce a probability model to simulate the decision-making process. We perform a high-resolution accurate modeling of the Louvre. Result shows that our model is able to quickly and accurately simulate the flow of people in an evacuation process on a large 3D map.

Secondly, we consider the auxiliary role of modern technology in the evacuation process. We envision a mobile app called Smart Guide that uses the data collected by Bluetooth sensors in the Louvre and plans the ideal escape route for users. Simulation shows that Smart Guide can significantly reduce congestion and improve evacuation efficiency. These advantages are even more pronounced when potential hazards may block certain roads. Besides, the introduction of the Smart Guide can bring about a 9% improvement of evacuation efficiency.

Thirdly, we analyze how to use other exits to maximize overall benefits. Through simulation, we verify the positive impact of opening other exits on evacuation efficiency, analyze the impact of secret exit points on evacuation efficiency, and quantitatively discuss the relationship between evacuation efficiency and the number of library personnel. Finally, based on utility analysis, we propose a trade-off strategy between evacuation efficiency and museum safety.

Finally, we analyze the strategy of emergency personnel entering the building. According to the actual situation, make reasonable assumptions about the behavior of emergency personnel and visitors, and determine the measurement indicators to measure the efficiency of emergency personnel entering the building. On this basis, we analyze the two strategies of building entry and their impact on efficiency indicators. Finally, we propose the optimal strategy.

Keywords: Cellular automaton; Evacuation model; Multilayer simulation

1 Introduction

1.1 Background

With the rapid growth of the global economy , the tourism industry is faced with increasing demand. The Louvre is one of the greatest art museums on our planet, with billions of visitors from different countries and cultures every year. In the past three years, the number of visitors to the Louvre has been largely increasing. In 2017 she received 8.1 billion visitors, and in 2018, a staggering number of 10.2 billion tourists visited her. [1]

Meanwhile, with the rapid growth of tourism, the risk of emergencies is also increasing, especially since the global political situation remains unstable. French scenic spots, including the Louvre, has long been a hot target for terrorism attacks. Especially because the geographic structure of the Louvre is overly complicated, the evacuation of tourists is more difficult. This has caused great concern about the Louvre evacuation [2] strategy in emergencies. An appropriate evacuation plan with both efficiency and flexibility can better ensure the safety of the Louvre visitors, thereby increasing the entry traffic to the Louvre and benefiting the museum as a whole.

1.2 Dillema

1. The interior of the Louvre is overly large, so the simulation in continuous space is computationally expensive.
2. Most existing evacuation models only deal with evacuation in a two-dimensional plane, but the Louvre's internal structure has multiple layers, and the connection between layers is not easy to characterize. [3]

1.3 Our Work

1. We adopt a cellular automata [5] based model, discretize both time and space and simulate crowd flow.
2. We use a multi-layer map to represent the internal structure of the Louvre and use pipes to simulate stairs to connect different layers. [4]
3. We extended our model to evaluate the effects of different evacuation strategies, such as the application of modern technology, the introduction of additional exit points, and the strategy of emergency personnel entering the Louvre.

2 Assumption

1. The Entire pavilion is a horseshoe-shaped structure and ignores the specific structure inside the middle exhibition hall. Due to the complexity of the internal terrain of the Louvre, we are unable to accurately simulate the internal structure of all corridors and exhibition halls. So map's simplification is necessary.

2. We assume that visitors can only move between different floors by stairs. Stairs can be thought of as pipes, and can be characterized by their rate of flow.
3. Visitors know the shortest path to the nearest exit. This is because in large museums, there are usually signboard indicating the shortest evacuation direction in most positions.
4. People have the inclination to follow others in emergency.
5. Visitors are uniformly distributed in the hall. As the Louvre is filled with exhibition hall and exhibits, visitors can be attracted to any location.
6. In case of emergency, the elevator cannot be used. Visitors can only use stairs to go up and down the stairs or escalators.

3 Basic Model

3.1 Model Description

3.1.1 Space Discretization

We discretize the inner space of the Louvre into square cells. Each cell can be and can only be occupied by one single individual. By evaluating the average area occupied by a person, we define the area of a cell as 0.5m $\times$ 0.5m.

We assume that at every timestep, each person can only move to one of its Moore neighborhoods, which is defined as below:

$$\mathrm{N}_{Moore} = \{v_f = (v_{ix}, v_{iy}) | \, |v_{ix} - v_{ox}| \leq 1, |v_{iy} - v_{oy}| \leq 1, (v_{ix}, v_{iy}) \in Z^2\} \tag{1}$$

Which is shown in Figure 1:

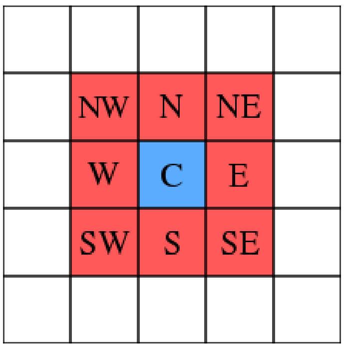


Figure 1: Moore Neighborhood

3.1.2 Shortest Distance From Exits

There are four major exits in the map: the Passage Richelieu entrance, the Carrousel du Louvre entrance, and the Portes Des Lions entrance.

We adopt the Euclidean distance and use the Uniform Cost Search (UCS) [6] method to calculate the shortest distance from exits [7].

Now we define the parameter - distance indicator D, which is used to measure the influence of the minimum escape distance factor on the selection of the moving direction. Considering that the bigger the minimum distance dmin from the gate, the smaller the probability of moving toward the gate; otherwise, the greater the probability, so we define:

$$D = \frac{1}{\sqrt{d_{min}}} \tag{2}$$

3.1.3 Herd Behavior

We believe that people will tend to follow the flow of crowd when panicked, especially when they are not sure about the optimal evacuation route [13]. Thus, we calculate the histogram of each person's movement direction in the individual's neighboring area, and identify the direction of crowd movement. We define a herd index as below:

$$C = \frac{n}{N} \tag{3}$$

$$n = \max\{n_i\}, i = 1, 2 \cdot \cdot, 8 \tag{4}$$

$$N = \sum_{i=1}^{8} n_i \tag{5}$$

Where n_i represents the number of people in a certain neighborhood, running at a certain direction i, i takes 1, 2, ..., 8. And n is the maximum of n_i, representing the direction in which the most people in the neighborhood of the L $\times$ L run. N is the area of the neighboring area.

Therefore, the herding indicator C indicates the ratio of the number of people running at a direction in a nearby space, to the area of this specific space. This indicator C represents the influence of the factor of herd behavior [9] on the individual's next direction of movement [10].

This definition is coordinate with common sense. The more people are running at a certain direction, the greater the probability that an individual will follow these people when they are panicked and helpless.

3.1.4 Panic

In dangerous situations, individuals are likely to panic and exhibit chaotic and irrational behavior. [11] In our model, we believe that when panicking, individuals randomly select a direction from the surrounding eight Moore neighborhood directions as the next direction of movement.

We define a constant value, the panic index e. It represents the individuals probability to move randomly out of panicking.

3.1.5 Probability Criterion

In Section 3.1, we defined a distance index D, a herd index C and a panic index e. Each of the three indexes will influence the individuals' movement direction in a certain timestep. Therefore, we need a method to combine these three factors to determine the next direction of each person's movement.

A more appropriate method is to construct a probability vector P = (p_1, p_2, p_3), and then assign a probability to each of the three according to the distance index D, the herd indicator C and the panic indicator e.

Assuming p_1, p_2, and p_3 respectively correspond to the distance index D, the herd index C, and the panic index e. Firstly, when the individual decides the next moving direction at the time of ti, the probability of moving to the nearest door is p_1. Secondly, the probability of following movement of the nearby crowd is p_2. In other words, the individual would choose the direction in which the crowds in the surrounding L $\times$ L neighborhoods move the most as the next moving direction. Finally, the probability of randomly selecting one derection from the surrounding eight directions is p_3.

Now we assign and quantify the probability vector P = (p_1, p_2, p_3). At first, we define the panic probability p_3 as:

$$p_3 = e \tag{6}$$

Where e is the panic indicator. And e is an adjustable constant.

Secondly, the normalized form of the distance probabilityp_1 and the herd probability p_2 is defined as:

$$p_1 = \frac{(1-e)\cdot D}{(D+k\cdot C)} \tag{7}$$

and

$$p_2 = \frac{(1-e)\cdot k\cdot C}{(D+k\cdot C)} \tag{8}$$

Where k is a constant parameter that can be adjusted according to the relative size of the distance index D and the herding index C to characterize the combined effect of the distance index and the herd index on the probability of the individual moving direction.

3.1.6 Evaluation

In order to measure the evacuation efficiency in different situations, we need to choose an indicator. We recommend measuring the evacuation efficiency using the ratio of the number of evacuated people in a given time t, to the total number of people in the building before evacuation. We denote this index as Evacuation Ratio Index (ERI).

$$RatioIndex = \frac{NumberofEvacuatedPeopleInTime(t)}{TotalNumberOfPeopleInTheLouvreBeforeEvacuation}, t > 0 \quad (9)$$

When t is too large or too small, ERI lacks characterization ability. In actual use, we can choose the appropriate t in this way: for a given number of people, t is equivalent to the average time required to evacuate 60% of people.

3.2 Experiment

3.2.1 Map Generation

We obtain a detailed map of the Louvre from the official website of the Louvre [12]. Due to the complexity of the internal terrain of the Louvre, we are unable to accurately simulate the internal structure of all corridors and exhibition halls. Therefore, we decide to simplify the map and only consider the main passage of the Louvre. Considering the size of ordinary people, we use a 0.5m $\times$ 0.5m square to represent visitors. We use Google Maps to measure the length (480 meters) and width (360 meters) of the Louvre and convert the simplified map into a grid map with a grid size of 0.5 m $\times$ 0.5 m and containing 960 $\times$ 720 pixels.

Then we accurately mark the location of the stairs and escalators in the grid map according to the official map. We assume that the elevator cannot be used in an emergency. Based on the actual width of the stairs in the Louvre (4.5 m), we estimate that stairs and escalators can pass nine people at the same time. Then we mark the location of the four main entrances in the grid map. According to Google Maps, we estimate the capacity of each entrance (7.5 meters) to be 15.

The Louvre has five floors. Since the Napoleon Hall is just a lobby connecting to Lower Ground Floor, we combine the Napoleon Hall and Lower Ground Floor as one single layer. Besides, due to the similarity of the terrain of the 1st floor and 2st floor, we use the same map to represent them.

3.2.2 Simulation Result

At the beginning of simulation, the visitors are uniformly scattered throughout the museum. The crowd distribution is shown from Figure 3 to Figure 9. The left column represents the initial distribution of the crowd, and the right column represents the distribution after the crowd gathers

In the simulation process, we found that the movement of the crowd has a certain regularity. That is to say, when moving away from the exit, the movement of the crowd is highly random; in the vicinity of the exit, the movement of the crowd is more purposeful and tends to move towards the exit.

In order to better analyze the evacuation process, we plot the evacuation rate - timestep relationship as follows.

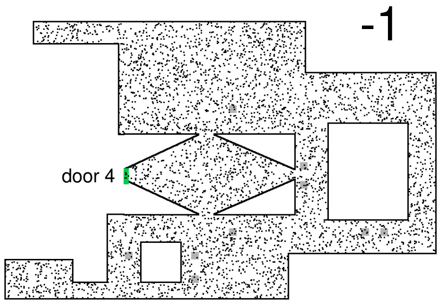


Figure 3: Initial Crowd Distribution on Lower Ground Floor

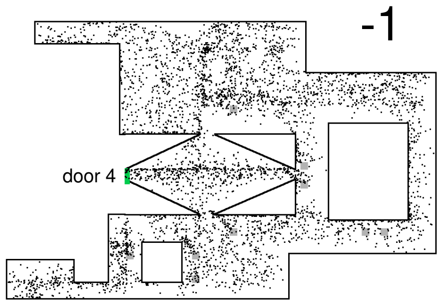


Figure 4: Gathering Crowd on Lower Ground Floor

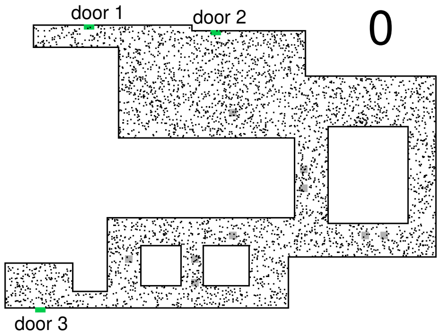


Figure 5: Initial Crowd Distribution on Ground Floor

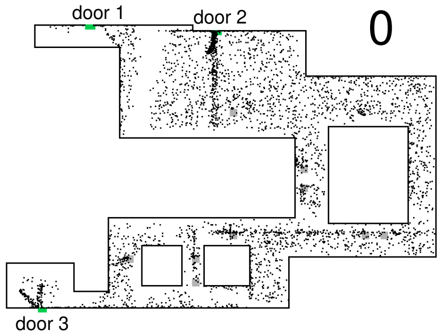


Figure 6: Gathering Crowd on Ground Floor

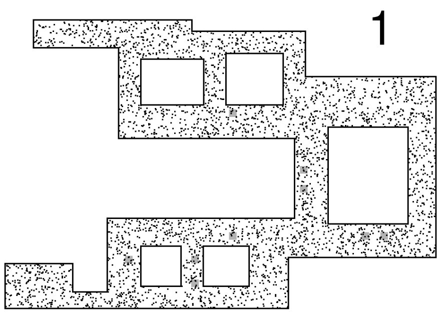


Figure 7: Initial Crowd Distribution on 1st Floor

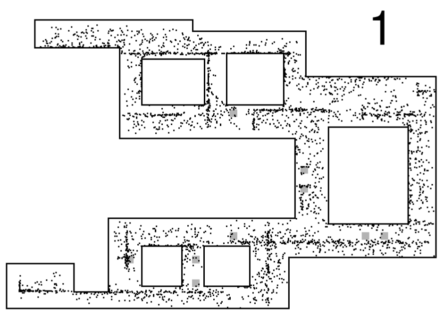


Figure 8: Gathering Crowd on 1st Floor

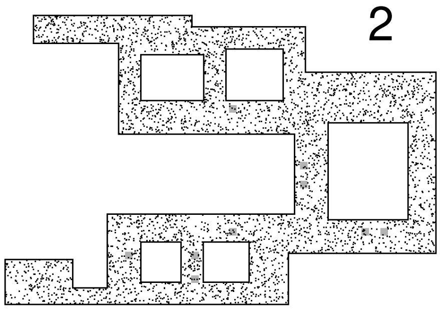


Figure 9: Initial Crowd Distribution on 2st Floor

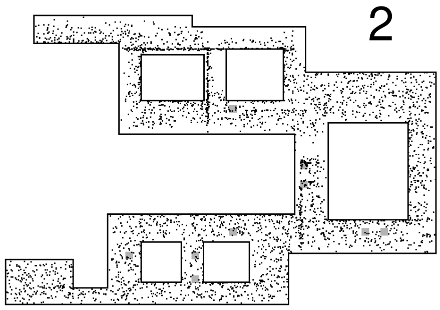


Figure 10: Gathering Crowd on 2st Floor

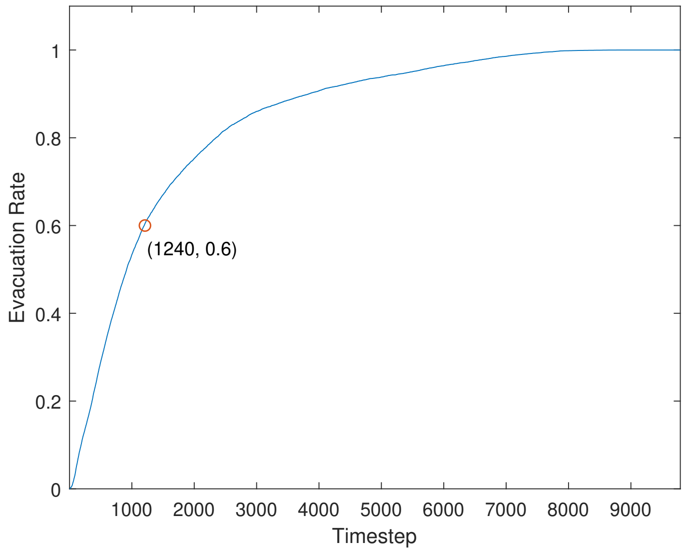


Figure 10: Evacuation Rate - Timestep Relationship

The picture shows that the evacuation speed is faster at the beginning of evacuation, but in the later period, begins to decrease due to congestion and the decrease in the number of people in the museum.

We also find that after 1240 timesteps, 60% visitors can evacuate from the Louvre. Based on the discussions in Section 3.1.6, we use $t = 1240$ to calculate ERI for evacuation efficiency evaluation in later sections.

3.2.3 Bottleneck Identification

We found two locations that are easily congested: the Main Stairs and the Passage Richelieu entrance, and their locations are already marked in Figure 11. The reasons are as follows:

1. For the Main Stairs, the tourists on higher floors need to reach the exit through the Main Stairs.
2. The entrance to Passage Richelieu is very close to the stairs and many people will go directly to the Passage Richelieu entrance via stairs.

Therefore, we recommend expanding the size of both the Main Stairs and the Passage Richelieu.

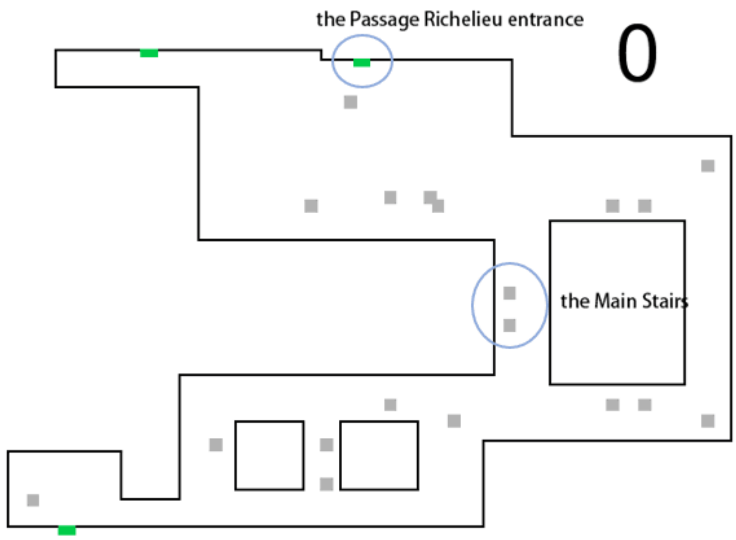


Figure 11: Locations of Two Bottlenecks

4 Application of technology: Smart Guide

In our basic model, the visitors are limited by their limited knowledge and thus largely influenced by their neighboring situations. However, in reality visitors are equipped with techonological methods such as GoogleMap, etc. In this section we propose an application called Clever Guide with the ability to offer highly acceptable escaping routes using existing technological methods. We believe this application can largely facilitate evacuation.

4.1 Strategy Description

We already know that in order to facilitate visitors to enter in the museum, the Louvre provides real-time updates of all entrance waiting times through the online application "Affluences". In the actual situation, because there are a large number of tourists in the Louvre, and there are only three main exits locate at the ground floor and one at the 1st floor, the congestion at the exit is inevitabe. Therefore, during the emergency evacuation process, the Louvre can provide real-time congestion for all exports through the online application "Affluences".

It should be noted that not all visitors have access to the information provided by the online application. We assume that the proportion of visitors who can receive the information provided by the online application to a total number of people is α. They can better determine their escape route based on the real-time exit congestion [15] given by the online application. However, the rest of the people, who are not able to reach the information given by the online application, can only escape according to the ordinary escape method - the basic model.

For those who have access to the information provided by the online application, they are able to know the shortest distance from exits d from each door and the congestion of each door. And the congestion situation is characterized as the waiting time from a individual reaching the neighborhood near the exit to leaving the exit door. Obviously, the waiting time T is positively related to the number of people in the neighborhood near the exit.

Now we discuss how to get T. Define the normalized congestion indicator [16] m:

$$m = \frac{M}{X \cdot Y \cdot G} \tag{10}$$

Where M is the number of people in a rectangular neighborhood with length X and width Y near a certain exit, and G is the width of the door. Therefore, the normalized congestion indicator m is the number of waiting persons in per unit area of the unit door. Obviously, the larger m is, the more congested the door is, and the longer it takes to wait. Thus, the waiting time T can be considered to be proportional to the normalized congestion indicator, namely:

$$T = b \cdot m \tag{11}$$

Where b is the proportionality factor and depends on the actual model tuning settings.

Substitute expression 11, we have:

$$T = \frac{b \cdot M}{X \cdot Y \cdot G} \tag{12}$$

Now we consider how to combine the shortest distance from the exits d and the waiting time T to generate a space-time indicator DT instead of the distance indicator D in the basic model.

Assuming a individual in a certain position obtain real-time data through the online application —- the shortest distance from exits d from exits and the waiting time T. However, finally choosing which exit needs to compare the two exports in pairs. Considering two exits i, j, the closest distance of the individual from the exit i is di, the waiting time is Ti; the closest distance from the exit j is dj, and the waiting time is Tj. Assuming that exit i is better than exit j, then there should be the following formula:

$$d_i - d_j < v \cdot (T_j - T_i) \tag{13}$$

The velocity v is assigned to the coefficient b in T=b*m, since they are all just a coefficient, then we have:

$$d_i - d_j < T_j - T_i \tag{14}$$

Move item:

$$d_i + T_i < d_j + T_j \tag{15}$$

Thus we can define the space-time indicator DT as:

$$DT = d_i + T_i \tag{16}$$

Obviously, the smaller the DT, the smaller the space-time distance from the individual to the exit. So the escape route is better.

Therefore, we just need to replace the distance indicator D in the basic model with the time-space indicator DT, and decrease the panicking index as well as herd index.

4.2 Results and Analysis

From the above analysis, we can boldly assume that the Smart Guide will bring the visitors at least two benefits:

1. Visitor movements are more purposeful. Because visitors know a better path recommended by the Smart Guide and have a high degree of trust in Smart Guides, they will head to the exits more purposefully and faster.

2. The application can help solve congestion. Visitors guided by the Clever Guide will head to less crowded exits. As a result, not only can these users evacuate faster, but the congestion near the exits will ease as well.

From the simulation, we can observe a similar phenomenon. Figure 12 shows the crowd distribution on the ground floor after 310 timesteps. The black praticles denote common visiters, and the blue particles denote Smart Guide users.

First we compare the Smart Guide users' behavior and common people's behavior. The users' trajectories are straighter, that is, their movements are more purposeful.

Second, we compare the basic model results (Figure 5) with the results here. It can be seen that in the basic model, almost no one left the building from the x gate. However, in the results of this model, many tourists went there under the guidance of the Smart Guide, thereby reducing congestion and increasing the evacuation rate.

We also calculate the ERI for three different group of people: all visitors, visitors without Smart Guide, and visitors with Smart Guide. The result is listed below.

As 0.6983 > 0.60, we can conlude that the Smart Guide can improve evacuation efficiency. More specifically, the evacuation efficiency of common visitors are not significantly improved (ERI = 0.5935 $\approx$ 0.60), but the evacuation efficiency of Smart Guide users are improved (ERI = 0.7689 > 0.60).

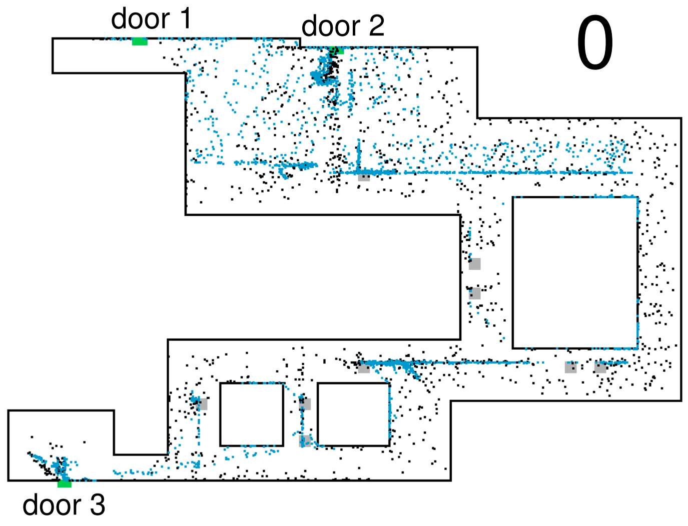


Figure 12: Crowd Distribution on Ground Floor When Some People Have Smart Guide

Group	ERI
All Visitors	0.6983
Visitors without Smart Guide	0.5935
Visitors with Smart Guide	0.7689

We further evaluate APP's effect on the evacuation rate - timestep relationship. The results are as follows.

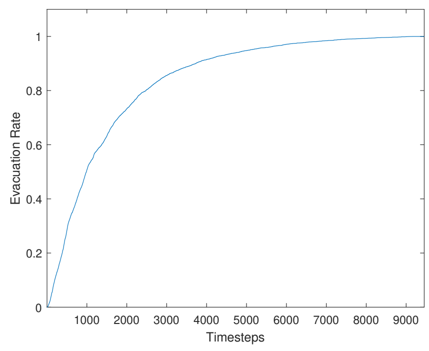


Figure 13: Visitors Without the Smart Guide

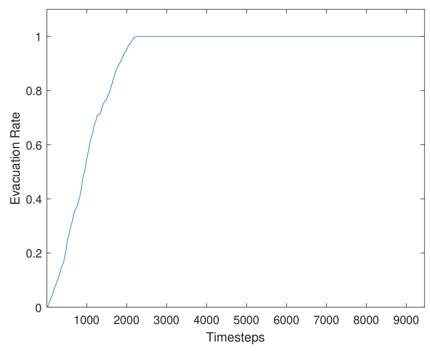


Figure 14: Visitors With the Smart Guide

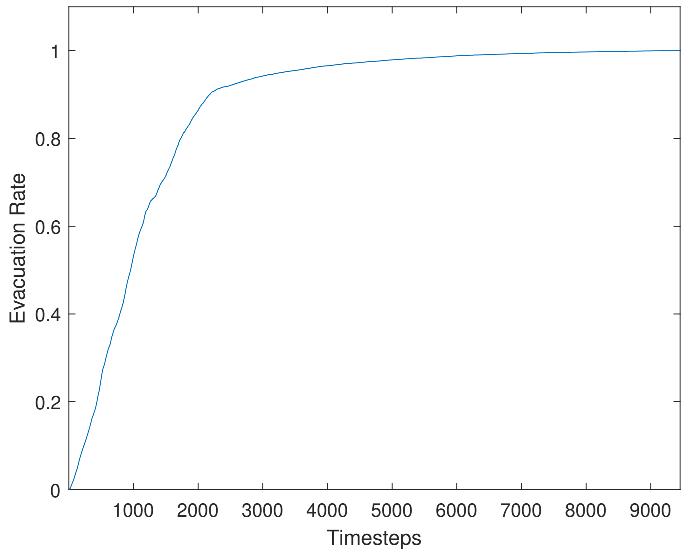


Figure 15: All Visitors

In conclusion, the Smart Guide can significantly increase the evacuation speed of its users and has a positive effect on overall evacuation.

5 Further Application of Smart Guide

In the previous model, we assume that the internal structure of the Louvre remaine unchanged throughout the evacuation process. In this section, we consider some common but very challenging situations: some roads may be blocked, some equipment may fail, and some roads will become impassable. We believe that these situations can be simulated by introducing new obstacles. We then discuss the necessary changes to the model to simulate visitor behavior in these situations and analyze the simulation results. Finally, we demonstrate that the application of the Smart Guide can largely help evacuate.

5.1 Model change

In Section 3.1.4, we discussed the impact of panic on people. An individual in panic may lose the ability to make rational decisions. In our model, everyone panicks with a certain probability p_e and adopts a random walking strategy.

We modeled some unexpected situations (such as falling ceilings and roads being blocked by waste) as new obstacles because the original was blocked. In the basic model, these barriers will not change the individual's strategy. However, this is inconsistent with the real situations, so we modify the model as follows.

We believe that unexpected obstacles will increase the level of panic. Therefore, without changing the basic model, we simulate the behavior of people near the obstacle by increasing the panic probability of visitors near the obstacle.

The specific calculation method is as follows: for the position i, traverse each cell j occupied by each obstacle. We use the exponential form to calculate the panic generated by cell j at i:

$$Panic_{ji} = exp\{-\lambda \cdot d(p, q)\} \tag{17}$$

Of which λ is a manually set parameter, and d denotes the distance between p and q. Its mathematical form is

$$d(p, q) = max(|p_i - q_i|, |p_j - q_j|) \tag{18}$$

Where (p_i, p_j) is the central coordinate of p, (q_i, q_j) is the central coordinate of q. That is, d(p, q) is the is the minimum number of steps that an individual needs to move from p to q.

In this equation, the increment of panic decreases with distance. This is reasonable for people will ignore distant obstacles.

However, such traversal calculations are too expensive, especially as exponentail calculations are particularly slow. Since the panic value decays with distance, we only do calculations in the neighborhood for each cell q. In this way, we maintain the locality of the cellular automata model without reducing the modeling ability of the model, thereby reducing the amount of calculation.

5.2 Simulation result

Figure 16 shows the crowd distribution on the ground floor after 354 timesteps.

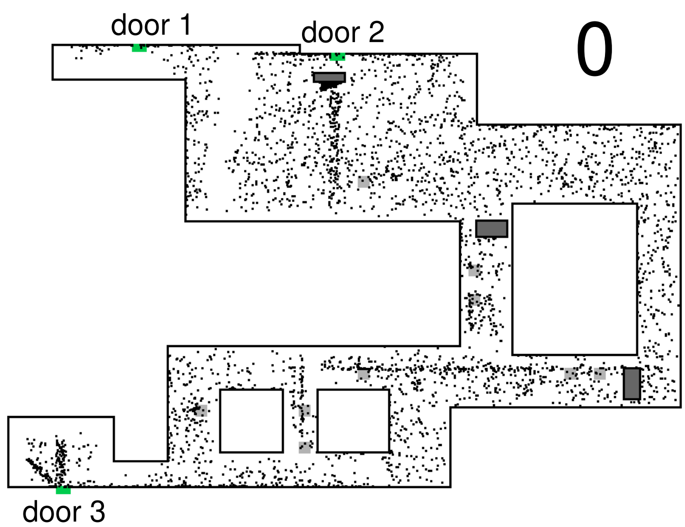


Figure 16: Crowd Distribution on Ground Floor With New Obstacles

It is shown that the crowd is confused in the vicinity of newly introduced obstacles, resulting in random movement, congestion and fewer people successfully reaching the exit.

And the ERI is as follows:

$$ERI = 0.5817 \tag{19}$$

This is because under the random walking strategy, visitors have a high probability of leaving the newly added obstacle area and moving to other exits, thus successfully leaving the building.

5.3 Effect of Smart Guide

Since we assume that the Smart Guide is fully aware of the real-time situation inside the Louvre, we believe that when introducing new obstacles, the Smart Guide can update its map and inform its users of the best route accordingly. We simulate the evacuation process with the assistance of Smart Guide, and Figure 17 shows the crowd distribution after 316 timesteps:

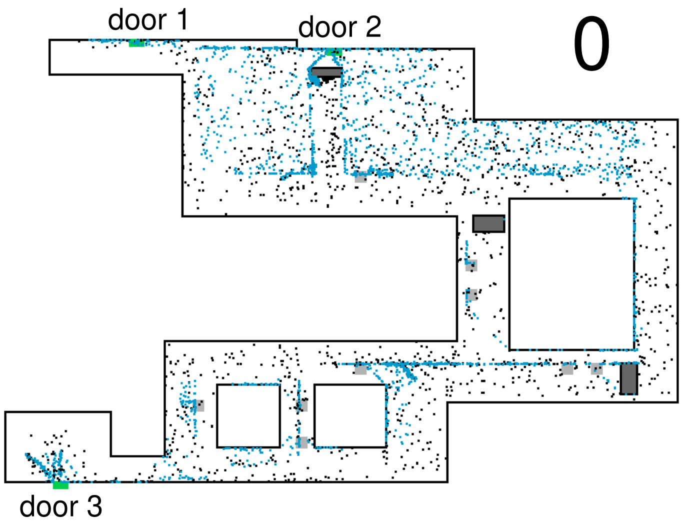


Figure 17: Crowd Distribution on Ground Floor With New Obstacles and Smart Guide

Compared with Figure 16, we can see that under the guidance of Smart Guide, its users (blue particles in the figure) will not congest near the blocks and will go directly to the exits. Due to herd behavior, their movement can also attract people without Smart Guide to other entrances.

The calculated ERI is listed below.

Similar with in Section 4, the Smart Guide users will largely outperform visitors without Smart Guide. Compare this statistics with equation 19. Compared to evacuation process without Smart Guide (ERI = 0.5817), the evacuation efficiency of Smart Guide

Group	ERI
All Visitors	0.6328
Visitors without Smart Guide	0.5897
Visitors with Smart Guide	0.6616

users is significantly improved (ERI = 0.6616), and that of the others also slightly increases (ERI = 0.6328).

6 How to make use of "exit points"

6.1 Problem Description

In this section, we will discuss a necessary problem: how to utilize secret exit points and how to tradeoff between evacuation efficiency and museum security? Although the disclosure of these exit points to the public can provide additional assistance to the evacuation plan, their use can also cause security problems such as ticket escaping, theft, or even terroristic attacks due to the lower or limited security compared with the four main entrances. These issues are what museum managers need to tradeoff.

In this section, firstly, we simulate the effect of "exit point" location on evacuation efficiency. Then we simulated the change in evacuation efficiency with the total number of visitors when opening an "exit point". For simple and effective analysis, we assume that the museum manager will inform everyone where the "exit point" is.

6.2 Exit point position analysis

We expect to identify locations that will obviously facilitate evacuation, or have no obvious influence on evacuation efficiency. So we choose two different "exit point" positions to see the difference in evacuation efficiency.

Two different exit point positions are shown as follows:

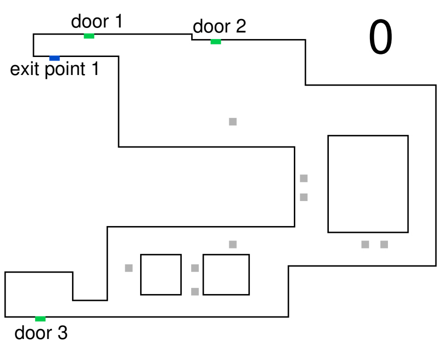


Figure 19: exit point 1

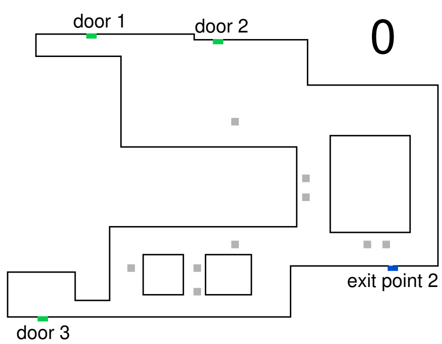


Figure 20: exit point 2

Simulation results are shown as follows:

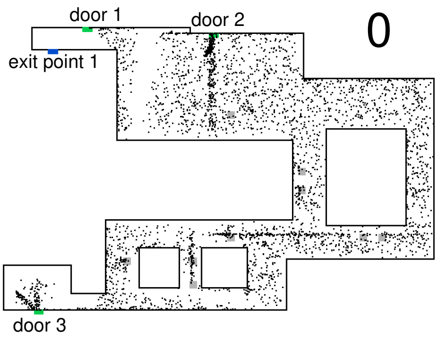


Figure 21: exit point 1

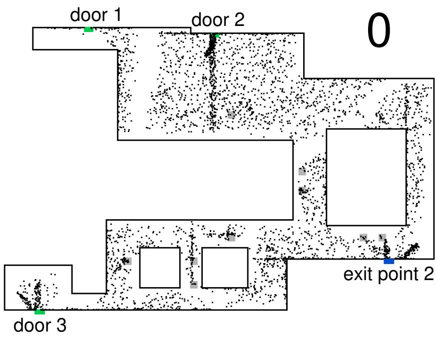


Figure 22: exit point 2

Simulation results shows that "exit point 1" doesn't make much difference to evacuation, while "exit point 2" well improved evacuation.

Calculated by Matlab, the evacuation efficiency in "exit point 2" increases 15.35%, and the evacuation efficiency in "exit point 1" increases 1.26%.

This result reflects that opening "exit points" around stairs, like "exit point 2", can obviously improve evacuation than opening "exit points" around corners, like "exit point 1".

6.3 Variation in evacuation efficiency as a function of total number of visitors

In Section 6.2, we find that opening "exit point 2" will obviously facilitate evacuation. So, in this part, we choose to open "exit point 2" to simulate variation in evacuation efficiency when total number of people changes.

Results are shown as follows:

Results shows that the number of evacuated people increases with the total number of people. This reflects that opening "exit point" will be much more important when visitor number increases.

The museum manager should tradeoff between potential security threats and better evacuation result. For example, if the museum manager think of potential security threats and 2000 more evacuated people as equivalent, he(or she) should open "exit point" when total number of people is larger than 13000 (approximately) and close "exit point" when total number of people is less than 13000 (approximately).

7 Entrance of Emergency Personnel

In emergencies, trained emergency personnel are needed to help evacuate visitors and protect museum property, thereby minimizing the loss of personnel and cargo caused by

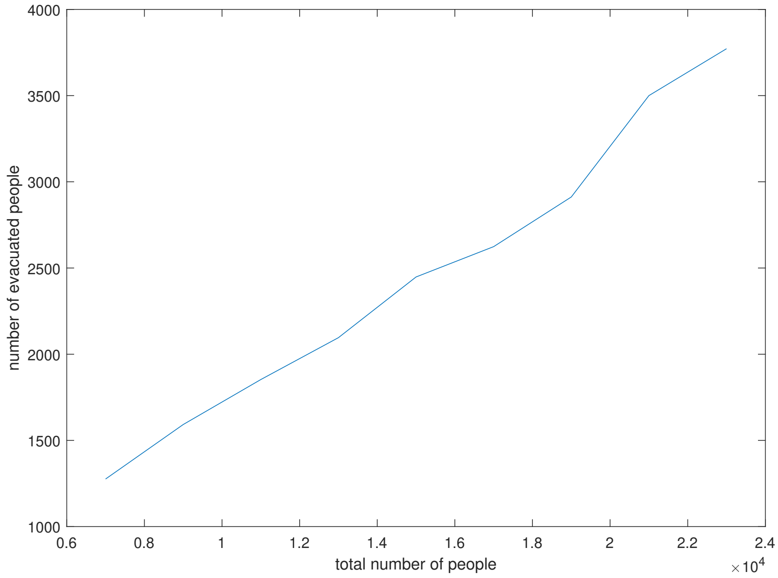


Figure 22: Variation in Evacuation Efficiency

emergencies. Therefore, they should enter the building as soon as possible. The speed at which emergency personnel enter the museum is an indicator that is as important as the speed of evacuation.

7.1 Method Description

7.1.1 Movement Strategy

In this part, we discuss the movement strategy taken by both emergency personnel and visitors.

First, we allocate a portion of the exits for emergency personnel entry, ie it cannot be used for evacuation. We assume that the emergency personnel will try to enter the building as fast as possible. Thus, once one of the reserved entrance is passable, one of the personnel will enter the building through the entrance.

Second, we consider how the personnel move on the map. To simplify our model, we assume that once entering the building, emergency personnel will move randomly. We argue that by moving randomly, the emergency personnel will naturally disperse [17], and thus can simulate the real situations.

For visitors, to simplify our model, we made two assumptions as below:

1. Visitors know the locations of all available exits.

2. The visitors will always head to the nearest exit, regardless of other factors including crowdness and the direction of other visitors.

Based on these assumptions, the visitors adopt a simplistic strategy that everyone flees to the nearest exit.

7.1.2 Entrance Setting Strategy

With the above assumptions, we can analyze different strategy of entrance setting. We consider two strategies.

Strategy I requires an exit is only used for emergency personnel entry, while other exits are only for the evacuation of tourists.

Strategy II is that, for each exit, a small portion is used for emergency personnel entry and the other is used for evacuation.

7.1.3 Evaluation

To evaluate the efficiency of entering the building, we define an index as follows: suppose there are N emergency personnel who need to enter the building, and the time required to fully enter the building is recorded as T_{in}.

However, the definition of "fully entering the building" remains ambiguous. To simplify our model, we assume that if an emergency person has entered the map and moved K steps, he is considered to have fully entered the building. Since the emergency personnel adopt a random movement strategy, we believe that after a certain number of random movements, the emergency personnel can reach the interior of the building and are sufficiently dispersed.

It is worth noting that although T_{in} is not be an accurately measurement of the required time for emergency personnel to enter the building, it can qualitatively indicate the difficulty of entering the building. Because the more congested inside the exhibition hall, the slower the emergency personnel can move, and thus the larger T_{in} is.

7.2 The Porte des Arts

In this section, we open the Porte des Arts to assess evacuation efficiency and personnel entry efficiency under both strategies. It should be noted that in order to fairly compare the two strategies, it is necessary to keep the area of the exit for evacuation and the area of the entrance for entering the building constant.

When calculating T_{in}, we set N = 1000 and K = 300, and the results as presented as below:

Figure 24 and 25 show the crowd distribution of zero layer after 350 time steps under Strategy I and Strategy II.

For Strategy I, the quantitative indicators for each strategy are as follows:

$$ERI = 0.5802 \tag{20}$$

$$T_{in} = 484 \tag{21}$$

And for Strategy II, the quantitative indicators are:

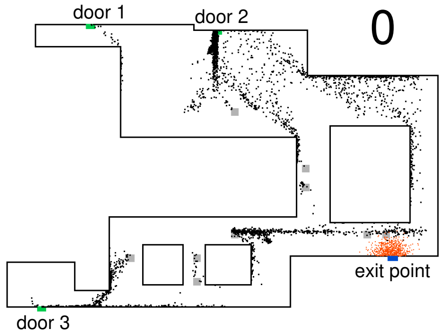


Figure 24: Crowd Distribution on Ground Floor Under Strategy I

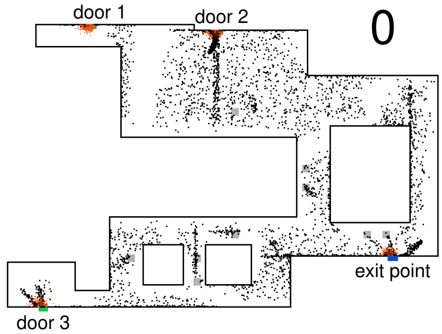


Figure 25: Crowd Distribution of Ground Floor Under Strategy II

$$ERI = 0.5209 \tag{22}$$

$$T_{in} = 2354 \tag{23}$$

It can be shown from the results that under Strategy I, emergency personnel can quickly enter the building and disperse without hindering evacuation. The entry of emergency personnel does not significantly reduce evacuation efficiency.

However, under Strategy II, the emergency personnel and tourists hinder each other's movements, and both the evacuation efficiency and the entry efficiency is significantly reduced.

7.3 The Remote Gate

We repeat the experiment using the Remote Gate. Figure 26 and 27 respectively show the crowd distribution of zero layer after 350 time steps under Strategy I and Strategy II.

Under Strategy I, the quantitative indicators are as follows:

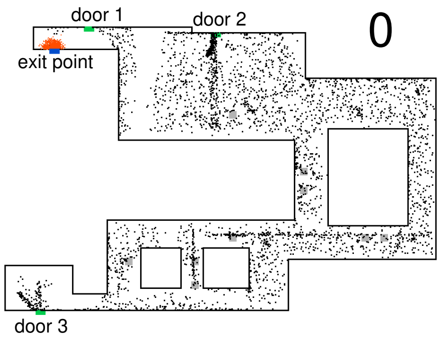
$$ERI = 0.5885 \tag{24}$$

$$T_{in} = 477 \tag{25}$$

And under Strategy I, the quantitative indicators are as follows.

$$ERI = 0.5209 \tag{26}$$

$$T_{in} = 2708 \tag{27}$$



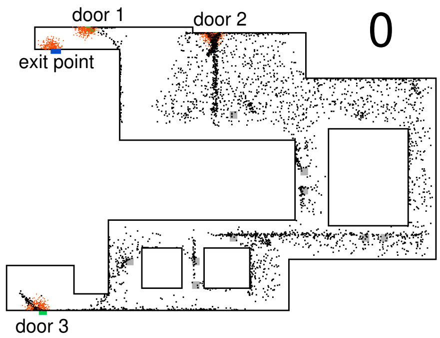


Figure 26: Crowd Distribution of Ground Floor Under Strategy I

Figure 27: Crowd Distribution of 1st Floor Under Strategy II

Similarly with the Remote Gate, Strategy II highly outperforms Strategy I in both evacuation efficiency and entry efficiency.

Further compare the results with that when using the Porte des Arts. When adopting Strategy I, the use of the Remote Gate can achieve better evacuation efficiency and entry efficiency. This is because the Remote Gate has fewer people and can avoid congestion between emergency personnel and tourists. On the contrast, under Strategy II, the evacuation efficiency will drop dramatically when using the Remote Gate, because the Remote Gate is less able to evacuate visitors.

8 Conclusions

8.1 Analysis and Policy Proposal

Based on the analysis above, we propose four suggestions:

1. **Increase the Passage Richelieu entrance and the width of the Main Stairs.** The Main Stairs and the Passage Richelieu entrance are two major bottlenecks in the Louvre and are easily congested, so it is neccessary to increase their passability.

2. **Use sensors and mobile phone applications to help evacuation.** We envision an application called the Smart Guide, which can highly improve evacuation efficiency. This benefit is especially significant when potential hazard blocks the path.

3. **Open "exit points" in areas where people move frequently when total number of visitors is high enough.** We found locations around stairs can significantly increase ERI, while locations around corners have little benefit. For locations with significant benefits, we found that this benefit is even more pronounced as the number of visitors in the museum increases. We then quantitatively assess this impact and propose a threshold for the number of visitors to decide whether to open the "exit points".

4. **Reserve seperate entrances for emergency personnel.** In all situations, this strategy outperforms other strategies. We specifically suggest to reserve an entrance in places where congestion are less likely to occur, such as the Remote Gate.

8.2 Strength and Weakness

8.2.1 Strength

1. Our model is based on cellular automata, which simulates the evacuation process in discrete time and space. Thus, the simulation is very fast.
2. Our model uses pipes to simulate stairs to connect different floors inside the Louvre, enabling the simulation of evacuation of people on multiple floors.
3. Our model considers several factors that influence visitor decisions to more accurately simulate the evacuation process.
4. Our model uses probability to guide individuals' behavior, so it is easy to introduce other influencing factors. Thus, our model is expandable.

8.2.2 Weakness

1. Our model assumes that everyone has the same scale and speed and does not analyze demographic diversity.
2. Our model does not analyze the impact of the internal structure of the exhibition hall on evacuation, but only considers the overall structure of the Louvre.
3. Our model assumes that the population is evenly distributed in the Louvre and is not exactly consistent with reality.

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