For office use only	Team Control Number	For office use only
T1 ________	**1915760**	F1 ________
T2 ________		F2 ________
T3 ________	Problem Chosen	F3 ________
T4 ________	**D**	F4 ________

2019 Mathematical Contest in Modeling (MCM) Summary Sheet
(Attach a copy of this page to each copy of your solution paper.)

Escape to Victory from the Louvre

Summary

The shadow of the Louvre terrorist attack has not yet faded, so it is essential to formulate a series of emergency evacuation plans for the Louvre. To solve this problem, we first establish an evaluation model to analyze the state and behavior of pedestrians in a room in the face of emergency. In this process, the best results can be obtained through theoretical analysis and practical optimization. Finally, some other factors are considered, and the model is modified to make it be suitable for more states.

Considering the conditions in the question, we use **modified cellular automata(MCA)** as the basic model. We improve the restrictive condition of CA that only one person can be in a cell. Instead, we use the relationship between the velocity of each person and the density of the surrounding people to restrict the density. The revised MCA model is consistent with the distribution of people in emergencies, including crashing and rejecting. In MCA model, we analyze the velocity of each person, introduce **potential field** to find the shortest path easily, and introduce **pedestrian-to-pedestrian force model (PPFM)** as control quantity.

Next, we apply the model to a simple room. Through simulation, we find that the results of MCA model basically coincide with the reality, so we apply the model to The Louvre. We qualitatively analyze the existence of the optimal solution by **graph theory**, and obtain the optimal solution by **simulated annealing algorithm**. In order to make the model more authentic, we introduce the elderly and group visitors, and analyze these special groups to get the corresponding optimal solution.

We abstract the Louvre into three layers. The first layer is a single room, which can be solved by using the MCA model proposed above. The second layer is a single floor, which contains many rooms. For this layer, it is regarded as a partitioned room. By simulating and optimizing the actual situation, a group of optimal solutions can be obtained. The third layer is the whole building which contains many single floors. For this layer, it can be analyzed as a number of rooms connected by hallways.

Finally, we conduct a sensitivity analysis in order to gain some deep understanding of our model, and verify the robustness of the model in many cases.

Contents

1 Introduction

1.1 Problem Background

As one of the most famous museums in the world, the Louvre attracts plenty of visitor from different areas of the world. A total of some 8.5 million visitors admired the Louvre's collections in Paris and Lens in 2017, which was a 16% increase compared with 2016.[1] However, from when students being killed in Toulouse to when a soldier attacked outside the Louvre museum in Paris, France has suffered at least 12 major terror-related incidents since 2012,[2] which put higher requirements on the emergency evacuation of scenery spots in France, including the famous Louvre. There is no doubt that a feasible emergency evacuation plan for the Louvre is needed urgently.

1.2 Our work

In this paper, we try to model the emergency evacuation process based on **modified cellular automaton (MCA)** then refine it, which can be reflected in **Figure 1**. The basic works are listed as below

1. We establish an emergency evacuation simulation model based on the idea of cellular automaton and some improved algorithms. After the MCA model is built, we apply our model in a simple case of the emergency evacuation in the classroom, to verify the reliability of our model.

2. We apply divide-and-rule to simplify the evacuation in The Louvre. We abstract the whole building into 3 layers

- Single exhibition rooms;
- Single floors;
- Multi-floor building.

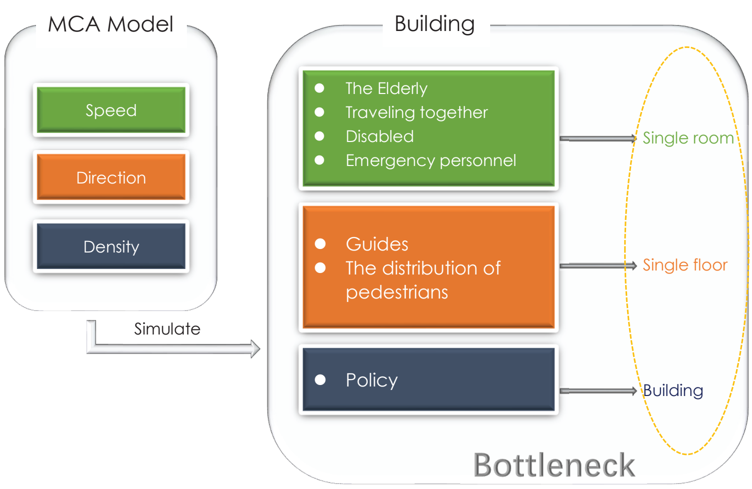


Figure 1: The generalize figure of our work

And the whole process is optimized by local optimization of each layer.

3. Using our model, we give the expected time to evacuate the pedestrians in different cases and analyze the potential *bottleneck* in The Louvre.

4. We do model evaluation and sensitivity analysis to verify the robustness of our model.

5. Based on the results of our work, we tentatively extend our model to other large, crowded structures. And based on the analysis of our result, we propose several suggestions to increase the efficiency of evacuation.

2 Preparation of the Models

2.1 Assumptions and Justifications

- No one wants to be thrown out of the breach in the emergency evacuation. That is to say, once an emergency happens, everybody tends to evacuate from the building.
- We divide the cell uniformly, each of the cell corresponding to a 0.5m $\times$ 0.5m area in reality. And we apply **Moore's neighborhood** as **Figure 2**. This method allows a person to move towards eight directions. This assumption is the precondition for us to build in our model.
- The vital improvement of our MCA model compared with CA model is that we separate pedestrians from cells. We don't limit how many pedestrians a cell can hold, however, due to the repulsive force we set, there is a density limit in a cell.
- To avoid using a more difficult 3-dimension cellular automata, we employ necessary simplification. We consider a multi-floor building as a single-story building, whose stairs can be regarded as narrow hallways to connect two adjacent floors. Due to it's narrowness, stairs are likely to become a *bottleneck* for the crowds to evacuate.

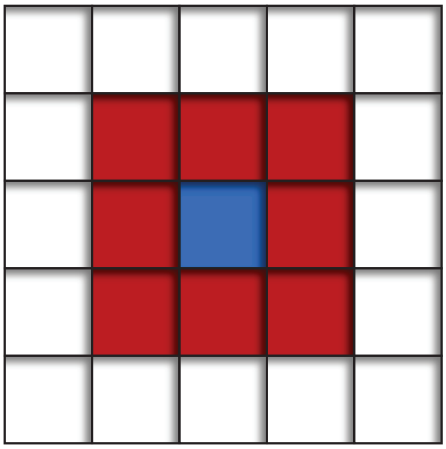


Figure 2: The relationship between a cell and it's neighborhood

- During the emergency evacuating process, neither elevators nor escalators operate. This assumption is rational for using them during the emergency evacuation is dangerous. Both of the two have a non-negligible possibility to be malfunction.
- One person's movement mainly depends on **three** factors
  - The position of exits;
  - The direction of the crowd;
  - The guidance.

  Though the factors that impact on the decision made by every individual are for sure more than the three factors mentioned above, to simplify the model, we select major influential factors.
- The guides have absolute authority, which means pedestrians will do what guides say. This assumption is to provide the precondition to achieve the optimization of our scheme.

2.2 Notations

The primary notations used in this paper are listed in **Table 1**.

Table 1: Notations

Symbol	Definition
ρ	the pedestrian density
v_i	the velocity of the i^{th} petestrian
φ_i	the potential energy of the i^{th} cell
$\vec{f_{mi}}$	the gravity force of exits on the i^{th} petestrian
$\vec{f_{ppi}}$	the pedestrian-to-pedestrian force on the i^{th} petestrian
$\vec{d_i}$	the expected movement direction the i^{th} petestrian
α	the weight of $\vec{f_{mi}}$ in $\vec{d_i}$
β	the weight of $\vec{f_{ppi}}$ in $\vec{d_i}$
p	the ratio of the crowd decentralization

3 The MCA Model

3.1 Sub-models

3.1.1 The Velocity of Pedestrians

We have two basic parameters to describe the movement's characteristics, velocity v and pedestrian density ρ. And it has been proved that there is certain relationship between v and ρ, which can be describe as Kladek formula[5] as below

$$v = v_M \left\{ 1 - \exp\left[-\gamma \left(\frac{1}{\rho} - \frac{1}{\rho_M} \right) \right] \right\}, \tag{1}$$

where $v_M = 1.32\text{m/s}$ is the average free speed of pedestrians, γ is the exponent that makes the relation sensitive to different scenarios. The jam density ρ_M is expressed as:

$$\rho_M = \frac{\beta_G}{S_m}, \tag{2}$$

where S_m is equal to 0.13m^2 as the mean surface occupied by a motionless pedestrian, and the geographic area coefficient β_G is equal to 0.847 for Asian countries or 1.075 for European countries.

The non-linear velocity-density function graph is in **Figure 3**. Kladek formula stipulates the maximum velocity of a pedestrian in a certain pedestrian density. In this way, we are able to describe the velocity in a certain position.

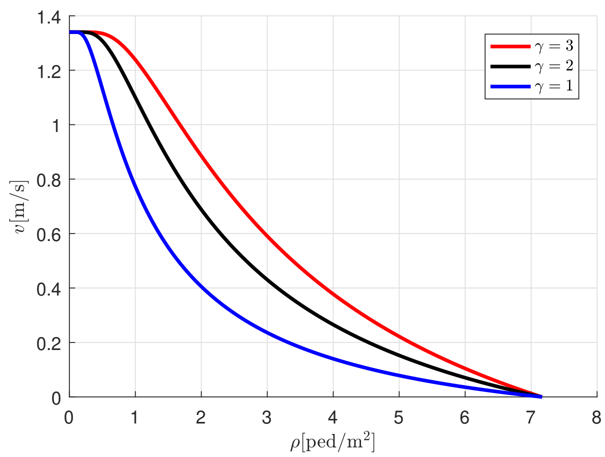


Figure 3: Velocity - density relations in literature

3.1.2 Potential-Field-Based Model

Once an emergency happens, almost everybody are chooses to evacuate from the building. Of course, it is natural for us to liken this process to the flow of water to a hole in lower ground.

The key point of water flowing to a lower place lies in the potential field theory. As is known to all, the water posited at higher levels has larger gravitational potential energy compared with the water at lower position. The driving force is the potential energy gradient $\nabla\varphi$. Water tends to flow towards the direction of $\nabla\varphi$.

In order to introduce this potential field theory to emergency evacuation, we adopt to **Breadth-first search algorithm (BFS)** to calculate the *potential energy* in every single cell. To make the potential field more accurate, we divide the neighbors of a cell into two parts, according to whether they are on the diagonal or not. On the first assignment of potential energy, we give 1.4 to those on the diagonal of the root(exit), and 1 to those not. And then every time we traverse a layer of cells, the potential energy is

$$\varphi_j = \min_{E_{ij} \notin \varnothing} (\varphi_i + 1), \tag{3}$$

where φ_j is potential energy of the i^{th} cell and E_{ij} is the edge between the i^{th} cell and i^{th} cell in the graph. The process to calculate is as shown in **Figure 4**.

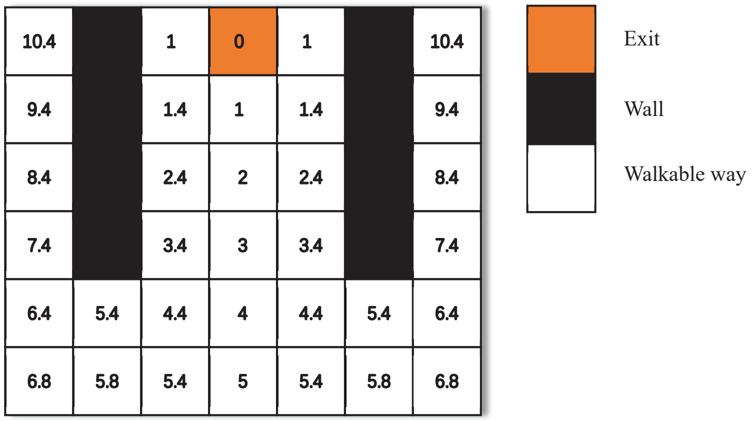


Figure 4: The process of calculating the potential energy of each cell

After applying the potential field to emergency evacuation, we have the method to quantify the attractive force of exits to pedestrians. Every pedestrian has a tendency to move towards the exits to reduce their potential energy. We have to point out that our potential field is a static field. Once the position of exits are determined, the potential field won't change with either time or pedestrians. A schematic of the potential field in one scenrio can be reflect on **Figure 5**.

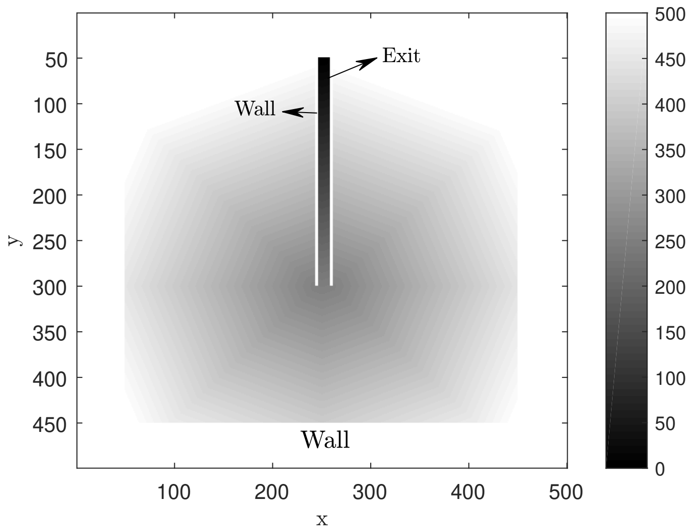


Figure 5: Schematic of the potential field in a $500m \times 500m$ room

3.1.3 Pedestrian-to-Pedestrian Force Model

Pedestrians are more inclined to draw closer to the crowd. Therefore, we cannot merely stipulate the direction of movement on the position of exits. That is to say, potential-field-based model alone is not enough, we need another **pedestrian-to-pedestrian force model (PPFM)** to reflect the influence of the crowd.

We first define the scope of f_{pp} (pedestrian-to-pedestrian force). We consider a 5×5 Moore's area as the scope $\mathbb{D}$, where pedestrians are more likely to be influenced by pedestrians closer to them than by pedestrians farther. Then we accumulate every pedestrian's velocity as the $\vec{f_{pp}}$. Here, we regard velocity as a vector, we consider its direction mainly.

$$\vec{f_{ppi}} = \sum_{j \in \mathbb{D}} \vec{v_j}, \tag{4}$$

where $\vec{v_j}$ is the velocity vector of a pedestrian located in the scope $\mathbb{D}$.

3.1.4 Total Impact on Movement

As we point out above, there are two main indicators that impact on the movement of pedestrians. Combining $\vec{f_{pp}}$ with $\vec{f_m}$, we can define the expected movement direction by following equation

$$\vec{d_i} = \alpha \cdot \vec{f_{mi}} + \beta \cdot \vec{f_{ppi}}, \tag{5}$$

where α is the weight of $\vec{f_{mi}}$ in $\vec{d_i}$, and β is the weight of $\vec{f_{ppi}}$ in $\vec{d_i}$.

In order to determine the numerical value of α and β, we assume that the impact of the potential field is as important as the impact of the pedestrian-to-pedestrian force. Based on the assumption, we have

$$\alpha = \frac{1}{2n},\ \beta = \frac{1}{2}, \tag{6}$$

$$\vec{d_i} = \frac{\sum_{j \in \mathbb{D}} \vec{v_j} + n\vec{f_{mi}}}{2n}, \tag{7}$$

where n is the number of pedestrians positioned in the 5×5 Moore's area $\mathbb{D}$.

So far, we have defined the rule of movement of pedestrians', which allows us to do further researches on emergency evacuation. And we will talk about it later in the next section.

3.2 A Simple Application of Our Model

3.2.1 Pedestrian Flow in a Simple Room

We have already assumed there is no limitation of pedestrians in a simple cell. However, it is obviously impossible for a cell to contain infinite pedestrians. In this section, we will prove that based on the restraint of Kladek formula in **3.1.1**, we do have a rational upper limit of density.

We presume a crowded $30\text{m} \times 30\text{m}$ room with a 1.5m-width exit. In initial state, 1000 pedestrians are distributed randomly in the room. It is not difficult to infer that the neighbor of the exit will be packed with people at the beginning of the evacuation. Therefore, the neighbor of the exit will be extremely crowded throughout. Our purpose is to verify that due to the repulsive force reflected in the Kladek formula, the density is always in a rational range.

In **Figure 6**, we can see that the mean density is around $4.5\text{peds}/\text{m}^2$, and the maximum density is around $7\text{peds}/\text{m}^2$, it is a high but rational number. We can also find that except for the start and the end stages, the mean velocity always keeps in a low level, it reflects the crowding from the other side.

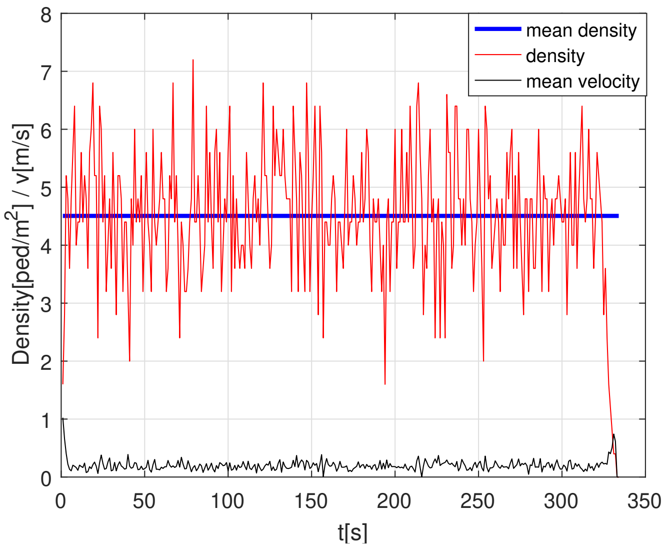


Figure 6: The density and mean velocity in the neighbor of the exit

It's also interesting to find the *bottleneck* near the exit. In emergency evacuation, when the rate of arrival near the exit is higher than the allowable rate, pedestrians will accumulate near the exit, forming an arched distribution. This is also a common method to visually verify the reliability of the model. In this simulation, we also observe this phenomenon in our model as **Figure 7**.

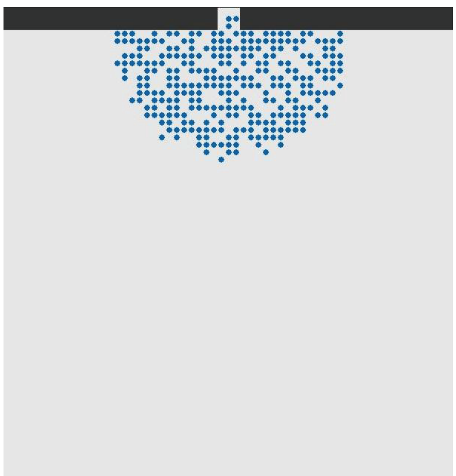


Figure 7: The arched distribution near the exit

And in order to embody the impact of the exit's size, we test our model in a set of sizes. The result in **Table 2** shows that the mean pedestrian flow and the exit's width have positive correction

Table 2: Mean pedestrian flow - exit's width

width[m]	mean flow[peds/s]	width[m]	mean flow[peds/s]
0.5	1.09	3.5	6.37
1	2.04	4	6.99
1.5	3.06	4.5	7.69
2	4.00	5	8.20
2.5	4.78	5.5	8.62
3	5.62	6	9.26

3.2.2 Classroom Emergency Evacuation Test

To prove that our MCA is feasible and able to reflect the real process of emergency evacuation, we apply our model to a simple case. Considering a rather simple and common scenario, we take the classroom as the evacuation background and simulate the process of evacuating students.

We assume the size of the classroom is $10\text{m} \times 8.5\text{m}$, which is a normal size in China. Then we add some barriers like desks and rostrums. Then we set two exits in the classroom and both of them are 1m wide. 80 students are of randomly distribution in the class. The result the simulation is shown in **Figure 8**.

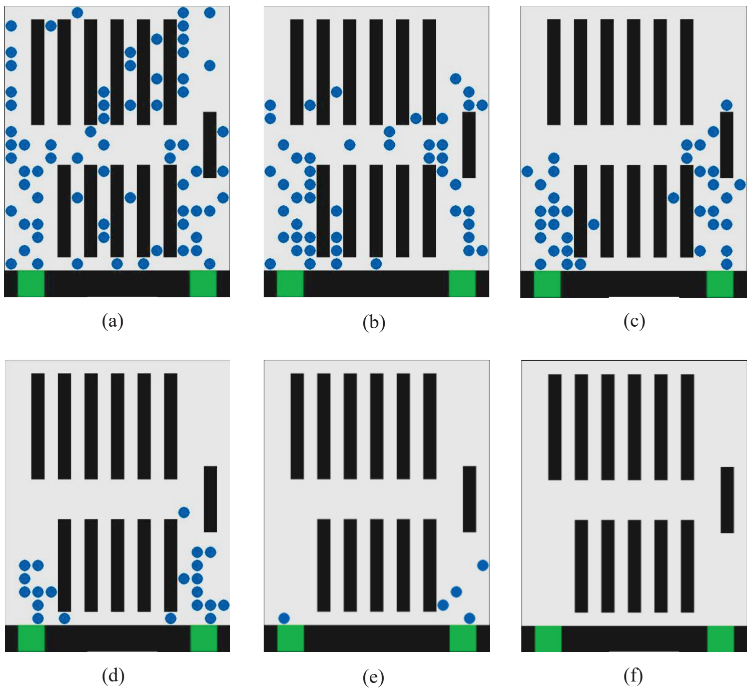


Figure 8: The simulation of classroom evacuation in every 5 seconds

As is shown in the figure, due to the attractive force of the exits, students who are close to exits quickly begin to gather together at the exits, and those who are farther also begin to move towards the closer exit under the impact of potential field. We can find that there is no congestion occurring near the exit, mainly thanks to the size of the exit. An 1m-wide exit is wide enough to provide 2 students pass through at the same time.

From the comparison of reality and simulation in **Figure 9**, we can also find that the simulated time costed in the emergency evacuation is less than a real process, mainly due to the velocity we set is a bit faster than the real velocity. However, the changing tendency of two processes is quite familiar, which adds the reliability of our MCA model.

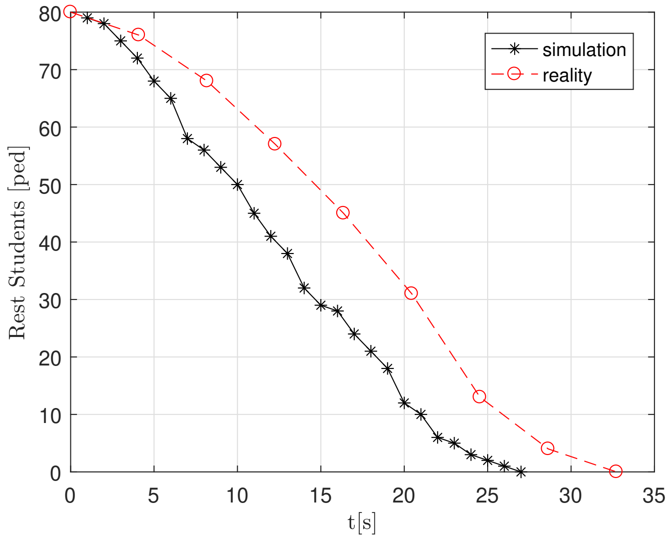


Figure 9: The comparison of reality and simulation

4 Simulations in the Louvre

We have demonstrated the reliability of the model above, so we decide to put the model into the Louvre for analysis and test. But limited by the scope of application of the model, we abstract the Louvre into three layers. On the first layer, we start with a single exhibition room. For such a room, we consider it as a whole, and we can use the above model for analysis. On the second layer, we consider an exhibition hall as a whole composed of multiple areas. In the following section, we will introduce and simulate the model in detail. On the third layer, we consider each exhibition hall as an area, and each floor is considered to be composed of multiple areas, which can be analyzed using the model below.

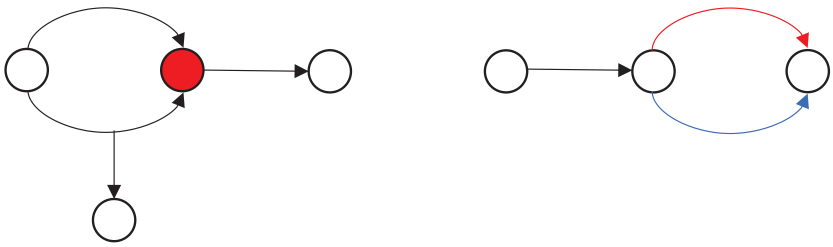
4.1 Two Basic Optimization Policies

In this section, we have two basic policies of isolating and decentralization to optimize the efficiency of exits. Our central purpose is to separate as many pedestrians as possible, not only to disperse the exits' pressure, but also to speed up the group movement by reducing the density of pedestrians.

We can abstract a room into a graph, applying graph theory to qualitatively analyze the existence of the optimal solution. At a node with two or more out-degrees, pedestrians always intend to go to the edge with less potential energy, resulting in an uneven flow of pedestrians between the edges. One side with a lot of pedestrians tends to start clogging up, while others are left "idle". Therefore, we should reasonably decentralize the nodes with larger flow of pedestrians to solve the problem of congestion in one edge.

On the other hand, when a node has more than two in-degrees, we are supposed to try to keep the number of people in the node as small as possible, so that people do not be squeezed in a node. That's the reason why we isolate some pedestrians.

Figure 10 shows two basic congestion scenarios mentioned above, Red indicates areas where congestion may occur.



(a) (b)

Figure 10: Two basic congestion scenarios

4.1.1 Decentralization Method

Given the enumerate method to solve the optimization problem taking too much time, we decide to adopt **simulated annealing algorithm (SA)**. We set the initial temperature: $T_0 = 1$, the terminal temperature: $e = 10^{-30}$, attenuation coefficient: $\alpha = 0.999$, the solution domain: $\mathbb{S} = \{p \in (0, \infty), t \in (0, t_{max}]\}$, where $p = p(\varphi_1, \varphi_2, \cdots, \varphi_n)$ is the ratio of the crowd decentralization, and t is the time used in decentralization. we set the initial value $p = 0,\ t = t_{max}$. The optimization function is the total time used in evacuation $f = f(p, t)$. The acceptance probability we set is

$$P(p(k) \to p', t(k) \to t') = \begin{cases} 1, & f(p', t') < f(p(k), t(k)) \\ \exp\left\{\frac{f(p',t') - f(p(k), t(k))}{T_0}\right\}, & \text{otherwise.} \end{cases} \tag{8}$$

4.1.2 Isolation Method

An isolation method is similar to adding a wall at a particular location to make the distribution of potential field more reasonable. In this case, the independent variables are the isolated location and the isolated time, and the objective function is the evacuation time. Similarly, we can use simulated annealing algorithm to obtain the optimal solution and its corresponding independent variables, the process is similar to 4.1.1.

4.2 The MCA Model in a Single Exhibition Room

Based on our classification method, we have three layers of problem to solve. In this section we apply our model to a single exhibition room. Then we choose three typical scenarios in a single room and find out the potential *bottleneck* in every scenario. Contrapose each phenomenon, we then introduce *guides* in our system to optimize the emergency evacuation plan. We have to point out that the shape of the room is based on a exhibition room in The Louvre, which has two exits. As shown in **Figure 11** We set the original population in the room to be 1000, and each exits is 2.5m wide.

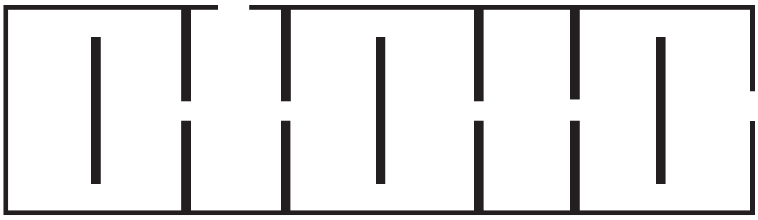


Figure 11: The layout of the room

4.2.1 A Simple Isolation Method

It's simple to consider the scenario when the two exits are symmetric distributed. In this case, when pedestrians are evenly distributed throughout the room, everybody will move towards the closer gate according to the potential field model. Therefore, pedestrians are likely to optimize their route even without a guide. We have already analyzed such cases in section 3.2.2.

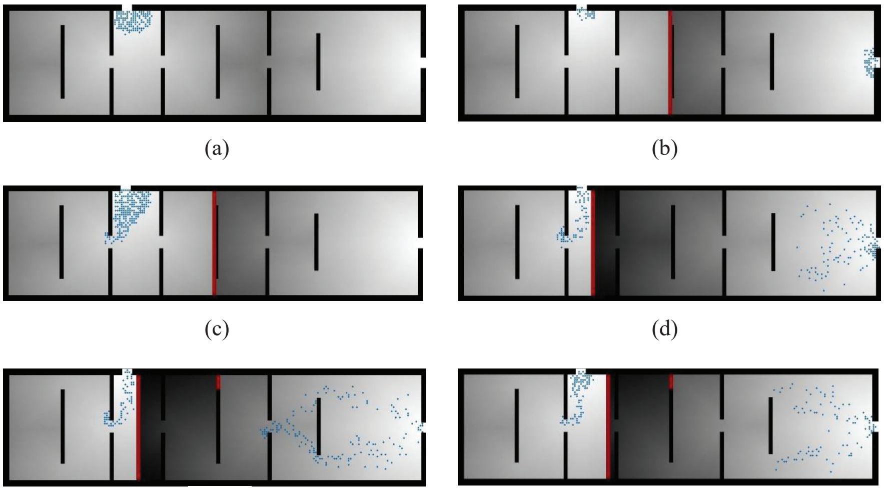
However, such a room is way too idealistic, therefore, we have to add other distractions to make our model more realistic, which is described as below

- When two exits are asymmetric distributed, the flow of pedestrians between the two exits will be uneven. The ability of exits to evacuate crowds cannot be fully utilized in consequence. Therefore, we need a guide to tell pedestrians which exit they ought to go.
- For visitors, a world-famous painting like Mona Lisa must be much more attractive than a relatively ordinary one, thus we cannot simply assume that the pedestrians are evenly distributed. In this occasion, we can infer it subjectively that the exit on the crowded side must be under more pressure. In this case, we set the number of people in the room to 8:2.
- Considering a fire hazard happens in The Louvre. As the fire spread, several segments of possible routes to safety may be removed, we simply consider it as a wall. And it will change the distribution of the potential field, then impact the movement of pedestrians.

In order to improve the efficiency of evacuation, we need a feasible guidance plan to maximize the flux of each exits. In consideration of the reality, the easiest way to handle this issue is to draw a boundary, which divides pedestrians into two groups.

The left group go to the left exit, vice versa. In this way we can significantly reduces evacuation time.

We apply exhaustive method to calculate the optimized solution of the boundary. And the result turns out that almost half time is saved after guidance. In **Figure 12**, where the red line infers to the boundary we draw, we can see that the guide's boundary redistributes the potential field (which is shown in the shades of color) and makes it more rational. We can draw the conclusion that with the help of a guide, the efficiency of evacuation will increase greatly due to using every exit wisely.



(a) (b) (c) (d) (d) (e)

Figure 12: The impact of guidance in 3 scenarios where the left is pre-optimization and the right is after-optimization

In **Figure 13**, we can clearly see the effect that guides bring. By comparison, the guide reasonably diverts the crowd, so that the flow of people in the two exits tends to be the same, so as to achieve the purpose of maximum utilization.

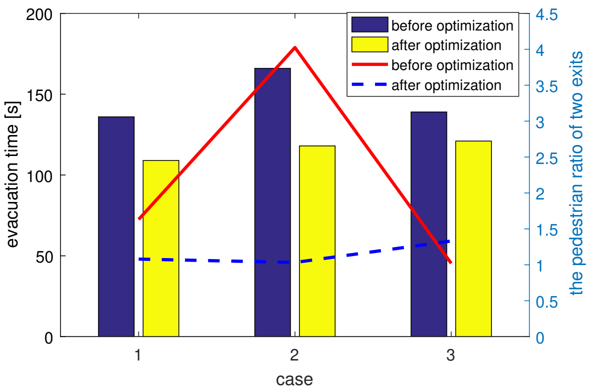


Figure 13: Guide vs. non-guide comparisons

4.2.2 Dynamic Decentralization & Isolation

We reset the position of exits to the same side without changing other original conditions. In this case, almost everyone would rush to one exit without any intervention, while left another exit has almost no pedestrian flow. However, since both exits are on the same side of the exhibition room, it's almost useless to simply draw a boundary to separate the crowd. We need to optimize pedestrians' paths by using decentralization and isolation method.

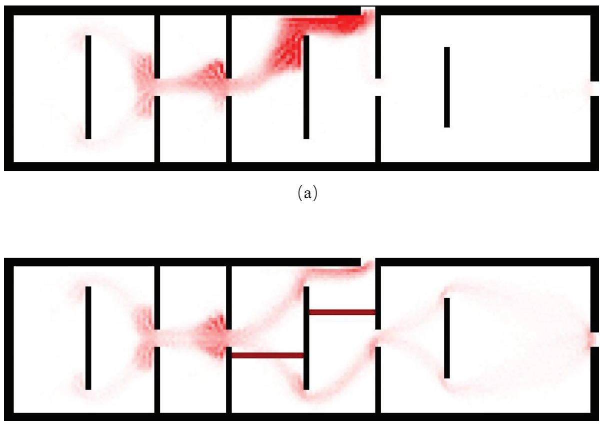
Applying SA algorithm, we first adopt the isolation method by blocking a way. We let the guide to divide the crowd evenly into two groups. Then we block another way in 89s which is calculated by SA algorithm. The result turns out that we almost save 1/3 of evacuation time by adopting these two policies. **Table 3** shows the result.

Table 3: The comparison before and after intervention

values	$t_L[s]$	$t_R[s]$	$f_L[peds]$	$f_L[peds]$
Before	233	28	901	99
After	160	156	487	513

where t_L and t_R indicates the time of last pedestrian in the left and the right exit. f_L and f_R indicates the flow in the left and the right exit.

In **Figure 14 (a)**, we see a huge *bottleneck* at the left exit before optimization, while there are few pedestrians at the right exit. The uneven distribution of pedestrians leads to the waste of resources. After adopting our optimization plan, part of the pressure in the left exit is distributed to the right exit, so that the bottleneck effect is greatly weakened as **Figure 14 (b)**.



(a)

(b)

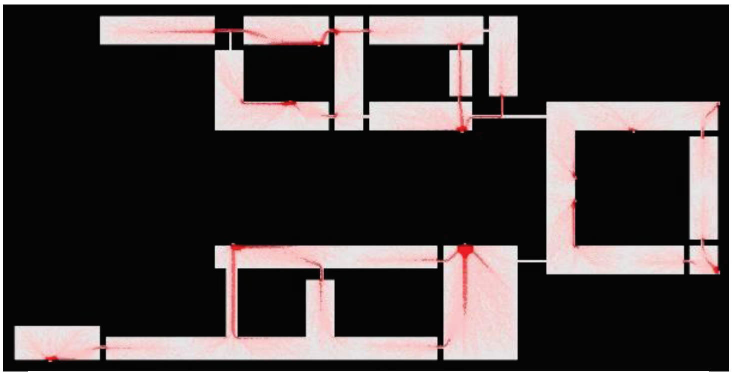
Figure 14: Heat map of personnel movement before optimization(a) & after optimization(b)

4.3 The MCA Model in a Single Floor

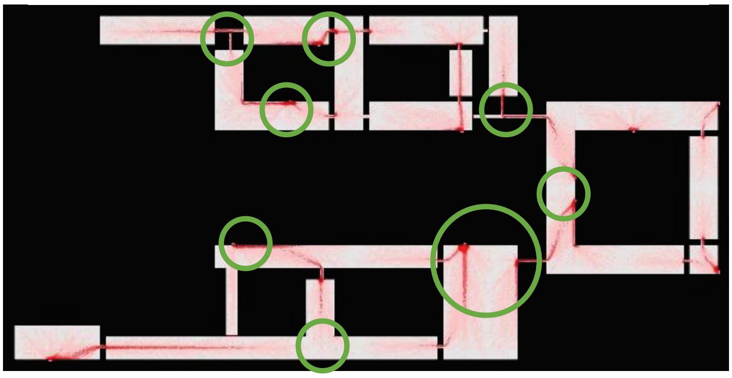
Based on our above discussion about the optimization of the first layer of the model, we can generalize it to the single floor scenario. The source of gravity changes from exits in the room to stairs. The floor consists of several exhibition rooms connected by corridors.

Here we adopt the method of "divide and conquer from top to bottom" to find the optimal solution for each exhibition room, and then take the whole floor as a whole, and use the method of isolation and decentralization overcome in the bottleneck to get the global optimal solution.

Figure 15 shows the impact of our policy, we add guide to lead the way of pedestrians on chosen places. Before intervention, almost 4 paths are almost in idle, while the number turns to be zero after intervention. We successfully decentralize the pedestrians, and take maximum use of paths to avoid *bottlenecks*. The result shows that before intervention, the 6000-pedestrian-evacuation takes about 240s, while only about 200s after intervention, which we consider as a satisfying optimized result.



(a) Heat map of personnel movement before optimization



(b) Heat map of personnel movement after optimization

Figure 15: Heat map of personnel movement, the green circles refer to guides

4.4 The MCA Model in Multi Floors

The third layer of our model is the whole building, which is a multi-floor structure. Based on our analysis above, the most time-consuming processes are always in the *bottleneck*. The time pedestrians waiting is far more than the time they spend on the way, the core question is how do you maximize wait times. Therefore, when simulating The Louvre, it's rational to neglect the fine structure of each layer. We consider the stairs as pipers connecting each floor, setting 3 exits on the ground floor and one exit on the -2 floor. We determined the number of pedestrians on each floor according to the Google search index of masterpieces on each floor. According to equation (1), the number of people passed by the unit length exit is

$$\int \rho \cdot v \mathrm{d}t, \tag{9}$$

Therefore, we can determine the optimal density of pedestrians in a stair by finding the maximum value of the function $f(\rho) = \rho \cdot v$. And the graph of $f(x)$ is shown in **Figure 16**. As can be seen from the figure, when $f(x)$ reaches its maximum, $\rho = 2.35$. Based on this density, We can further refine our guidance strategy of decentralization.

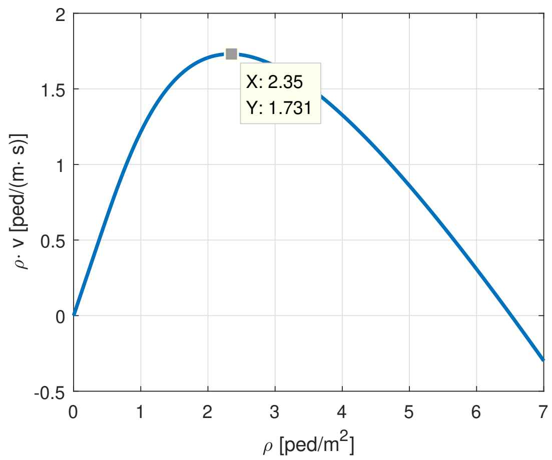


Figure 16: The graph of $f(x)$

Figure 17 shows that under the intervention measures, each stair is utilized to the maximum, and the density of people nearby is close to the optimal value, which rationalizes crowd evacuation. And the result is also satisfying: we reduce the evacuation time from 1495s to 784s.

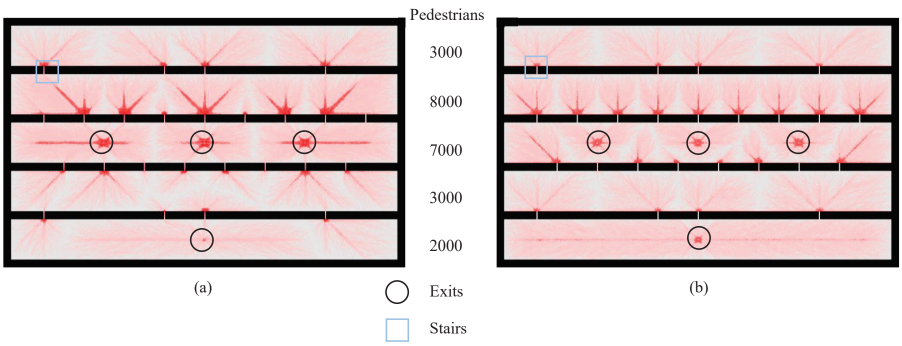
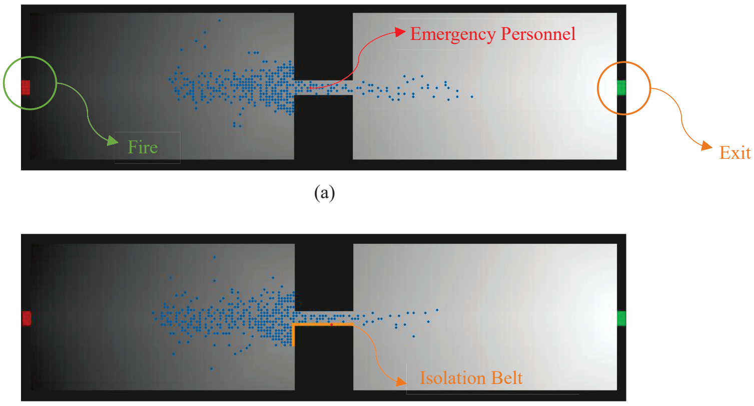


Figure 17: Simulation results of multiple floors in The Louvre

4.5 Emergency Personnel

In order to avoid colliding with the pedestrians who evacuate from the building, emergency personnel are given priority to enter the building through employee access or through small doors that unknown to visitors. If a fire accident occurs, emergency personnel need to rush to the fire as soon as possible to control it. If he encounter narrow terrain such as corridors in disaster without any intervention, they will be blocked by serious congestion, leading to worse results. Therefore, when encountering a narrow terrain, the isolation belt will be used to temporarily separate a 1-2 person wide passage from the stream for fire fighters to enter, and then close the passage after all consumers enter. As **Figure 18** shows, proper setting the isolation belt can greatly speed up emergency personnel to reach the fire.



(a)

(b)

Figure 18: Emergency personnel entered the room with and without isolation belt

4.6 Policies

By analyzing the evacuation in The Louvre, we have several policies to make it more efficient, which is stated below

- Publicizing safety knowledge to increase the ability of tourists to guard against potential safety hazards;
- Strengthen the security measures of the Louvre, arrange regular inspections of staff to eliminate hidden dangers;
- Appropriate dispersal of the population at potential bottlenecks to prevent excessive pressure at one area;
- Managers of The Louvre should use simulation programs to familiarize themselves with the population distribution in various situations, so that they can accurately carry out macro-control at the beginning of an emergency.

5 Sensitive Analysis & Special Pedestrians' Analysis

We perform sensitivity analysis on our model by considering different parameters' impacts on the result. Specifically speaking, we examine several different velocities and different types of pedestrians and model them as changes to input parameters of our model. Then we can get the exact impact of different parameters.

5.1 Modeling Different Types of Pedestrians

We will present our test of model on different types of pedestrians(the elderly and group visitors) in this section to verify the robustness of our model. And we also represent the accommodation to these situations.

5.1.1 The Elderly

We hypothesized that the motor ability of the elderly decrease compared with the normal, which can be reflected by the velocity equation we give in section 3.1.1, we set the $v_m = 0.4\text{m/s}$, and neglect other differences.

Figure 19 shows the evacuation time with respect to the different elderly's ratios. We see that as the percentage of the elderly increases, evacuation time increases rapidly at first and then tends to be stable. The data fluctuates slightly because the velocity of the elderly is slow, and the location distribution of the elderly will have a certain impact on each simulation. But overall, our model is stable for the percentage of the elderly.

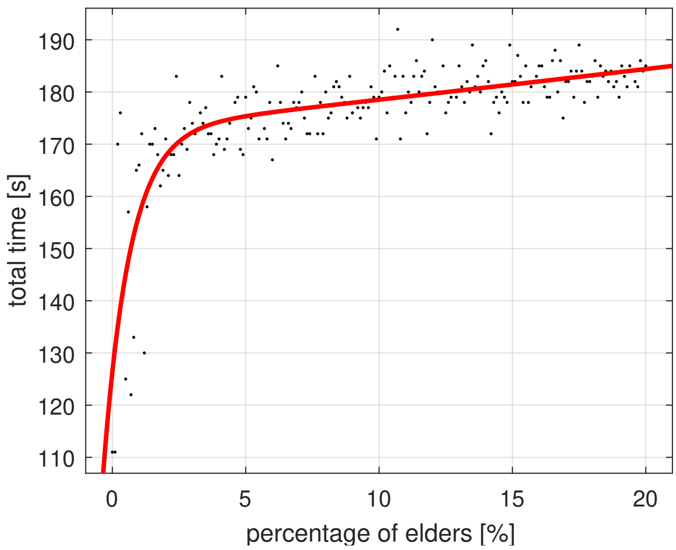


Figure 19: Evacuation time with respect to the elderly's ratio

5.1.2 Group Visitors

We assume that there is a certain amount of attraction between pedestrians on the same group that affects their movement, which is inversely proportional to the distance between the group center, so that everyone will not be too far away from the group. Pedestrians in the same group always intend to gather together, the density of pedestrians will increase than individuals.

Figure 20 shows the evacuation time with respect to the number of groups. For the sake of simplicity, we define a group of 20 pedestrians. As can be seen from the figure, with the increase of the number of groups, the evacuation time increases almost linearly ($R^2 = 0.9782$), and it also can be seen that our model is stable for the number of groups.

5.1.3 Accommodations for Situations

In this section, we will provide some accommodations that correspond to the previous type of pedestrians we have discussed.

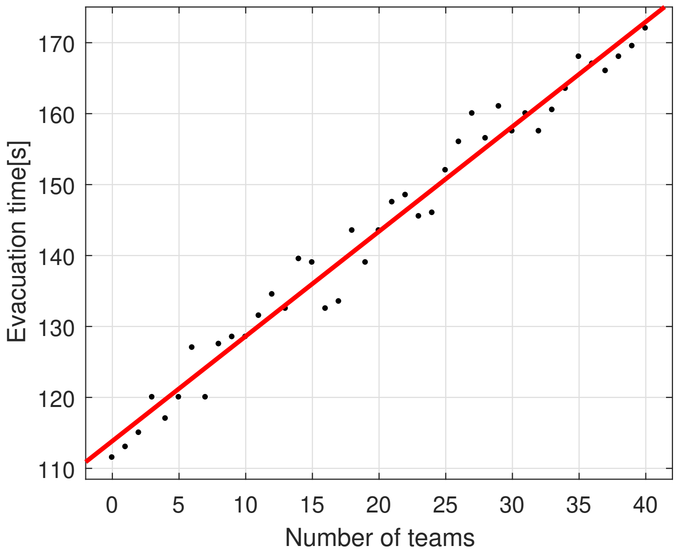


Figure 20: Evacuation time with respect to the number of groups

- Since both the elderly and group visitors will obviously increase the evacuation time, the manager of The Louvre have to set limits on the percentage of the elderly and group visitors.
- The elderly are often the last to escape in an evacuation because of their low velocity, in order to ensure the safety of them, dedicated channels for the elderly can be set nearby to faster evacuation. Or evacuate with guide with most of pedestrians are evacuated.
- Each group should have a guide to lead their evacuation, so as to prevent the group from missing the best time to escape because they are crowded together.
- In order to prevent the dispersal of group members in an emergency from affecting the speed, we suggest that group actions should be as consistent as possible.

We simulate a 1000-pedestrian room that consists of 20% group visitors and 5% elderly. The evacuation time before and after optimization are 176s and 154s respectively, which improve the evacuation efficiency to a certain extent.

5.2 Parameter of Velocity

In section 3.1.1, we use Kladek formula to describe the velocity of pedestrians, in the above simulation, we default to the scenario parameter $\gamma = 3$. And in this section, we try different values of γ range from 1 to 3, and the result in **Figure 21**, which shows a curve of steady decline for γ.

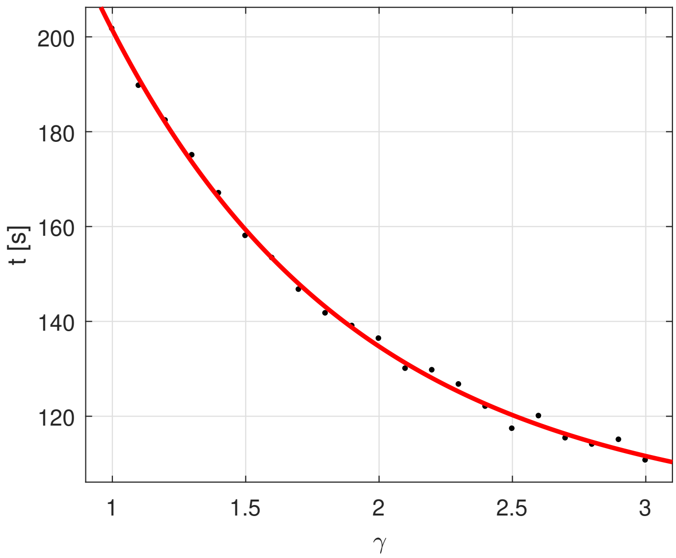


Figure 21: Evacuation time with respect to γ

6 Strengths and Weaknesses

6.1 Strengths

- The use of cellular automata to simulate pedestrian behavior in emergencies, through the simulation process to find the shortcomings of the model and adjust it, which will make our model more feasible.
- The relationship between pedestrian speed and the density of the people around enables the model to be independent from the simple cellular automata, so the improved accuracy of calculation makes our model more precise.
- Introducing a unique potential field model to describe quantitatively the trend of people fleeing towards doors in the form of potential field, so as to improve the accuracy of the model.
- Introducing PPFM parameters and optimizing classical cellular automata with the combination of PPFM and pedestrian velocity.
- In the modification of the model, we will lay the Louvre to adapt to the model to determine better results. This layering method can also be used in other large buildings to improve the availability of the model.

6.2 Weaknesses

- For people in emergencies, we can also consider the degree of tension, which can affect people's compliance with staff guidance and speed of movement, so as to make the model more accurate.
- The stratification of the Louvre simplifies the structure of the Louvre and makes the simulation results deviate greatly from the real situation.

7 Conclusion

To sum up, we first established and improved the MCA model to simulate the evacuation in more complex emergencies more realistically. In addition, we have also made restrictions on each individual's specific code of conduct, making individual behavior more authentic. After applying the model to a simple room, we extend it to the Louvre. After layering the Louvre, we use simulated annealing algorithm to optimize the model.

Our model results show that queuing through the exit takes up a larger proportion of the time than running time in the evacuation, so how to reduce queuing waiting time is the core problem.

For the Louvre exhibition hall, we can speed up the evacuation of tourists in emergencies by adding boundaries and guides. After simulation, we can draw a conclusion: under different circumstances, the time has been greatly shortened, and the time after intervention has been reduced by about 33% compared with that before intervention. At the same time, we also simulate the congestion situation in the evacuation, find out the places where the flow of people is more easily blocked, reduce the congestion situation by adding guides, and accelerate the evacuation speed.

In other large-scale buildings, we can still take similar measures to reasonably control the flow of pedestrians at the potential bottleneck through decentralization and isolation, so as to take full use of exits. Meanwhile, real-time monitoring of pedestrians' distribution is also essential, which helps decision makers make correct judgments.

References

[1] "Interactive Floor Plans." *Louvre - Interactive Floor Plans | Louvre Museum | Paris*, 30 June 2016,
`http://www.louvre.fr/en/plan`.

[2] Reporters, Telegraph. "Terror Attacks in France: From Toulouse to the Louvre." *The Telegraph, Telegraph Media Group*, 24 June 2018,
`https://www.telegraph.co.uk/news/0/terrorattacks-france-toulouse-louvre/`.

[3] Burstedde C, Klauck K, Schadschneider A, et al. Simulation ofpedestrian dynamics using a two-dimensional cellular automaton. *Physica A*, 2001, 295: 507-525

[4] Wikipidia: Cellular automaton. 2019.1.14.
`https://en.wikipedia.org/wiki/Cellular_automaton`

[5] Venuti, Fiammetta, Bruno, Luca. Crowd-structure interaction in lively footbridges under synchronous lateral excitation: A literature review. *Physics of Life Reviews*, Volume 6, Issue 3: 176-206.

[6] Wikipidia: Breadth-first search. 2019.1.20.
`https://en.wikipedia.org/wiki/Breadth-first_search`

[7] Zhu, K, J. *Study on evacuation characteristics and evacuation strategies of typical areas in buildings* (Doctor Thesis) University of Science and Technology of China, Hefei, Anhui, China, 2013.

[8] Zhao Yibin, et al. A multi-exit occupant evacuation model based on fuzzy cellular automaton. *Jounrnal of Natural Disasters*, 2013, Vol.22, No.2: 13-20.