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2019 Interdisciplinary Contest in Modeling (ICM) Summary Sheet
Summary Sheet

Time to leave the Louvre

In recent years, terrorist attacks has become a nerve-wracking problem in France, especially on crowded public areas such as squares and museums. So it is crucial to explore optimal evacuation plans in public areas. Taking the famous Louvre Museum as specific case, we design an adaptive evacuation model. In our model, we take into consideration people's individual and collective behaviors during evacuation, museum officers' management and emergency personnel's movement. Our model is suitable for multi-floor structures with obstacles. We build our model in threesteps. The first step is to design the single-floor model. The second step is to develop the stair corridor model and the elevator model. The third step is to connect each floor with stairs and elevators and then to generate the multi-floor model which accords with the characteristics of the Louvre.

Our single-floor model based on Cellular Automaton combined with Ant Colony Algorithm simulates the evacuation process on a single floor. People's movement during this process is portrayed using 3 sub-models. These sub-models simulate how people choose their direction, exits to leave and compete for one position. Besides, we add the competitive factors in the human social power model and simulate the escape under obstacles to make the model more .

We use the corridor model and elevator model to connect single-floor models and then get our multi-floor model. Corridor model is designed based on queuing theory. Thanks to online applications like "Afflurences", corridors' state can be fed back to a cell in single-floor model. With this feedback, we can balance loads among exits to avoid potential bottlenecks. Elevator model are designed for the special groups, such as the elderly and the disabled.

Then, we implement our model with Python. The feasibility of the model is verified. We make data analysis on Louvre's structure of fine and coarse granularity to test the influence on evacuation result of the number of exits, people's cognition ability and the presence of guidance. We also compare the evacuation results with various initial visitors layout.

Based on the data analysis, we finally come up with options that can help minimize evacuation time as recommendation to museum leaders. Museum leaders may arrange staffs to guide people during evacuation and make exits more conspicuous. These kinds of management help people to find an exit, and more importantly, an less-congested exit. At the same time, we also simulated the evacuation of people in different initial states, and proposed the form of the Louvre's tour queue to achieve the shortest evacuation time.

After trying out our model on other structures and get evacuation process similar to reality, model's adaptability proves.

Keywords: Ant Colony Algorithm, Cellular Automata, Multi-level Evacuation Model, Asymmetrical Pedestrian Layout, Queuing Theory

Contents

1 Introduction

1.1 Problem Background

In recent years, there have been more terrorist attacks in France, especially in the crowded scenic spots, leading to casualties as well as affecting the development of French society seriously [1]. The Louvre, located on the north bank of the Seine River in the center of Paris, is on the victim list.

As one of the most famous museums in the world, Louvre attracted as many as 8.1 million visitors in 2017 [2]. Such a great number of people make it hard to get all the people out of the building in short time. So we are urged to develop an emergency evacuation model to help finding an optimal evacuation plan.

Because of the complicated structure of Louvre, a traditional singular model cannot meet our requirement. Instead, we consider multiple impact factors, the main issues involved are:

- The Louvre has multiple floors and multiple exits on each floor.
- There are some additional exits (service doors, employee entrances and VIP entrances et al.) that can be used during emergency. But only emergency personnel and museum officials know their location. These exits have lower level of safety.
- When visitors inside building moving outwards, emergency personnel move inwards. We want to ensure both process go smoothly.
- The evacuation model should be an adaptive model to apply on various kinds of emergencies (fire, terrorist attacks).
- Potential risks may change or delete safety sections that are essential in a single optimization path, and the time and place of risk occurrence is also highly uncertain.

Based on the above multiple considerations, effective crowd management and control procedures need to be proposed. More importantly, the model can be extended to other large, crowded building structures.

1.2 Literature Review

Based on the problem background, we summarize that our model should first solve the optimal emergency evacuation planning problem of the Louvre, and then can be fully expanded on this basis.

Existing evacuation models can be classified into 2 types, continuous models and discrete models.[3]. The focus of the continuous model is to study the microscopic characteristics of humans. Using virtual pedestrian modeling with autonomous behaviors, focusing on people's minds and real-time environmental impacts, this is very close to reality, and groups can generate individual behaviors. However, the continuous model has many shortcomings. The most serious is its complex model and huge computational complexity, which is inefficient in multivariate environments. Common continuous models are: fluid kinematics models [4], social force models, and so on [5]. The discrete model first separates the regions, simulates the evacuation of the personnel according to the specific evacuation rules, and overcomes the shortcomings of the continuous model with a large amount of computer. The most classic models are the cellular automata [6], the lattice gas model, and so on [7]. In addition, some scholars have grasped the advantages of continuous models and improved the discrete models. Some of them have excellent models, such as introducing the concept of social force model into the cellular automata model. A model based on the interaction between pedestrians and obstacles [8]. There are also some scholars who are concerned about the speed of evacuation. Ansgar et al. discussed the influence of the maximum movement speed of different pedestrians on the pedestrian density distribution and the shape of the crowd during the evacuation process [9]. But most of the above discussion is defined in the shape of a rule, such as squares, circles and other evacuation areas. The above model does not give advice on evacuation under irregular shapes, especially for buildings like the Louvre, multiple floors, even layers with underground, multiple exits and unknown exports, many types of visitors.

Based on the above models and theories, in order to achieve the adaptability of the model and put it into use in the Louvre, this paper mainly constructs a joint ant colony algorithm and a cellular automaton model, which can be used for special devices and special populations. Processed and provided evacuation guidance for complex buildings, with the advantages of continuous and discrete models.

1.3 Our Work

1. We developed an optimal evacuation model based on Cellular Automaton and Ant Colony Optimization algorithm which is suitable for complicated structures such as the Louvre. Our model can simulate the evacuation process and find an optimal evacuation plan after optimization process converges.

2. We modelled in details people's individual and collective behaviour during emergency evacuation with 3 sub-models in our floor model.

3. Our model can be applied to building with multiple floors after we designed our corridor model and elevator model taking use of queuing theory and Client-Server structure.

4. We implemented the simulation of the model through Python programming.

5. After implementing our model on the the Louvre, we studied the factors affecting the evacuation effect in data analysis, such as the number of escape doors, the state of the crowd, the use of elevators, etc.

6. Based on the above research results obtained from data analysis, we gave advice to museum leader to help achieve better evacuation result.

7. We discussed how we adapt our model on other structures and verified our model has satisfying adaptability.

2 Preparation of the Models

2.1 Structure of the Louvre

The structure of Louvre can be abstracted as Figure 1 based on floor plans from official website `https://www.louvre.fr`. In Figure 1, we mark a corridor or an elevator as a red dot. .

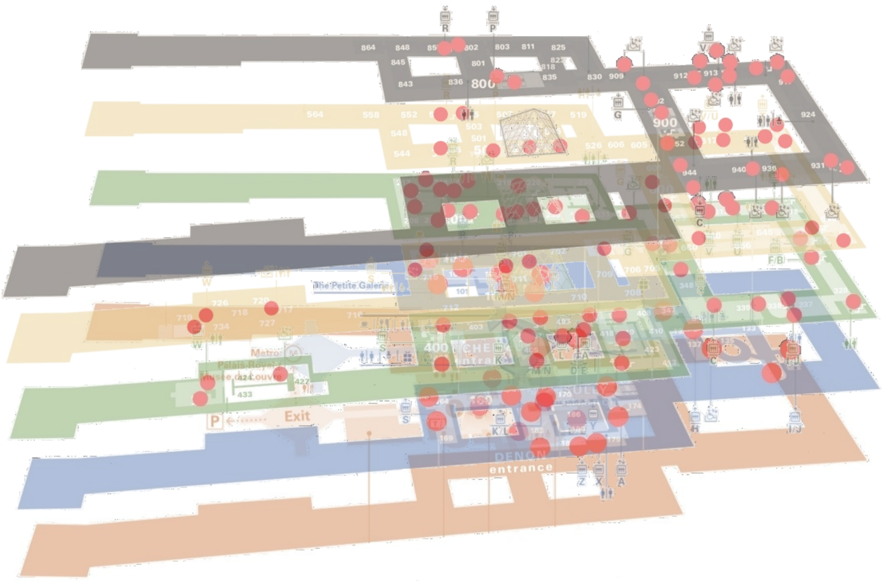

Figure 1: The structure of the Louvre

2.2 Assumptions

- Overlapping (e.g. Adults carrying a baby) is ignored.
- People move continuously once emergency takes place. They should never stay still.
- People moved with constant initialized velocity.
- People have cognition of exits nearby.
- People can tell whether or not an area is crowded.
- People stay alive before moving out of the building.
- The structure of building stays the same. Situations such as building collapse are ignored.
- Online application such as "Affluences" can provides real-time updates on estimated waiting time at doors even during emergency evacuation.

2.3 Notations

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

Table 1: Notations

Symbol	Definition
T^i_{escape}	Total time for cell i to reach one of the exits
T^i_{floor}	Total time of cell i to move on floors
T^i_{stairs}	Total time of cell i to move on stairs
$T_{threshold}$	Time threshold
W_{exit}	Width of exits
V_{floor}	Velocity of a visitor moving on floor
L_{stairs}	Length of stairs
W_{stairs}	Width of stairs
h^k_i	Heuristic function for cell i to choose its k^{th} neighbour
p^k_i	Heuristic function for cell i to choose its k^{th} neighbour
N	Total number of cells in single floor
M	Total number of visitors to quit
$M^{‘}$	Total number of emergency personnel to enter
$\boldsymbol{\rho}$	Visitor density
C	Competition capability
$\boldsymbol{\tau}$	Pheromone strength on the edge between cell i and its k^{th} neighbour
$\boldsymbol{\alpha}$	Information heuristic factor
$\boldsymbol{\beta}$	Expectation heuristic factor

3 The Models

3.1 Overview

To simulate a complicated structure with multiple floors connected with stairs and elevators, we divide the entire building into single floors and connection parts between neighbor floors.

We first design an optimal emergency evacuation model for a single floor using Cellular Automata based on Ant Colony Optimization algorithm (ACO-CA). When building Single-floor Model, we also take into consideration the importance to avoid congestion on stairs by constructing Corridor Model with queuing theory. Finally, we model the message-passing process on applications such as "Affluences" with Client-Server structure and obtain Multi-floor model.

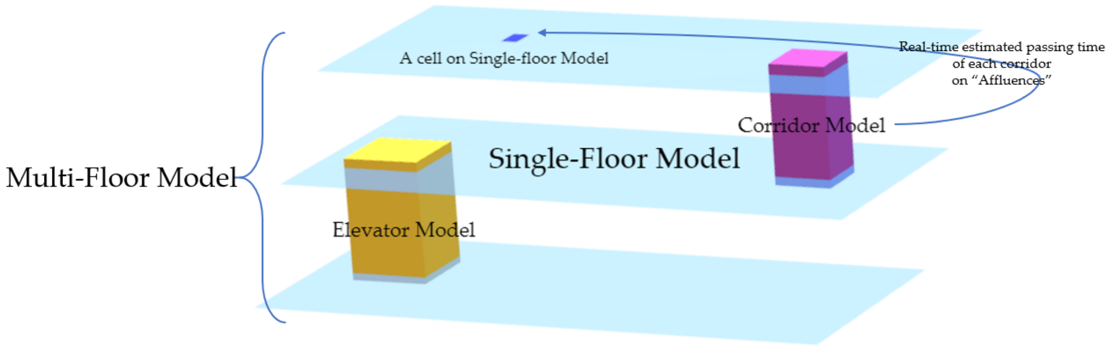

Figure 2: Overall model design

3.2 Single-floor Model

3.2.1 Design of ACO-CA

Cellular Automata model a suitable and effective choice for building our model because it can model individual and collective behavior despite of computation simplicity [10]. First, a cellular automaton consists of a collection of cells on a grid which can be set into different shapes to adapt various structures, including Louvre. Second, each cell is in one of a finite number of states, so we can represent the movement of visitors, emergency personnel and threats by changes cells state through discrete time steps. Third, cells state translation according to a set of rules based on its neighbor cells, so we can simulate individual and collective behavior by setting transition rules. All in all, it is reasonable for us to simulate the evacuation process with CA model.

We always keep in mind that we develop evacuation model in order to help the museum leaders to explore an optimal emergency management plan, so we then combine the Ant Colony Optimization algorithm (ACO) with CA model to get our optimal evacuation model Ant Colony Optimized Cellular Automata (ACO-CA) [11]. With ACO algorithm, we can iterate evacuation tours till it converges to the global optimum evacuation path.

3.2.2 ACO-CA Structure

In our Single-floor Model, each floor is divided into cells each $0.5m * 0.5m$ in size, which is the approximate space a person occupies. Each person occupies a cell. The movement of each person is confined to a cell. After each time step, a person moves to one of its valid neighbor cells with the greatest transition probability. Each movement leaves pheromone on the edge.

Transition probability of the movement i, j of each cell (denoted in matrix below) at the t^{th} time step is defined as Equation 3.2.2 and Fig 3.

$$P_{i,j} = \begin{cases} \frac{(\boldsymbol{\tau}_{i,j}(t))^{\boldsymbol{\alpha}}(h_{i,j}(t))^{\boldsymbol{\beta}}}{\sum_{m,n \in allowed}(\boldsymbol{\tau}_{m,n}(t))^{\boldsymbol{\alpha}}(h_{m,n}(t))^{\boldsymbol{\beta}}}, & k \in valid_i \\ 0, & otherwise \end{cases} \tag{1}$$

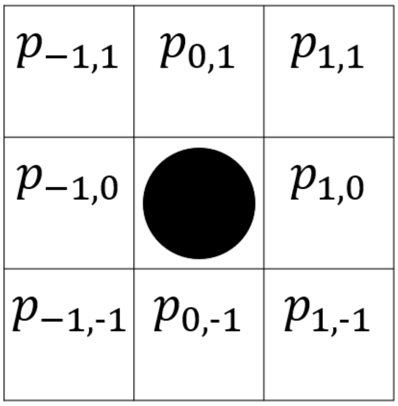

Figure 3: Cell transfer probability matrix

where $\boldsymbol{\tau}_{i,j}\left(t\right)$ is the amount of pheromone deposited on this edge and $\boldsymbol{\alpha}$ is a parameter to control the influence of $\boldsymbol{\tau}_{i,j}\left(t\right)$. $h_{i,j}\left(t\right)$ is the heuristic functions value describing the desirability of this transition and $\boldsymbol{\beta}$ is the parameter to control the influence of $h_{i,j}\left(t\right)$.

When all people have reached an exit, strength of pheromone on each edge is updated by Equation 3.2.2 Equation 3.2.2

$$\boldsymbol{\tau}_{i,j}\left(t+1\right)=\left(1-\boldsymbol{\rho}\right)\boldsymbol{\tau}_{i,j}\left(t\right)+\textstyle\sum_i \boldsymbol{\Delta\tau}_{i,j}\left(t\right) \tag{2}$$

$$\boldsymbol{\Delta\tau}_{i,j}^{k}\left(t\right)=\begin{cases}\frac{Q}{L_k}, & if\, the\, k^{th}\, cell\, uses\, this\, edge\, in\, its\, tour\\ 0, & otherwise\end{cases} \tag{3}$$

where $0\leq 1-\boldsymbol{\rho}\leq 1$ is the pheromone residual factor to avoid informations unlimited accumulation and $\boldsymbol{\Delta\tau}_{i,j}^{k}\left(t\right)$ is the amount of pheromone the k^{th} ant left on edge after the t^{th} time step. L_i is the cost the k^{th} person tour and Q is a constant.

It is significant find an ideal heuristic function $h_{i,j}(t)$ for simulating individual and collective behavior. We use 3 sub-models, namely Exits-Searching-with- Obstacle-Avoiding Model, Position-Competing Model and Cognition Model to construct $h_{i,j}(t)$.

3.2.3 Initial Visitor Layout Model

The initial visitor layout of the Louvre is a little different from that of a public square or a shopping mall et al. In the museum, visitors usually stay besides exhibits rather than wander around at random.The nearer to exhibits, the more fascinated visitors are. When it comes to ACO-CA, it means cells are more likely to generate on spots near to exhibits. The generation probability of a cell is defined as

$$P=\frac{F}{\sqrt[r]{d}} \tag{4}$$

where F is the fascination of an exhibit, d is the distance between the cell and exhibit and r controls the influence of distance.

We summarize the exhibit placement style in different halls in the Louvre and come up with 4 typical sorts of initial visitor layout as following. (real pictures are from `www.louvre.fr`)

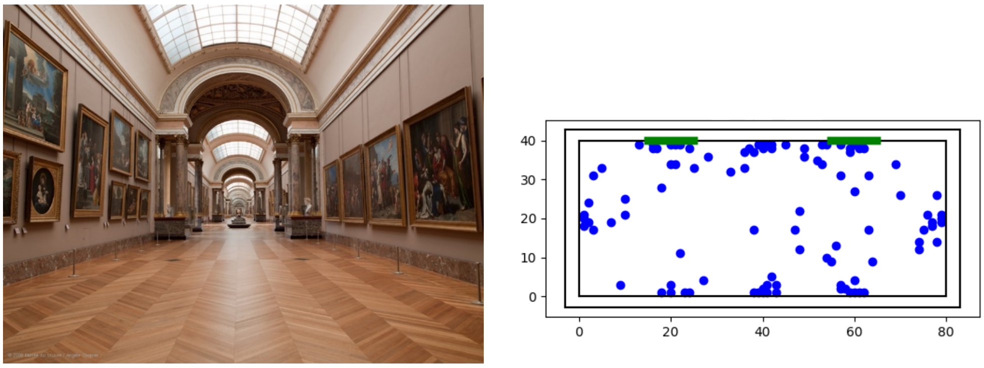

Figure 4: Wall model

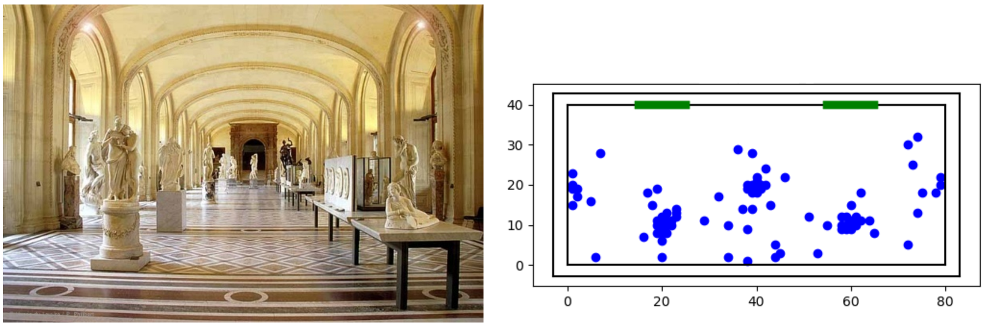

Figure 5: Heaps model

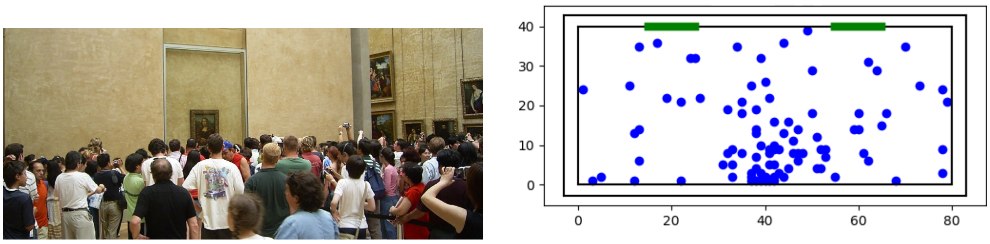

Figure 6: Mona Lisa model

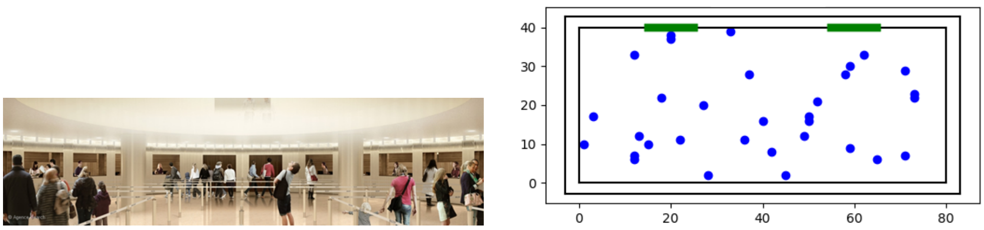

Figure 7: Random model

3.2.4 Exits-Searching-with-Obstacle-Avoiding Model

A visitor has estimation of the shortest distance from a cell he stands on to one of the exits. Cells with smaller shortest distance are more desirable for visitors so they tend to move to those cells. We use static floor field $S_{(x,y)}$ [12] to indicate the shortest distance from the cell at coordinate $(x, y$ to one of the exits. If obstacles within the space are ignored, $S_{(x,y)}$ can be easily calculated as Euclidean distance between two positions. After taking obstacles into consideration, we develop an algorithm based on Dijkstra algorithm to calculate $S_{(x,y)}$ as following:

step 1 Initialize sets of cells, namely cells whose shortest path to one of the exits have been found P, explored cells E and unexplored cells U, $P = \phi$, $E = \phi$, $U = c|c \in all\, cells\, on\, floor\, space.$

step 2 Add cells in exits area into P, set their "previous detour point as themselves, namely

$$previous((x, y)) = (x, y) \tag{5}$$

step 3 For each cell (x, y) in set P, expand it to its each neighbor cell (i, j) that has not been added into set P. If there any obstacle on the straight line from (x, y) to (i, j). If not, it means the visitor can go directly from (x, y) to (i, j), go to Step 4. Otherwise, it means the visitor need detour once more to go to (i, j), go to Step 5.

step 4 a If (i, j) is in E

$$previous_{(x,y)} = \begin{cases} previous_{(i,j)}, & P(previous_{(i,j)}) + \|previous_{(i,j)} - (x, y)\|_2 \leq E_{(x,y)} \\ previous_{(x,y)}, & otherwise \end{cases} \tag{6}$$

$$E_{(x,y)} = \min(E_{x,y}, P(previous_{(i,j)}) + \|previous_{(i,j)} - (x, y)\|_2) \tag{7}$$

b If (i, j) is in U

$$E_{(x,y)} = P(previous_{(i,j)}) + \|previous_{(i,j)} - (x, y)\|_2 \tag{8}$$

$$previous(x, y) = previous(i, j) \tag{9}$$

step 5 a If (i, j) is in E

$$previous_{(x,y)} = \begin{cases} (i, j), & P((i, j)) + \|(i, j) - (x, y)\|_2 \leq E_{(x,y)} \\ previous_{(x,y)}, & otherwise \end{cases} \tag{10}$$

$$E_{(x,y)} = \min(E_{x,y}, P((i, j)) + \|(i, j) - (x, y)\|_2) \tag{11}$$

b If (i, j) is in U

$$E_{(x,y)} = P((i, j)) + \|(i, j) - (x, y)\|_2 \tag{12}$$

$$previous(x, y) = (i, j) \tag{13}$$

step 6 Move the cell in set E with smallest function E value into set P. If all cells are in set P, algorithm terminates. Otherwise, go back to Step 2.

After getting static floor field of each cell, we define direction payoffs of transition P as

$$D_{ij} = \frac{S_{00} - S_{ij}}{\sqrt{i^2 + j^2}} \tag{14}$$

Among them, D_{ij} is the direction parameter; S_{00} is the static domain parameter value at the center of the mobile domain; S_{ij} is static field parameter values in the pedestrian mobile domain.

3.2.5 Position-Competing Model

When moving in hall, more than one visitor may wish to occupy one cell, which leads to position competition. We define competition capability C as

$$C = \frac{A}{d} \tag{15}$$

where A is the strength of a visitor and d is the distance between visitor current cell and target cell. The greater C is, the more likely this visitor win in this position competition and occupy the target cell. Other competitor losing competition turn to find other target cells. We set A of young and middle-aged adults to $\sqrt{2}$, and A of people with physical inconvenience to 1. For example Fig. 8. Assuming that $1, 2, 3$, and 4 all want to compete for position 5 and have the same ability, then their respective competitiveness calculations are: $\frac{1}{\sqrt{2}}, \frac{1}{1}, \frac{1}{\sqrt{2}}, \frac{1}{1}$.

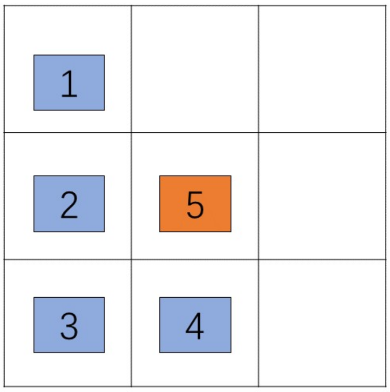

Figure 8: Competition capability of evacuees

3.2.6 Jam-avoiding Model

When trying to escape, it is natural for visitors to choose those less crowded, wider exits because they are less likely to get stuck there. We model this kind of cognition with jam-avoiding model [13].

$$J_{ij} = \max_{m}(\max_{n}(\frac{d_m * \frac{P_{in}^t}{S_{in}^t}}{d_L * \frac{P_{in}^t}{S_m^t}})) \tag{16}$$

Among them, d_m is the width of the m^{th} door;d_L: the sum of all the widths; P_m^t is the number of pedestrians near the m^{th} door at the time t to be selected; $P_i^t n$ is the number of pedestrians in all door evacuation spaces at the time t; S_m^t is the evacuation area of the m^{th} door at the time t to be selected; S_{in}^t is the sum of the evacuation space areas of all the doors at the time t to be selected.

3.2.7 Rules of ACO-CA

Based on models introduced above, now we can determine the rules of ACO-CA.

1 A visitor move to its neighbor cell with the greatest transition probability (defined in expression above). With Exits-Searching-with- Obstacle-Avoiding Model, Position-Competing Model and Cognition Model, we now define $h_i^k(t)$ as

$$h_i^k(t) = w1 * P_{ij} + w2 * J_{ij} \tag{17}$$

2 If more than one visitors choose one same cell, calculate the winning probability of competitor k as the visitor with greatest probability occupy this cell, Other visitor try other cells according to rule 1.

$$D_k = \frac{C_k}{\sum_S \in competitorsC_s} \tag{18}$$

3 If more than one neighbor cells have identical greatest transition probability, calculate the selection probability of cell i of them as

$$P_{ij} = \frac{P_{ij}}{\sum_{mn} \in greatestProNeighorsP_{mn}} \tag{19}$$

Because a visitors ultimate target is to get to an exit as quickly as possible, we emphasize the influence of distance when making choice.

4 If a visitor is on F_0 or F_{-2}, where there are exits of the building, they leave the artificial space of single-floor model at next time step. If a visitor in on F_{-1}, F_1 or F_2, where there is no exits directly leaving the building, they leave the artificial space of single-floor model at next time step and then go into the corridor or elevator model. After going through corridor or elevator model, this visitor is added to the artificial space of the next single-floor model.

3.3 Corridor Model

3.3.1 Queuing Theory

Melinek and Booth and Pauls et al. have given the stair evacuation model and given the established empirical formula [14]. The simplified high-rise building evacuation time mainly includes: the time of leaving the room, the time from the corridor to the front hall of the stairs, from the front of the stairs, the time when the hall enters the stairs to evacuate to a safe place.

Although this model has certain universality, it cannot handle the U-shaped structure of the Louvre and its unique architectural structure. Considering that the Louvre is a multi-storey building with multiple exits and corridors, and the corridor has a certain amount of space, it must not be overlooked. However, the corridor is not the same as the ordinary plane. Considering the uninterrupted flow of the corridor, it is inefficient to design the discrete cells. We introduce the queuing theory model. Queuing theory, also known as stochastic service system theory, is a mathematical theory and method for studying the stochastic dispersion phenomenon of systems and the working process of stochastic service systems [15].

A queuing system consists of an input process, a arrival rule, a queuing rule, a service organization structure, a service time, and a service plan. For the plane structure of the Louvre, the corridor is set as the service organization, and other definitions are given by the following formula. We can abstract the situation of the corridor entrance as Figure 9.

3.3.2 Model formula and Calculation

(i) average service time
The average service time is set to the time when a person waiting for evacuation on the Louvre floor passes through the corridor.

$$T_f = \frac{L_{stairs}}{V} \tag{20}$$

Among them, T_f is the average service time, L_{stairs} is the length of the evacuation corridor, and V is the speed at which the personnel pass.

(ii) Average service rate
To measure the efficiency of evacuation of corridors, the average service rate is defined as the number of people served in a unit of time.

$$\boldsymbol{\mu} = \frac{1}{t} \tag{21}$$

$\boldsymbol{\mu}$ is the average service rate.

(iii) Average arrival time
The average arrival time is generally set to the number of people entering the

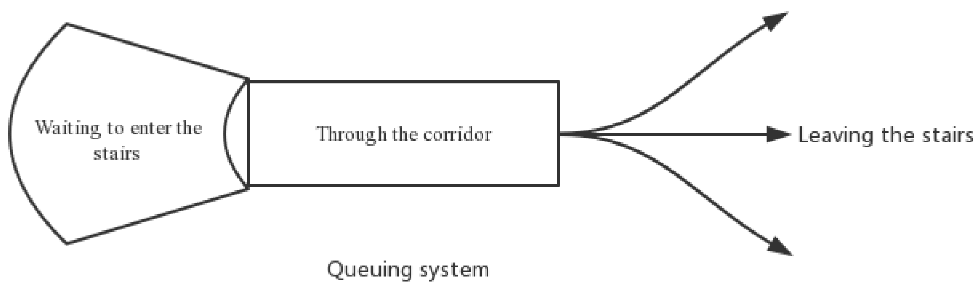

Figure 9: Queuing system

waiting area by each route in the unit time. Considering the model design of the plane layer cellular automaton, the number of people who will pass through the corridor can be directly calculated within a certain period of time. Therefore, it is not necessary to calculate the number of entrance branches and the split density of the incoming.

$$T_d = \frac{\boldsymbol{\rho}' L_{stairs} W_{stairs}}{M_i} \tag{22}$$

$\boldsymbol{\rho}'$ is the flow density of people, W_{stairs} is the width of the corridor, and M is the number of people to evacuate the corridor.

(iv) Average arrival rate
The average arrival rate can be understood as the number of people who arrive at the entrance of the corridor per unit time.

$$\boldsymbol{\lambda} = \frac{1}{T_d} \tag{23}$$

(v) Congestion judgment

$$\boldsymbol{\lambda} < \boldsymbol{\mu} \tag{24}$$

3.3.3 Use of the Corridor Model

According to Equation 24, when the average service rate $\boldsymbol{\mu}$ is less than the average arrival rate of $\boldsymbol{\lambda}$, it means that during the evacuation process, the person cannot send the evacuation channel, it is equivalent to blocking the channel port. At this time, the information is fed back to the heuristic function of the cellular automaton, providing real-time blocking information for subsequent evacuation personnel.

3.4 Elevator Model

3.4.1 Model with Elevator Factor

We have established the $ACO - CA$ model and the corridor model, but considering that the actual building facilities in the Louvre are elevators and the tourists are categorizable, the elevator model is proposed to serve the people with mobility problems (elderly and disabled People, young children, pregnant women, etc).

3.4.2 Model Calculation Formula

1. Escape time
   The time to evacuate a person in a building with a group of elevators takes into account the time of the person to a particular elevator location, the elevator operating time (including the round-trip between the floors and the elevator start-up time), and the time from the elevator to the escape.

$$T_{total} = T_e + T_i + T_o \tag{25}$$

Among them, T_i means time of cell from initial place to elevator, while T_o means time of cell from elevator to entrance. Both of them are calculated by the cellular automaton model. T_e includes the time when the elevator is opened and closed twice, the time when the personnel enters and leaves the elevator. In the calculation of the Louvre model, T_e can be calculated as an average constant. Considering the situation that the elevator can be used for emergency personnel, a coefficient $\boldsymbol{\eta}$ is added here to indicate the efficiency of evacuation. The calculation can be 0.5. So we can get the final time calculation formula of T_e.

$$T_e = (T_e + T_i + T_o) * (1 + \boldsymbol{\eta}) \tag{26}$$

3.4.3 Use of Elevator Model

We can compare the elevator evacuation density with the corridor evacuation density. If the number of elevators used is very small and the evacuation density of the corridor is extremely low, it is allowed to consider the use of the elevator by the normal group.

3.5 Extended Model

In the study of the evacuation model, it is necessary to set the model according to the actual situation. Under the evacuation of an emergency, due to the psychological effects of the person and the dynamic evacuation environment around the pedestrian, the pedestrian may panic and leave the scene, so the pedestrians will squeeze each other, which may lead to the presence of multiple pedestrians in one cell. . We are here to expand the original cell model and consider the changes in cells during extrusion.

3.5.1 Introduction to Herd Parameters

After comparing the cellular automata related to social psychology in several papers, we introduce the calculation formula of the herd parameters Z.

$$Z_{ij} = \frac{N_k}{\sum_{k=1}^{8} N_k} \tag{27}$$

Among them, N_k is the number of pedestrians along a certain angle of view, and the denominator is the number of pedestrians within the radius of view. The field of view can be abstracted into Figure X. In Figure 10, the person will select the direction with the largest number of people in a certain perspective.

3.5.2 Introduction the Factors of Extrusion

The crowd evacuation model with extrusion situation should consider the influence of direction parameters and herd parameters on pedestrians, that is, from the distance

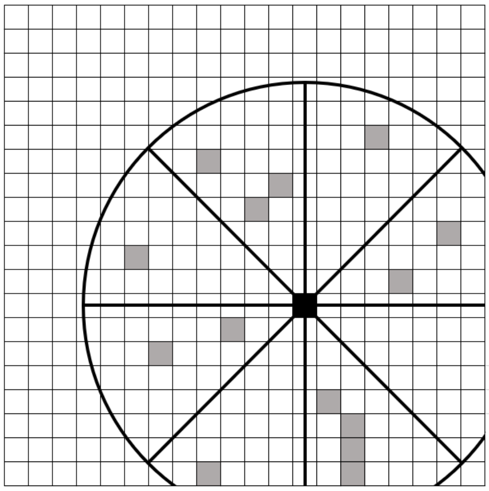

Figure 10: Individual field of view radius

between the location of the pedestrian's cell and the safety exit and the number of pedestrians within the horizon. Redefine the previous formula.

$$P_{ij} = k_D * D_{ij} + k_Z * Z_{ij} \tag{28}$$

k_D,k_Z correspond to the weight coefficient of the direction parameter and the paradigm parameter respectively, $k_D + k_Z = 1$, and the other symbols have the same meaning as before.

3.5.3 Use of Extended Model

In the case of emergency evacuation, people are panicked and may not be able to make the correct evacuation decision. Add this factor to the model of the cellular automaton and choose to evacuate in the direction of the number of pedestrians in the field of view.It evolution rule improvement as following:

1. Set the number of people a cell can hold twice as much.
2. The original heuristic function is still used, but the method of judging the conflict is inconsistent with the original. The specific rules when multiple pedestrians compete for one position at the same time are:
   (a) If there are already two people in the next location, the pedestrian will choose another location or keep the location unchanged.
   (b) If there is already one person at the location, then one of the plurality of pedestrians is selected to enter the location.
   (c) If there is no one at this location, two of the plurality of pedestrians are randomly selected to enter the location.

4 Model Implementation and Data Analysis

We implement our model on the Louvre's structure of different granularity. In fine-grained implementation, we study how our models work on a single hall. In coarse-grained implementation, we study how our models work on a floor consisting of several halls.

4.1 Implementation and Analysis on a Hall

When applying our model on a hall, we aim to find an evacuation plan that can minimize the total evacuation time from this hall. By modifying the number of exits and influence of jam-avoiding cognition, we analyze their influence on the total evacuation time. In our simulation such like Figure 11-14, blue dots stands for visitors, green bar stands exit,green path stands passages and lobbies, red block stands unreachable places and rooms, red dots stands key places marked by $path - finding$ algorithm to lead the visitors through barriers.

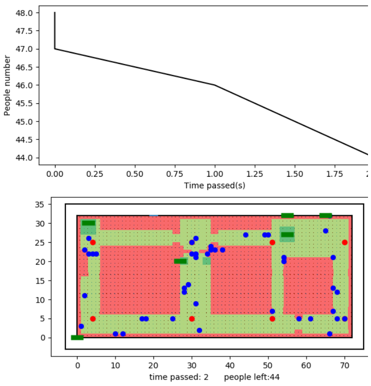

Figure 11: State 1

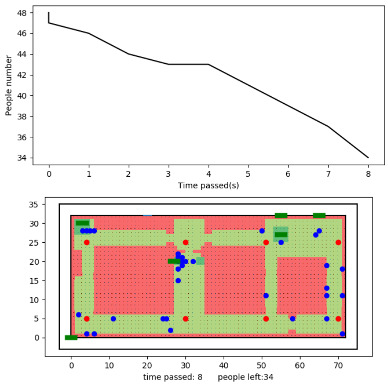

Figure 12: State 2

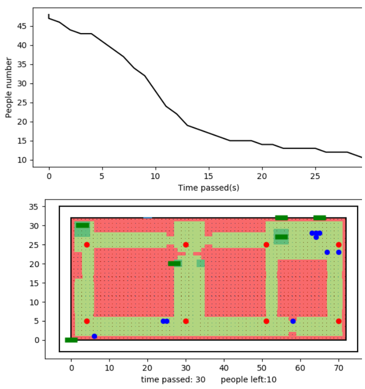

Figure 13: State 3

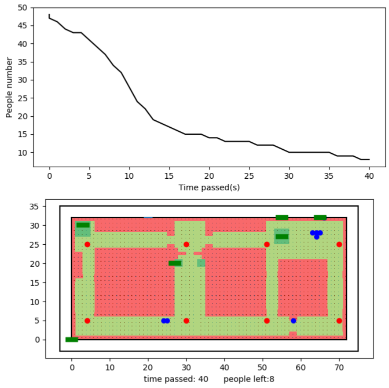

Figure 14: State 4

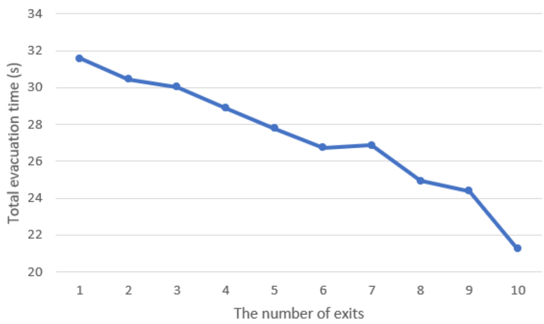

Figure 15: Impact of the number of exits

4.1.1 The Number of Gates

From the Figure 15, we can find that the total evacuation time decreases as the number of exits increases. This relationship suggests that emergency personnel and museum officers may consider opening additional exits during emergency.

4.1.2 The Influence of Jam-avoiding Cognition

We also try different weight of jam-avoiding model when calculating the heuristic function in transition probability. It turns out that greater weight leads to shorter evacuation time, which means strong cognition of the congestion near exits is beneficial to find better evacuation plan. Thus we suppose that it may help evacuation with some officers have better cognition to guide visitors.

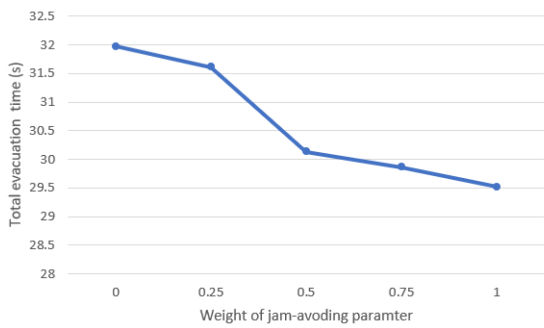

Figure 16: Impact of the influence of jam-avoiding model

4.2 Implementation and Analysis on a Floor

When implementing our model on a floor, our target is to balance the loads of stairs. Stairs can be used more effectively if their loads are balanced, because queuing time at the end of stairs is small in such situation. The degree of load balancing is evaluated with the variance of the stairs' used times. We compare the variance with and without online application such as "Affluences to tell real-time state of stairs. If people are unaware of stairs' state, the number of available stairs stays the same. Otherwise, we regard a stair as "unavailable" if its average service time is over our threshold. Stairs' states update from time to time. The results in Figure 17 show that awareness of stairs' state improves loads balance since the variance gets smaller.

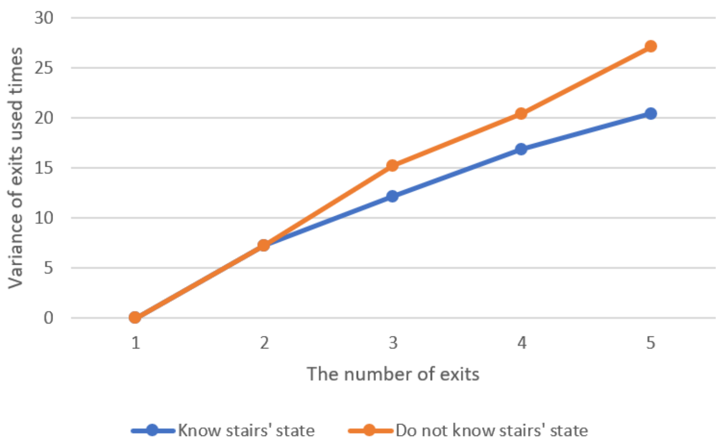

Figure 17: Impact of the awareness of real-time state of stairs

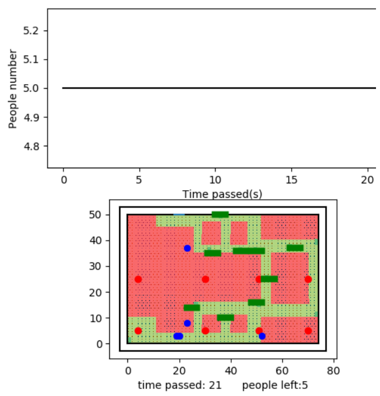

Figure 18: State 1

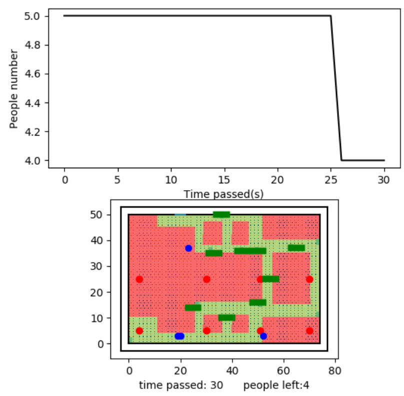

Figure 19: State 2

5 Sensitivity Analysis

In Figure 15, we depict the relationship between the number of exits and the total evacuation time using random model to simulation the initial layout of visitors. In Figure 20, we try out the other three initial layout models, namely Wall Model, Heaps Model and Mona Lisa Model and find that the relationship stays similar to that in Figure 15. We also use rooms of different shapes to repeat our work in section 4. Relationships also stay similar. Therefore our model have adequate robustness to adapt to variety of building structures and initial layouts.

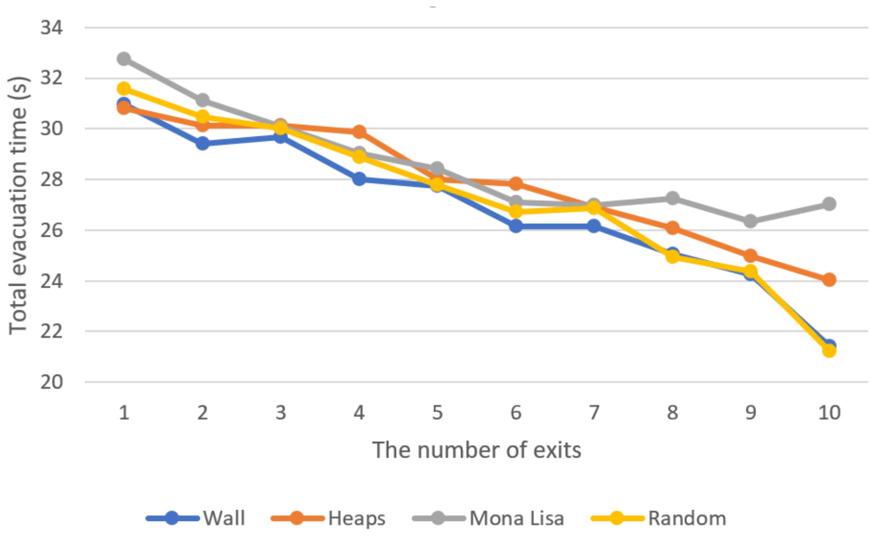

Figure 20: Sensitivity Analysis

6 Conclusion

6.1 Strengths and Weaknesses

6.1.1 Strengths

- Because the model is discrete, the model fully demonstrates the advantages of simple calculation methods.
- Because the model is not singular, the model takes into account multiple factors, making the model more suitable for simulating complex architectural scenarios like the Louvre.

6.1.2 Weaknesses

- Because the advantages of the continuous model are integrated, the complexity of the model is increased to some extent, especially the design of the heuristic function is difficult.
- Because the accurate data of each exit of the Louvre cannot be accurately obtained, it is relatively simple to implement in the simulation part of the model.

6.2 Emergency Management Recommendations of the Louvre

Based on our modeling analysis and experimental verification results, combined with the actual situation of the Louvre, we propose the following three points for emergency evacuation:

- When an objective emergency such as a fire occurs in a venue, it should be exported as much as possible.
- The model proves that because the crowd is prone to herd mentality, the correct evacuation direction is extremely important. Therefore, the museum should provide special training for the staff to enable them to respond to emergencies and to make correct direction judgments, thus indicating the evacuation of the crowd.
- The model demonstrates the role of the software "Affluences", which helps people determine the degree of export congestion. We also recommend that the software update the congestion of the major corridors on each floor.

6.3 Adaption for Other Structures

This model is very suitable if other buildings also have the characteristics of multiple layers and multiple exits. When the proposed model is used for similar types of buildings, the main modified parameter is the heuristic function in the cellular automaton, which needs to be formulated according to the characteristics of the actual plane and the characteristics of the actual service. Among them, the planar features mainly consider the design of the cell structure and the definition of export attractiveness, and the service population largely affects the application of the herd parameters and the extrusion model. In addition, the actual situation of the access facilities such as stairs and elevators needs to be considered. For example, the corridor of the teaching building is on a vertical line, and the corridors of the museum are usually scattered. For the ordinary single-layer model, only the part combining the cellular automaton and the ant colony algorithm in the model can be used.

6.4 Future Work

We focused on the theoretical analysis of the model implementation and the simulation of specific scenarios, and listed some of the factors that influence the quality of the model. In the future practice, we will further extend the model to more application scenarios and consider how to design better heuristic functions for different scenarios. Our goal is to enhance the universality of the model and make the model truly play a role in emergency evacuation activities.

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