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2019
MCM/ICM
Summary Sheet

Crowd Evacuation Plan Based on Constraint Satisfaction Problem

Summary

The evacuation plan is undoubtedly essential for a large crowded structure.

Potential bottlenecks that may limit movement towards the exits includes the mobility of tourists and their psychological stress, which would be taken into consideration in our model. We have established four basic models. The first is the "Tourist Distribution Model", which analyses the distribution of tourists in the building. The second is the "Tourist Mobility Model", which describes the moving speed and the longest moving distance of tourists. The third is the "Congestion Model", which considers the degree of congestion in exits. The last is the "Psychological Stress Model", which takes Psychological Stress of crowds into consideration.

Our model will reserved access for rescuers and is adaptable to those hidden channels that only known by managers of the building. Then we establish the "Path Selection Model" base on the Constraint Satisfaction Problem, in which the optimal evacuate plan is searched. In our simulation, 423 seconds are needed to evacuate 10000 people in the Louvre.

Based on the models above, we mainly build three efficient modification models to optimize the current situation. The first one is "Pedestrian Flow Velocity Model". It shows the changes in mobility of crowds as they move intensively in the corridor. The second one is "Panic Intervention Model", which suggests how the staff in Louvre should be arranged in peacetime. The third is the "Advanced Congestion Model", which describes the degree of exit congestion using discrete element method.

Otherwise, some routes or exits might be blocked. However, this should not be of much impact on our model. Blockage of certain exits or channels will affect the result, but the path planning would still be optimal in the end. In other words, our models have high stability, high error-tolerant rate and extensive applicability.

Keywords: Evacuate; Congestion; Mobility; Psychological Stress; Path Planning

Contents

1 Restatement of the Problem

1.1 Background

1.1.1 An Overview of the Problem

More and more terrorist attacks are taking place in France. Therefore, for large crowded structures, it is necessary to design a reliable crowd evacuation plan.

The Louvre is one of the world's largest art museum. Our ICM team need to design an evacuation plan for the Louvre. The aim is to evacuate everyone as quickly as possible. The difficulty is that the number of guests in the museum varies from day to day, and people speak different languages, have individual, group and disabled tourists.

1.1.2 The Process of Evacuation

The process of evacuation can be decomposed into following processes:

- Process of tourists moving to the exit.
- Process of crowds passing the exit.
- Additional process: Reserve access for rescuers to enter the scene.

1.2 The Task at Hand

- Construct a mathematical model to simulate the situation of the evacuation of each floor.
- Propose some factors that could affect the current plan.
- Based on the model, give a plan to evacuate people from Louvre as fast as possible.

2 Model Assumptions and Notations

2.1 Assumptions and Justifications

In order to simplify the course of modeling and draw some reasonable conclusions from our model, we make assumptions as follows:

- The composition of tourist is relatively fixed. According to the previous data, there are the elderly, children, adults and the disabled, their proportion is relatively fixed.

- The distribution of tourist is relatively fixed. Exhibitions with masterpiece gather most of the crowd, a small number of people gather near other exhibitions, and other people are in the corridors, stairs, toilets and other places. Therefore, the initial distribution of personnel is fixed when the evacuation process is modeled.

- Emergencies, such as terrorist attacks, are controllable to a certain extent. Obviously, what we are talking about is the evacuation plan in the face of panic on a small scale. If a large-scale terrorist attack, or uncontrollable natural disaster, which directly cause many casualties or block all safe passages, occurs in the building, then the effectiveness of these programs will obviously be reduced, or even ineffective.

- All staff are trained to guide the crowd when an emergency occurs, rather than fleeing with the crowd. They are already at the designated location before the emergency, instead of taking time to get in place. And they will work until all the tourists evacuate.

- Particular tourists, such as the elderly, children and the disabled, will not visit the Louvre by themselves. They will be accompanied by adults. When evacuating, adults will not leave themselves alone. It means that there will be no visitors with no mobility. We can also assume that people will run after the crowd during emergency, so tourists in the same area can be treated as a unit.

- Basic communication is guaranteed. We can assume that tourists who cannot communicate with staff would visit with a team, and there must be people with linguistic foundation in the group.

- All the elevators are out of operation and rescue channels will be decided in peacetime, instead of being decided when emergency occurs.

- In emergencies, there will be no man-made closed roads (such as closed exhibition halls).

2.2 Notations

Symbol	Description
S_i	Speed of i_{th} category of people
J_{ij}	Jam degree of the j_{th} exit at i_{th} floor
C_{ij}	Carrying capacity of the j_{th} exit at i_{th} floor
A_{ix}	Gathering speed of people from x_{th} area at i_{th} floor
A_{ijx}	Gathering speed of people from x_{th} area to j_{th} exit at i_{th} floor
P_{ix}	Psychological Pressure of people in x_{th} area at i_{th} floor
L_{ijx}	Length people have moved from x_{th} area to j_{th} exit at i_{th} floor
W	Contribution of workers
T_{ix}	Time spent to evacuate x_{th} area at i_{th} floor
T_{total}	Time spent to evacuate the whole building

3 The Basic Model of Evacuation

In this section, we establish some basic models, which simulate the effective elements during the evacuation. Then we discover that the path planning can be described as a constraint satisfaction problem.

3.1 The Design of the Model

Potential bottlenecks that may limit movement towards the exits includes the mobility of tourists and their psychological stress. In our model, we have taken those elements into consideration.

In order to demonstrate our basic model clearly, we divide it into the four following submodels.

- Tourist Distribution Model: This model is used to describe the general distribution of tourists in the pavilion. From the hypothesis in 2.1, we can conclude that the distribution of tourists is related to the exhibits displayed in the pavilion, and is relatively fixed.

- Tourist Mobility Model: This model estimates tourists' mobility. Due to the different composition of tourists, they can be roughly divided into three categories based on the hypothesis of 2.1.

- Congestion Model: This model estimates the congestion degree of exits. The degree is mainly described by the amount of people gathered in the exit and the cayying capacity of the exit.

- Psychological Stress model: We assume that tourists will be under psychological pressure in the process of evacuation. Over-long evacuation time, lack of staff guidance, or congestion will cause the increase of pressure. We reckon that there is a threshold of psychological stress, once exceeds, it will produce panic, which is unacceptable.

3.2 SubModels

3.2.1 Tourist Distribution Model

The distribution of tourists is assumed to be fixed and regular by hypothesis 2.1. We should be able to predict the distribution of the tourists in Louvre base on the previous data.

We assume that there are two kinds of exhibits, including masterpiece and ordinary relics. 60% of tourists would gather in those areas with masterpieces, while 20% would gather in those without. The rest 20% scatter in areas like corridors, toilets and so on.

Among all the tourists, 0.3% are the disabled, 32% are the elderly and children and the rest are adults.

3.2.2 Tourist Mobility Model

The mobility can be measured by the moving speed and the longest moving distance. Tourists will be fatigued as the distance increases, so their velocity decreases. The velocity-distance formula is as follows:

$$S_i = \begin{cases} B_i & L < L_i \\ \frac{L_i}{L} \cdot B_i & L \geq L_i \end{cases} \tag{1}$$

Suppose an adult's velocity is $B_0 = 7$ and the maximum distance threshold is $L_0 = 160$. The crowd's velocity can be described by the formula $B_i = \mu_i * B_0$, the maximum distance threshold can be described as $L_i = \mu_i * L_0$.

Normally, $\mu = 1$.

If there are the disabled in the team, μ should be 0.5.

If there are children and the elderly in the team, μ should be 0.8.

3.2.3 Congestion Model

Define congestion degree J.

While evacuation, the tourists will gather at the exits, and that will cause congestion. We assume each exit as an area, the congestion degree will be determined by the amount of people and the carrying capacity of the exit.

The speed that tourists leave can be represented by carrying capacity of the exit, which we assume to be fixed. So we just consider the speed that tourists converge.

Because the arrangement of the exhibition area is linear and the speed of the same category of tourists is uniform, we assume that the speed of the tourists gathering at the exit is also uniform.

The formula describing the degree of congestion is shown below.

$$J_{ij} = \begin{cases} \frac{\lambda_1(A_{ix}-C_{ij})t+K}{\lambda_2 C_{ij}} & t < t_1 \\ \frac{\lambda_1(A_{ix}t_1-C_{ij}t)+K}{\lambda_2 C_{ij}} & t_1 < t < t_2 \end{cases} \tag{2}$$

We assume $C_{ij} = 8$, which means 8 people leave per second from an exit. A_{ij} will be counted during iteration. $\lambda_1 = 1$ is the weight of the speed of amount of people increasing, and $\lambda_2 = 1.5$ is the weight of carrying capacity of the j_{th} exit on the i_{th} floor. $K = 10$ is the amount of people around the exit while the emergency occurs. In t_1 time, people that choose to leave from this exit has all arrived.

3.2.4 Psychological Stress Model

Define the psychological stress of tourist P.

When an emergency occurs, due to different conditions, there will be a base pressure M, that is, the pressure at the beginning of evacuation. We define the pressure threshold P_{max}, if it exceeds, there may be trampling accidents and other unacceptable situations.

Psychological stress increases as congestion degree and the distance people have moved increase, and decreases due to the comfort of staff.

The formula describing the psychological stress is shown below.

$$P_{ix} = \frac{\mu_1 L_{ijmax} + \mu_2 J_{ij}}{W} + M \tag{3}$$

$\mu_1 = 1$ is the weight of longest Distance that people move to get to the exit, $\mu_2 = 0.5$ is the weight of Congestion degree.

3.3 Path Selection Model Based on CSP

3.3.1 Design

In the path planning model, we devide the evacuation plan into sub plans of individual floors. Each floor has entrances and exits. Visitors get into the floor from other floors pass through the entrance and then converge to the exit and leave.

Rescue channels should be set before the path selection, and corresbonding exits will be dismissed while searching the path. We divide the pavilion into several areas, and each entrance is treated as a single area. The evacuation of each area can be treated as a Constraint Satisfaction Problem.

Requirements: For an area, suppose that the number of people is m. It is known that i_{th} floor has j exits. Find a path to evacuate all tourists from one exit.

- Constraint 1: A smooth entrance must be reserved for rescuers. When the congestion degree of an exit reaches J_{max}, tourists should not try to leave from this exit, instead, they should go for another exit. That is to say:
$$\frac{\lambda_1 \sum_x A_{ijx} + K}{\lambda_2 C_{ij}} < J_{max} \tag{4}$$
- Constraint 2: The psychological stress of tourists must below the threshold P_{max}. In other words:
$$\frac{\mu_1 L_{ijmax} + \mu_2 J_{ij}}{W_{ij}} + M < P_{max} \tag{5}$$
- Constraint 3: Tourists should move as short as possible to avoid the situation that their mobility decrease caused by fatigue.

In this way, the idea of artificial intelligence can be applied to solve this problem. We search shortest path of each area under those constraints.

3.3.2 the Algorithm of the Model

For each floor, we divide the exhibition area and entrance into several areas, and treat each area as a unit. The unit will constantly produce 'people' of three categories at a fixed probability. The total number and the probability of all three categories of people produced by the unit is described in the Tourist Distribution Model, and the total number of people in the entrance is the sum of the number of people in the upper level who choose to leave from this exit. Units will produce people, and their departure speed can be expressed by the Mobility Model. Once produced, people will move towards the nearest exit.

During each iteration, we calculate the mobility of each people on the base time t. Once a people arrives at the exit, calculate the congestion degree and the distance the people has moved. If the degree of congestion exceeds the threshold, the people should not be evacuated from this exit and will reselect the exit to leave . However, if the moving distance has exceeded the threshold, he will not choose to find another exit.

If the congestion degree of the exit meets the requirements, the people is considered to be evacuated, and the congestion degree of corresponding exit will increase. All evacuation paths will be obtained by iterating when all the people on the floor have been evacuated. Return the total time t that the process spent.

During the iterate process, if some people's psychological pressure is too large according to the Tourists Stress Model, staff should be arranged there to appease the masses.

3.4 The Result of the Model

We use matlab to realize the model programmatically.

3.4.1 The result of Tourist Mobility Model

We try to simulate the relationship of Speed and Length with regard to the model above. See Figure 1.

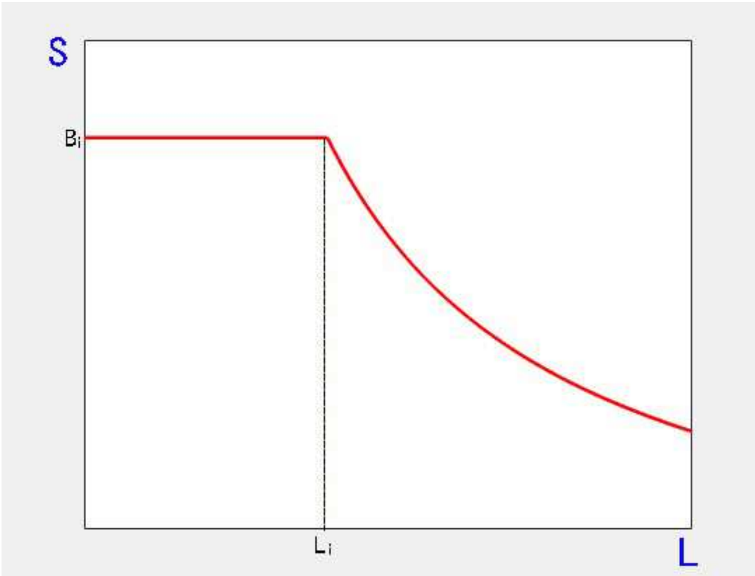

Figure 1: relationship of Speed and Length

3.4.2 The result of Congestion Degree Model

We consider the congestion degree. Generally, the degree of congestion is related to time and the exit's carrying capacity. The number of people arrived at the exit is determined by the path our Path Selection Model generated, which will also affect the selection of the path.

Due to the interaction of Path Select and Congestion Degree, it's hard to describe the relationship of amount of people and congestiojn degree directly. But we can try to simulate the relationship of congestion degree and time according to hypothesis of 2.1. See Figure 2.

3.4.3 The result of Path Selection Model

According to information from official website of the Louvre, there is no exhibition hall on B2, so we can consider that there are few visitors on B2 while the emergency occurs. At the same time, the path of B2 is relatively single and the carrying capacity of exits is strong (directly connected to the subway entrance), therefore the evacuation capacity of B2 is far greater than the speed of the people entering B2 from B1, so we would not try to consider the path selection of B2.

We use matlab to simulate the selection process. Input the information of route, entrances and exits of each floor and run the simulation programme. We

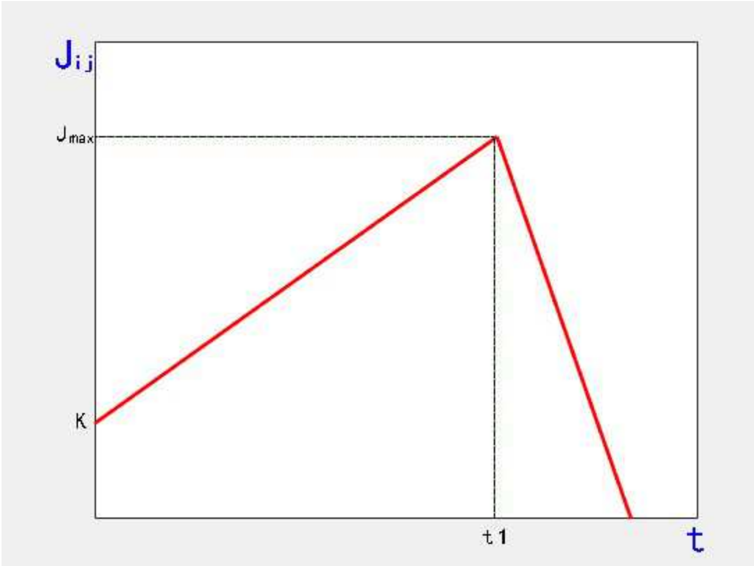

Figure 2: relationship of congestion degree and time

trace inviduals during the iteration, and get the following result, see Figure 3 $\sim$ 7.

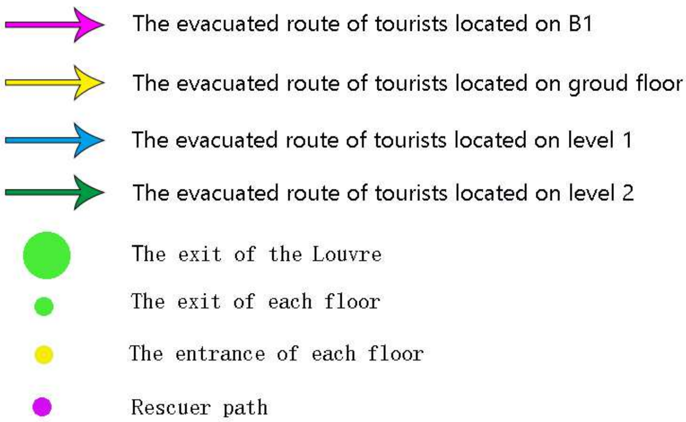

Figure 3: Legend

3.5 Total Time

Next, calculate the time of the whole plan. In fact, while simulating the process of evacuate, the time will be count directly, but we will provide a method to measure the total time.

Mobility and congestion degree will greatly affect the total time. We take each area as a unit when calculating, and assume that people in the same area will evacuate from the same exit based on the hypothesis of 2.1.

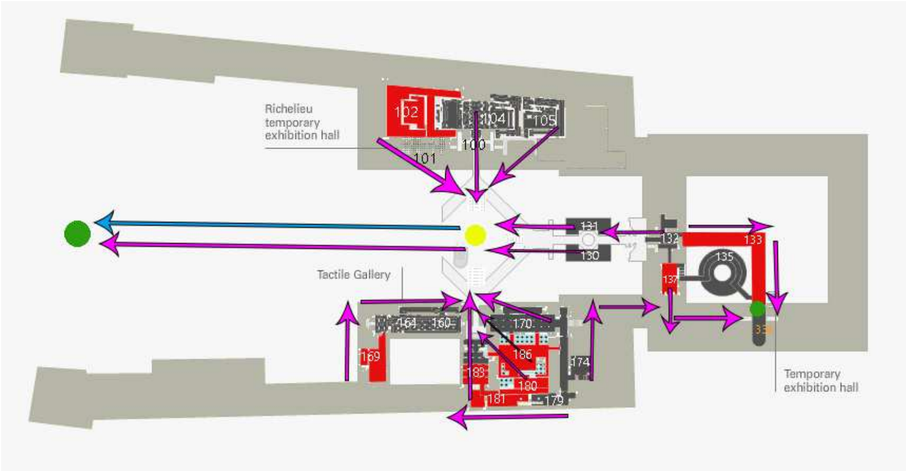

Figure 4: path plan of B1

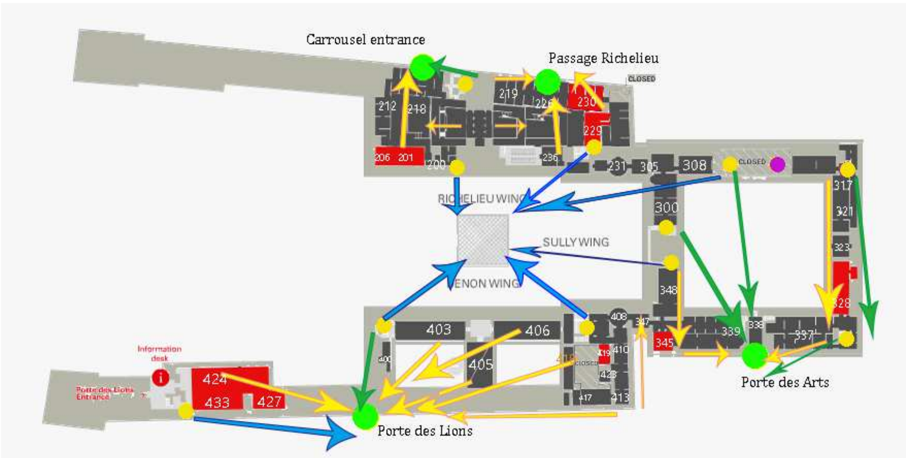

Figure 5: path plan of the ground floor

The formula to caculate time for an area to evacuate is as follows:

$$T_{ix} = \frac{J_{ij}}{\lambda C_{ij}} + \frac{min(L)}{S_x} \tag{6}$$

Since the ground floor will accept people from the first and the second floor, and bear the greatest pressure, we consider that when the first floor evacuation is completed, the entire evacuation plan is completed.

Therefore, the formula of total time is as follows:

$$T_{total} = \frac{J_{ijmax}}{C_{ij}} + \frac{\sum N_i}{\sum_j C_{ij} - E_i - \sum_j A_{ij}} \tag{7}$$

We set the amount of people from 200 to 17000, and run the simulate program. Although we gave the formula to describe the total time, while simulating, we can directly count the time that the evacuation time spent. See Figure 8.

Figure 6: path plan of first floor

Figure 7: path plan of second floor

4 Modifications to the Current Process

According to the Path Selection model, we can figure out the optimal path plan to evacuate tourists from any crowed building, however, to simlify the process, we just ignore some elements. In this section, we build three extra models to modify the current process and make attampt to make our model more convincing.

4.1 Impedance Model of Crowd Moving

4.1.1 The Design of the Impedance Model

It is obvious that the Mobility Model above is too simple to describe the speed of crowds, so we introduce the Impedance Model[1] to study the crowd

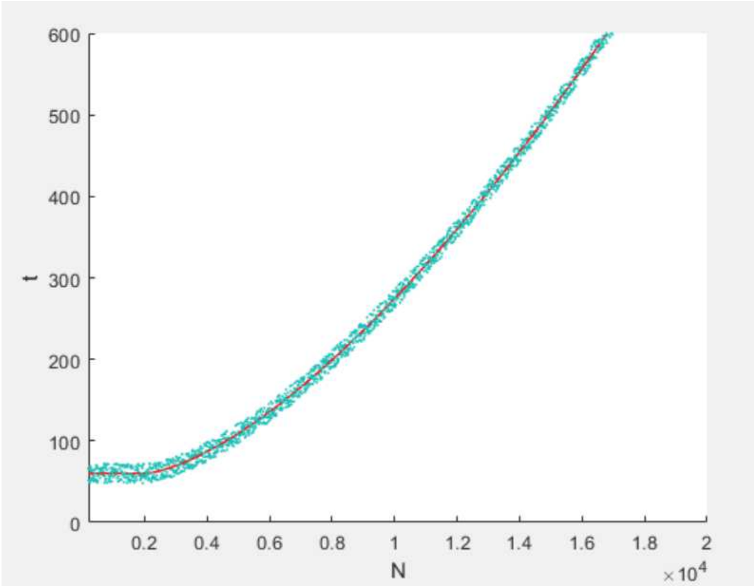

Figure 8: The relationship between evacuation time and amount of people

moving.

Some experts have studied pedestrian flow by means of traffic dynamics. They believe that velocity is mainly affected by three factors: front and rear direction resistance, left and right direction resistance, and the basic dynamic factors of pedestrians themselves. Among them, the resistance in the front and rear directions is mainly logarithmic to the crowding density, while the resistance in the left and right directions is linear to the population density.

$$v(\rho) = v(\rho_1, \rho_2) = v_m(\alpha A + \beta B + \lambda) \tag{8}$$

$$A = \frac{ln(\frac{\rho_{1m}\rho_2}{\rho})}{ln(\frac{\rho_{1m}}{\rho_{1c}})} \tag{9}$$

$$B = \frac{\rho_1\rho_{2m} - \rho}{\rho_1(\rho_{2m} - \rho_{2c})} \tag{10}$$

From the study of the relationship between pedestrian density and mobility, we can conclude that in general, the obstruction of left and right directions in pedestrian flow has little effect on pedestrian movement, so it can be neglected, that is $\beta \approx 0$. Therefore, the velocity-density equation can be further simplified.

$$v(\rho) = v_m(\alpha A + \lambda) = v_m(0.851\alpha - 0.737\alpha \ln \rho + \lambda) \tag{11}$$

Thus:

$$\rho(v) = v^{-1}(\rho) = \exp(1.155 - 1.357\frac{v - v_m\lambda}{v_m\alpha}) = \exp(1.155 - 1.357\frac{v-\gamma}{\eta}) \tag{12}$$

For the pedestrian flow rate q, the relationship is $q = v \cdot \rho$. From this, the pedestrian flow rate-velocity equation is obtained.

$$q = v \cdot \exp[1.155 - 1.357(v - \gamma)/\eta] \tag{13}$$

Simplify to: $q = ave^{bv}$

Among them, $a = \exp(1.155 + 1.357\frac{\gamma}{v}) = \exp(1.155 + 1.357\frac{\gamma}{\alpha})$, $b = -\frac{1.357}{\eta} = -\frac{1.357}{v_m\alpha}$.

Find its inverse function and get the formula of v:

$$v = \frac{1}{b}lambertw(\frac{b}{a}q) \tag{14}$$

Where $w = LAMBERTW(x)$ is the solution of transcendental equation $w * \exp(w) = x$.

4.1.2 Effectiveness

The Mobility Model we previously mentioned did not consider the effect of pedestrian resistance on each other in crowds. With this model, we provide a more reliable method to measure the mobility of tourists during emergency.

Therefore, when calculating the moving distance during iterating, we can use this scheme to replace the Mobility Model, which will make our path planning more reasonable.

4.2 Social Network Model of Panic Intervention

4.2.1 The Design of the SN Model

It's obvious that the psychological stress is not a simple linear growth. Once a tourist is panicked, it will quickly affect other people and then spread rapidly. So we introduce a Social Network Model[2] to describe the degree of psychological stress.

Based on the SIR theory(suscepticle-inspected-recovered), we devide individual emotion state into three categories: susceptible individuals(S), inspectable individuals(I_1), inspected individuals(I_2). When individuals(S) are affected by the source of panic(I_2), their stress will increase rapidly. Once exceed a threshold T_1, they will transfer to class I_1. Once exceed a threshold T_2, they will transfer to class I_2 and become a new panic source. Then we have:

$$T_1 = \lambda C - \beta N + \gamma \tag{15}$$

$$T_2 = \delta - \xi E \tag{16}$$

On the basis of BASAK's achievement, $\lambda = 0.1$, $\beta = 0.1$, $\gamma = 0.15$, $\delta = 0.35$, $\xi = 0.1$

When an individual is within the radius(r_c) of the source of panic(I_2), he will be affected. So the effection of the panic source $E_i^c(t)$ can be described as:

$$E_i^c(t) = \sum_{s=1}^{n} \Gamma_s(t) - W \tag{17}$$

$$\Gamma_s(t) = \begin{cases} \frac{\chi_i(t)\alpha}{\sqrt{2\pi}r_c} e^{-\frac{d_{is}^2}{2r_c^2}}, & if\ d_{is} < r_c \\ 0, & others \end{cases} \tag{18}$$

$\Gamma_s(t)$ is the effect of single panic source; r_c is the radius of the source of panic; d_{is} is the distance between individual and panic source; $\alpha(\alpha > T_2)$ is the strength of the source; $\chi_i(t)$ is the attenuation coefficient of panic propagation, which subjects to normal distribution $N(0.3, 0.01)$.

With time goes on, psychological stress tends to decline. Define an individual's recovery as $E_i^d(t)$, we can describe the emotion of individuals in time t like:

$$E_i(t) = E_i(t-1) + E_i^c(t) - W \sim E_i^d(t) \tag{19}$$

4.2.2 Effectiveness

Once an individual transfer to state I_2, he should get comfort from staff as soon as possible. With our SN Model, we can recaculate the psycological stress of crowds while iterating, and make the arrangement of staff more effective.

4.3 Discrete Element Model of Congestion

4.3.1 the Design of the Discrete Element Model

The Congestion Model we built above assumes that the speed people leave the exit is fixed, however, as an individual, pedestrian has the characteristics like complex interaction in the process of movement, then whether the carrying capacity of the exit will decline or not? We introduce a new Particle-Base Discrete Element Model[3] to verify that whether our congestion model is reasonable.

During the emergency, the process of evacuation is similar to the process of particulate matter flow. Therefore, we can apply the Particle-Base Discrete Element Model for crowd evacuation simulation, and regard each pedestrian as a separate particle unit to establish a mathematical model and give it basic properties such as particle size, mass and speed to describe the pedestrians' escape process. Properties such as speed can make the simulation calculation model closer to reality. We use the Softball Contact Model to simulate the relationship between people and people, people and border in the process of crowd movement. According to the soft ball model, the contact process between pedestrians and pedestrians, pedestrians and boundaries is summarized as normal movement and tangential movement. When the tangential force exceeds the threshold, the pedestrian slides under the action of tangential force and friction.

The normal force f_{nij} pedestrian i subjected from pedestrian j can be described as:

$$\vec{f_{nij}} = (-k_n\alpha - c_n\vec{v}_{ij} \cdot \vec{n}) \cdot \vec{n} \tag{20}$$

k_n and c_n are the normal elasticity coefficient and the normal damping coefficient of pedestrian i, v_{ij} is the relative velocity of pedestrian i and pedestrian j.

$\vec{n}is$ the unit vector from pedestrian i to pedestrian j.

The tangential force f_{tij} pedestrian i subjected from pedestrian j can be described as:

$$\vec{f_{tij}} = -k_t\vec{\delta} - c_t\vec{v}_{ct} \tag{21}$$

k_t and c_t are the tangential elasticity coefficient and the tangential damping coefficient of pedestrian i, $\vec{\delta}$ is the tangential displacement of pedestrians at the contact point, and $\vec{v}_{ct}$ is the slip velocity of the contact point.

Based on particle discrete element method, the evacuation process in emergency can be simulated by programming. The size of the room is 20 m *20 m. An exit is located in the middle of the right side of the room. The width of the exit A is a variable. In Figure, each circular particle represents a pedestrian. In the initial state, 100 people are randomly distributed in the room. According to the body shape of normal people, the particle radius is randomly distributed from 0.25 m to 0.35 m. The maximum moving speed of each pedestrian is the same, v = 5m/s. The outlet width A is 1.0 m, 2.0 m and 3.0 m.

The simulation result is shown in Figure 9[3]:

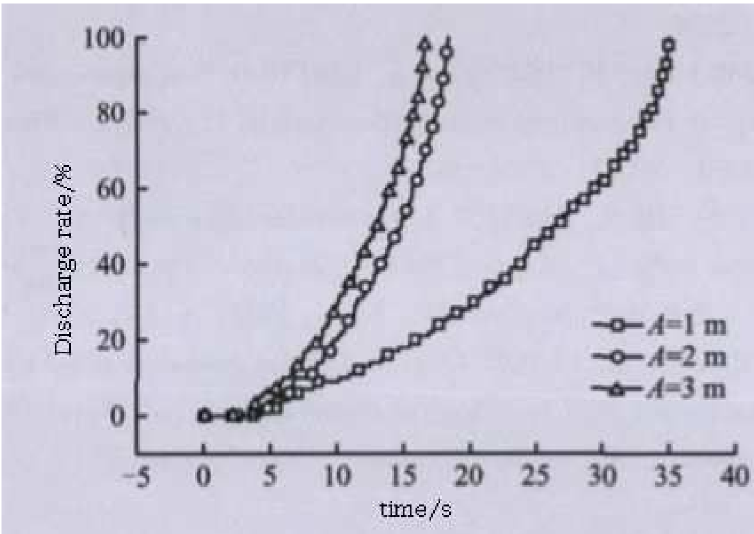

Figure 9: curve of egress under three conditions

4.3.2 Effectiveness

With matlab, we can simulate the process of the evacuation, see Figure 10 ~11[3]

From the result of the sumilation, we can learn that with the increase of the amount of people, the time that evacuation takes increases linearly. Which means that the hypothesis in our basic Congestion Model in 3.2.3, that the carring capacity of the exit is fixed, is reasonable.

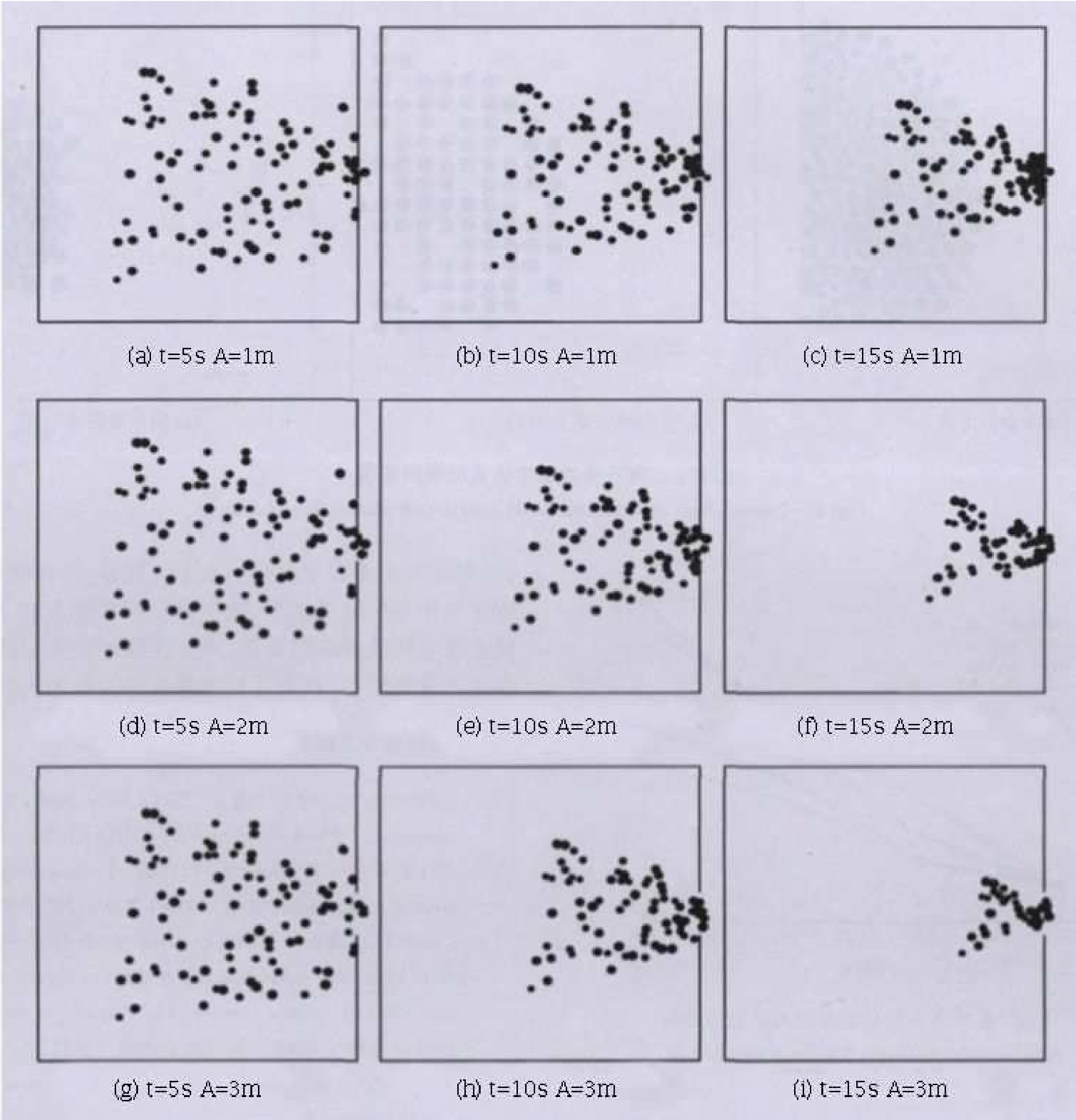

Figure 10: distribution of pedestrians in different time

5 Model Evaluation and Sensitivity Analysis

People will give priority to the nearest exit. Thus, once a path is planned, we can consider it as an optimal result.

While evaluating the model, we need to consider some additional situations, such as road congestion caused by emergency or enable of some emergency access. These situations may have an impact on the model, so additional consideration is necessary.

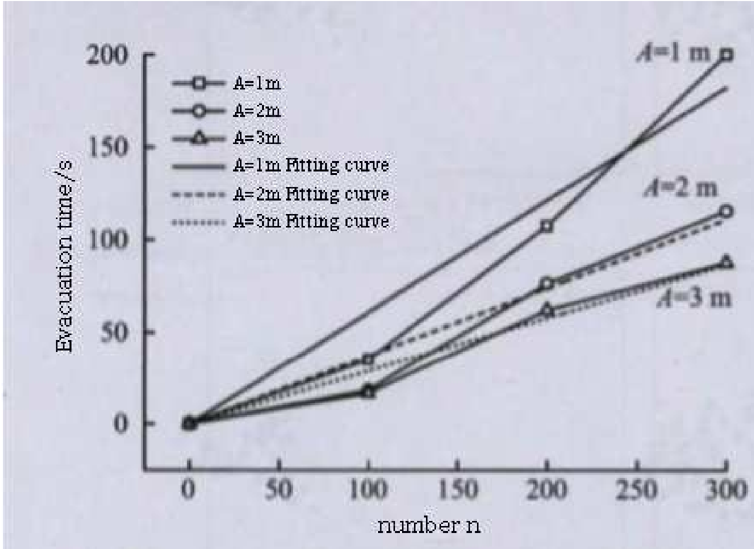

Figure 11: relationship of total number of people and evacuation time

5.1 Road Congestion Caused by Emergencies

Some emergencies may cause the blockage of road or exit, which may affect the results of Path Selection Model.

In fact, such a situation will not have a great impact on our model. Because the whole area is represented by entrances, exits and routes in general, if some routes or exits are blocked, only the corresponding elements need to be deleted. The results of the model may change, but the optimal solution can still be guaranteed.

5.2 Impact of Hidden Channels on Evacuation Plan

As the amount of people continues to rise, our Path Selection Model may be confused, for example, the congestion degree of an exit can't be lower than the threshold. In this situation, emergency access should be activated, which is equivalent to an extra exit. In this case, we only need to add corresponding exits when initializing the model, which will not change the optimality of the results.

Only emergency personnel and museum officials know the actual number of total available exit points, so we can't simulate them. However, it can be predicted that the activation of emergency access will greatly reduce the evacuation time.

6 Conclusion

6.1 Strengths and Weaknesses

6.1.1 Strengths

The path selection model we built is very robust. When building the model, we do not need to pay attention to specific scenarios. We only need to input the data of route and entrance while initialize the model. Thus, we can apply the model to almost all large, crowded structures.

Our model has taken tourists, psychological stress into account while planning paths, so accidents, such as trampling accidents, can be avoided to a great extent. Moreover, since we incorporate the physical strength of tourists into the Mobility Model, our model will not come out evacuation routes beyond the capacity of tourists, that is, all tourists will have sufficient physical strength to evacuate.

6.1.2 Weaknesses

Models we established do have some weaknesses.

The biggest problem is that we make the assumption that staff have the ability to persuade tourists to follow their guides and work till all the people are evacuated. In other words, all the staff are well trained. In reality, some staff may flee with the crowd instead of keep working, and our model dismisses such situation.

Furthermore, we assume that people will help with each other and nobody will lose his mobility. If someone is tracked on someplace and nobody is going to help him, the evacuation time will be unpredictable, and wo didn't take this situation into consideration.

6.2 Suggestions to the Louvre Manager

Once an emergency occurs, managers should gather the information of the blockage of routes and amount of tourists immediately. The rescue channel should also be decided. Our model is able to work out an evacuation plan in seconds, so managers have enough time to delivery tasks to staff to guide the people.

According to our algorithm, we found that during the evacuation, the Denon on the level 1 and the Richelieu on the second floor will be more crowded, because there are some popular collections (Mona Lisa's smile) and relatively fewer stairs in these areas. Therefore, we suggest to arrange more staff and set up more alternative stairs in these areas.

The flow density should be monitored in real time. Based on the density of visitors, the distribution of staff should be pre-arranged. The arrangement should be adjusted based on real-time distribution of tourists. When the flow density reaches the threshold, limits of the entrance are required.

Otherwise, increasing the volume of broadcasting, posting notices at key locations and setting emergency lights are optional measures to enhance the comfort effect of staff.

References

[1] GuangJun Hu, "Research on Problems Related to Evacuation Path Assignment Model of Metro", China Academic Journal Electronic Publising House, 2011.

[2] K.Xie, Y.Song, B.Liang, "Research on Panic Transmission and Intervention Strategy in Crowd Evacuation", Chinese Journal of Management, Vol.16 No.2, Feb 2019.

[3] X.Tong, "Simulation of Crowd Evacuation Based on Particle Discrete Element Method", Journal of Safety and Environment, Vol.18, No.6, Dec 2018.

[4] www.louvre.fr/en/plan

Appendices

Appendix A Pseudo code of Path Selection Model

```
initialize();//input the information of the Louvre
             //and devide each floor into several units.
while true:
    for unit in All_Units:
        people = unit.produce_NewPeople()
        // the unit produce a number of people
        people.choose_exit()
        //people produced in the same time will head to the same exit
        All_People.append(people)
    for people in All_People:
        people.move()//the distance is dicided by Mobility Model
        stress = caculate_Stress_Of_People(people)
        if stress > S_threshold:
            record the location of people;
            //record the place that espacilly needs staff
        if people is in exit:
            if exit.Congestion_degree > C_Threshold
                and people.Move_Distance < L_threshold:
                people.choose_exit()
                //head to another exit if this exit is too crowded
            else:
                unit.target_exit
                All_People.delete(people)
                recaculate(Congestion_degree)
                //successfully departure
    t = t + t0;
    if All_People == NULL://evacuate over
        break
t is the total time we get.
```